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Developing and applying synthesis models of emerging space systems

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MONTEREY, CALIFORNIA

THESIS

DEVELOPING AND APPLYING SYNTHESIS MODELS OF EMERGING SPACE SYSTEMS

by

Michael M. Ordonez

March 2016

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DEVELOPING AND APPLYING SYNTHESIS MODELS OF EMERGING SPACE SYSTEMS

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

The Department of Defense's (DOD) large satellites provide robust capabilities, but they are ill designed to combat emerging threats and concerns like anti-satellite weapons and a shrinking defense budget. Small satellites are a potential solution to this challenge, but the technology is too nascent for the DOD to deploy. This thesis addressed the DOD's need for further research on small satellites by providing a set of decision support tools that enables the exploration of small satellite physical trade-offs early in the conceptual design phase of the DOD space acquisition process. Early phases of the systems engineering process were used to identify DOD small satellite requirements and key input factors and output responses that drove meta-model development through the use of model-based systems engineering. Microsoft Excel and JMP software were employed to build synthesis models used in the decision support tools developed. The decision support tools analyzed the relationship between small satellite design inputs and outputs to provide trade space insights that can assist DOD space acquisition professionals in making better decisions in the conceptual design phase. More informed decision-making in the space acquisition process might preserve valuable DOD resources that may have otherwise been wasted.

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LIST OF ACRONYMS AND ABBREVIATIONS

1U	one-unit CubeSat
2U	two-unit CubeSat
3U	three-unit CubeSat
ADCS	attitude determination and control system
AEHF	Advanced EHF
AFRL	Air Force Research Laboratory
AO	area of operations
AOA	analysis of alternatives
AOR	area of responsibility
ASAT	anti-satellite
BLOS	beyond line of sight
bps	bits per second
C2	command and control
Cal Poly	California State Polytechnic University
COA	course of action
CONOP	concept of operations
DOD	Department of Defense
DOE	design of experiments
DSCS	Defense Satellite Communications System
EHF	extremely high frequency
EO	electro-optical
EPS	electrical power system
FOB	forward operating base
FOR	field of regard
FOV	field of view
FY	fiscal year
GAO	Government Accountability Office
Gbps	gigabits per second
GEO	geosynchronous orbit
GNSS	global navigation satellite system

GLONASS	Global Navigation Satellite System
GPS	Global Positioning System
HAAS	high-altitude air ships
HALE-D	High Altitude Long Endurance-Demonstrator
HEO	highly elliptical orbit
HUMINT	human intelligence
IA&T	integration, assembly, and testing
IC	intelligence community
ICE-Cap	Integrated Communications Extension Capability
IPL	integrated priority list
IR	infrared
ISR	intelligence, surveillance, and reconnaissance
JFCC-Space	Joint Functional Component Command for Space
JP	Joint Publication
kbps	kilobits per second
KKV	kinetic kill vehicle
LEMV	Long Endurance Multi-Intelligence Vehicle
LEO	low Earth orbit
M&S	modeling and simulation
MAP	microsat acquisition paradigm
Mbps	Megabits per second
MBSE	model-based systems engineering
MEO	medium Earth orbit
Microsat	microsatellite
MILSATCOM	military satellite communications
MILSTAR	Military Strategic and Tactical Relay
MIO	maritime interdiction operations
MOE	measures of effectiveness
MOP	measures of performance
MS	Microsoft
MUOS	Mobile User Objective System
Nanosat	nanosatellite

NOLH	Nearly Orthogonal Latin Hypercube
NPS	Naval Postgraduate School
ORS	Operationally Response Space
ORSES	ORS Enabler Satellite
OTH	over the horizon
OV-1	operational view-1
PEO	program executive office
PNT	position, navigation, and timing
R&D	research and development
RDT&E	research, development, test, and evaluation
SATCOM	satellite communications
SBIRS	Space-based Infrared System
SE	systems engineering
SMAD	Space Mission Analysis and Design
SMDC	Space and Missile Defense Command
SMDC-ONE	SMDC Operational Nanosatellite Effect
SNaP-3	SMDC Nanosatellite Program-3
SOF	special operations forces
SPAWAR	Space and Naval Warfare Systems Command
SWORDS	Soldier-Warfighter Operationally Responsive Deployer
SwRI	Southwest Research Institute
SHF	super high frequency
STK	Systems Toolkit
TPM	technical performance measures
TT&C	telemetry, tracking, and command
TT&C&DH	telemetry, tracking, command, and data handling
UFO	UHF Follow-On
UHF	ultra high frequency
ULA	United Launch Alliance
U.S.	United States of America
USAF	United States Air Force
USPACOM	United States Pacific Command

USSOCOM	United States Special Operations Command
USSOUTHCOM	United States Southern Command
WGS	Wideband Global SATCOM

EXECUTIVE SUMMARY

The Department of Defense (DOD) relies on space-based capabilities to maintain the advantage in modern warfare. Satellites have been critical force enhancement tools for over two decades, and have been particularly important in the mission areas of military satellite communications (MILSATCOM) and intelligence, surveillance, and reconnaissance (ISR) collection. While the DOD's large satellites provide a robust capability, they are ill designed to combat emerging threats and concerns like anti-satellite (ASAT) weapons and the DOD's gradually shrinking defense budget. If the DOD wants to maintain its military advantage, it must seek out innovative solutions to protecting its space-based capabilities. One solution is the disaggregation of large satellites in favor of constellations of smaller satellites. Unfortunately, small satellites are still a relatively new technology whose application needs further exploration before deployment, especially by the DOD. This thesis sought to address the DOD's need for further exploration by providing a set of decision support tools that enable the exploration of small satellite designs early in the conceptual design phase of the DOD space acquisition process.

This thesis used two techniques to develop the decision support tools, the systems engineering process and model-based systems engineering. The systems engineering process is a well-known methodology that assists in mapping stakeholder needs and requirements to specific functions the system must perform in order to be an effective solution. This thesis was concerned with supporting decision making during the early conceptual design phase, so it focused on the first two phases, definition of need and conceptual design. Completing those phases identified DOD small satellite requirements and traced them to key input factors and output responses that informed the initial tool built in Microsoft Excel. After identifying the key input factors and output responses, a design of experiment (DOE) was applied to produce data that could then be analyzed in JMP. The JMP software provided an opportunity to analyze the relationships between the input factors and output responses of satellite design both quantitatively and graphically. The meta-models derived from the JMP statistical analysis were used to build the

synthesis model of DOD small satellites that allowed for exploration of the spacecraft design trade space through a trade space analysis worksheet developed in Microsoft Excel. The Excel model computes values of specific output responses based on input factor values submitted by a user. Those estimated values provided an understanding of how changes to input values can also manifest changes in the output responses, thus providing an opportunity for exploring different trade-offs in small satellite design. The JMP software provided an additional opportunity to graphically explore the trade space of a small satellite design through the trade space exploration tool, which was developed by this thesis. This trade space exploration tool also provides estimated output response values, but then displays them in a graph, allowing the decision maker to visualize the amount of margin available to make changes in the feasible design. The resultant insights can assist DOD space acquisition professionals in early conceptual design of a small satellite to make better decisions.

With the analysis and information provided by the decision support tools, DOD decision makers now have an opportunity to conduct quick feasibility assessments on proposed small satellite designs very earlier in the conceptual design phase rather than discovering problems later in the process. By receiving the feasibility analysis earlier, decision makers may have an opportunity to more effectively apply resources to small satellite programs that meet mission requirements. Additionally, the decision support tools can be used in conjunction with a utility assessment method. In the case of equally feasible designs, the two decision support tools can provide a means for space system design adjustments during utility analysis. In the long run, more informed decision-making in the space acquisition process might preserve valuable DOD resources that would have otherwise been wasted. This thesis was a proof of concept that sets a foundation for future work. With additional analysis and expansion of the scope and focus, the products of this thesis can be enhanced and possibly one day operationally deployed to the benefit of the DOD.

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In addition, I would like to thank Mary McDonald of the NPS SEEDS Center for her help with the DOE and building the macro used in this thesis.

Finally, I would like to thank my wife, Laurie, who has listened to me complain about this thesis for close to a year. It is finally over!

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I. INTRODUCTION

A key area of concern regarding modern and future asymmetric warfare is the adversary’s growing desire and capability to diminish and degrade the United States’ space capabilities. Satellites have been force-enhancing tools for the U.S. military for decades, but threats have emerged that force the Department of Defense (DOD) to reconsider the future of its space-based capabilities. This chapter introduces the problem with the DOD’s current fleet of large satellites. Also discussed are the research questions that drove this thesis, the contributions provided by the work, a short discussion of the methodology and scope of the work, and finally a description of the rest of the thesis chapters.

A. PROBLEM STATEMENT

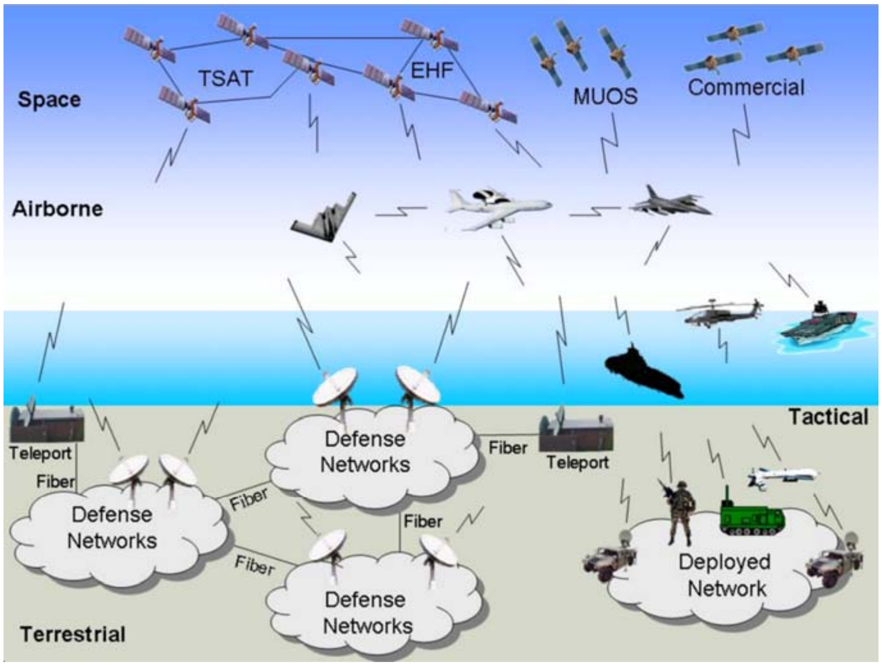
U.S. forces increasingly depend on space systems to provide and/or enhance command and control (C2), communications, and intelligence, surveillance, reconnaissance (ISR) capabilities for warfighters in every domain. While the satellites in use by the DOD are highly capable, these satellites cost hundreds of millions of dollars to develop and require several years to design and build, due in large part to their massive size (i.e., a mass of several thousand kilograms). As a result, only a few satellites are made for each program. For example, it is not uncommon for DOD constellations to have just three to six satellites. China and Russia are well aware of the military advantage gained by space-based capabilities, and in a potential conflict with the United States, they will likely attempt to disable or destroy key U.S. military satellites early using anti-satellite (ASAT) weapons. Adversaries recognize that destroying a few key satellites could significantly degrade U.S. military operations, and it would cost the United States considerable time and resources not available during a conflict to reconstitute that capability. This threat makes it imperative that the DOD seek out new and innovative ways to mitigate risk and ensure continued access to space assets while meeting increasingly restrictive resource requirements.

To accomplish this task effectively, DOD decision makers must be provided with more accurate design information earlier in the space acquisitions process. This information could better support decision makers to sort through proposed space programs and determine which solutions are physically feasible, meet cost and schedule needs, and improve combat effectiveness in the face of adversary threats. Decision makers need the ability to explore the trade space of emerging space programs to gain insight and make educated acquisition decisions focused on operational effectiveness. Unfortunately, there is currently no tool available to assist decision makers in assessing a design's physical feasibility or relate operational performance to design trade-offs.

B. SATELLITE USE IN THE U.S. MILITARY

Since the first Gulf War in 1990, space-based capabilities have been a crucial component in modern warfare. Space-based technology has expanded the reach of military operations beyond "over the horizon" (OTH), allowing militaries to sustain a global presence. Satellites have also increased the speed of communications and information flow, allowing military operations to move much faster than ever before. Tactics and commands that previously took hours to days to disseminate and execute now take as little as a few minutes or possibly even seconds. Joint Publication (JP) 3–14: Space Operations was written to address this emerging war-fighting domain, stating that space-based capabilities "have proven to be significant force multipliers when integrated into military operations" (Joint Chiefs of Staff 2013, ix). JP 3–14 defines various space mission areas, including space force enhancement, which is meant to "increase joint force effectiveness by increasing the combat potential of that force" (Joint Chiefs of Staff 2013, xi). Satellite technology is an important tool in the space force enhancement mission area. As the last superpower after the Cold War, the United States has taken advantage of satellite technology, incorporating its capabilities into all war-fighting domains. Figure 1 is an operational view (OV-1) chart illustrating how satellites are generally used to transmit data throughout the DOD's information network, including to airborne, sea-based, and terrestrial platforms.

Figure 1. MILSATCOM OV-1



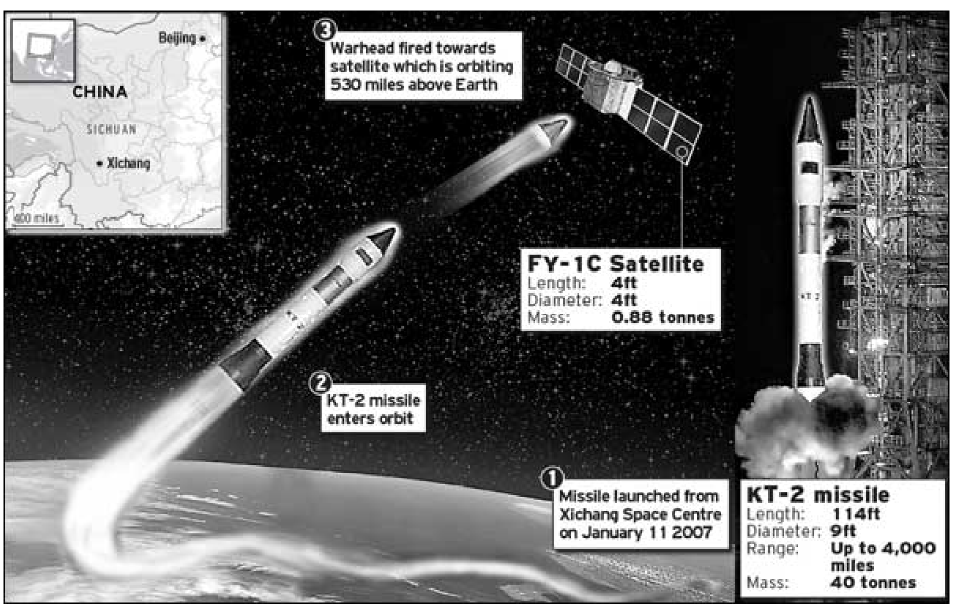
Source: Ballard, Mark. 2014. "Drone Kill Communications Net Illustrated." *Computer Weekly*. June 13. http://www.computerweekly.com/cgi-bin/mt-search.cgi?blog_id=102&tag=GIG&limit=20.

As the figure shows, satellites have become an integral part of communications and information exchange across different warfare domains in the DOD. Satellites provide different capabilities to the DOD, chief among them communications and ISR data collection. Military satellite communications (MILSATCOM) allow warfighters around the world to communicate with fellow warfighters and strategic leaders. Recent technological advances have increased SATCOM throughput and capacity, allowing more users to share voice, written, and visual/video information at data rates previously achievable only through terrestrial landlines. These let the U.S. military act and react faster than adversaries to the changes on the battlefield, providing the United States a tactical advantage in war. Likewise, ISR data has been invaluable to strategic and tactical operations planning, allowing staffs, decision makers, and warfighters to drastically reduce the "fog of war" during operations. ISR data can provide information on adversary force positioning and strength, and confirm enemy locations and current state. ISR can now be collected and shared more quickly and securely through the use of satellites, gathering information nearly nonstop and reducing the need for riskier forms of intelligence gathering (i.e., human intelligence or HUMINT or airborne ISR over denied areas).

C. THREATS TO DOD SATELLITE CAPABILITIES

For years, the United States has used space to maintain a military advantage, but new threats have emerged that could jeopardize this advantage by negating the benefits provided by satellites. China has surfaced and Russia has re-emerged as near-peers with regard to military space capabilities, competing for the use of space to gain the advantage in combat. The recent reintroduction of ASAT weapons and their testing is particularly alarming for U.S. space operations. China first revealed its ASAT weapons technology in January 2007, when it launched a ground-based ballistic missile into low Earth orbit (LEO) to purposely destroy one of its own weather satellites (Gruss 2015). Figure 2 is a graphic from *The Telegraph*, a United Kingdom newspaper, illustrating the process of China's ASAT test in 2007.

Figure 2. Chinese ASAT



Source: Spencer, Richard. 2007. "Chinese Missile Destroys Satellite in Space." *The Telegraph*. January 19. http://www.telegraph.co.uk/news/worldnews/1539948/Chinese-missile-destroys-satellite-in-space.html.

Additional Chinese ASAT demonstrations include a missile launch in 2013 and a "nondestructive missile defense test" in July 2014. Dean Cheng, a senior research fellow with the Heritage Foundation, a conservative think tank in Washington, DC, has said that China's ASAT development appears to be ongoing. Cheng's research also indicates the Chinese missile launch in 2013 was testing for an ASAT system meant to target satellites in geosynchronous orbit (GEO) (Gruss 2015). While speaking about China's successful ASAT testing in 2014, Lieutenant General John "Jay" Raymond, former commander of the Joint Functional Component Command for Space (JFCC-Space) and Air Force Space Command, commented that "soon every satellite in every orbit will be able to be held at risk" (Clark 2015). China's development, testing, and use of ballistic missiles as ASAT weapons is unlikely to cease or slow down in the near future, posing an immediate and future threat for U.S. space systems. The United States may be unable to stop China from using ASAT weapons, but it can take action to better protect its assets. One potential solution is the disaggregation of U.S. constellations composed of few large satellites into constellations containing a greater number of smaller satellites.

Another obstacle DOD space programs must face is the recent reduction in the U.S. defense budget, which has declined over the last several years. Based on data from the Office of Management and Budget, the U.S. defense budget is estimated to be $601.3 billion in fiscal year (FY) 2017, a loss of $120 billion from FY 2010's budget of $721.3 billion (Spring 2012). The DOD's current effort to reduce its budget has a negative effect on the continued evolution of U.S. military satellite technology. Space programs are notoriously expensive, typically costing hundreds of millions of dollars and sometimes billions of dollars. Figure 3 shows the decrease from President Barack Obama's military space budget request to the military space budget Congress approved for FY 2014.

Figure 3. Military Space Budget FY14

Military Space Budget

Figures are rounded and in millions of U.S. dollars.

Selected Programs	2013 Sequester Appropriation	2014 President's Budget Request	2014 House Appropriations	2014 Senate Appropriations	2014 Conference Appropriations
EELV	$1,482.6	$1,880.9	$1,867.9	$1,730.9	$1,512.9
SBIRS	$918.9	$964.0	$934.3	$934.3	$873.1
AEHF	$688.4	$652.5	$638.5	$652.7	$614.6
WGS	$47.8	$52.3	$52.3	$52.3	$46.6
GPS 3	$783.8	$698.9	$639.7	$693.9	$651.9
GPS 3 OCX	$320.7	$383.5	$365.5	$383.5	$373.5
Space Situational Awareness	$247.9	$419.1	$369.1	$419.1	$327.8
Joint Space Operations Center Mission System	$53.0	$58.5	$56.5	$58.5	$56.5
MUOS	$206.2	$89.2	$83.1	$89.2	$83.1

Sources: Congressional Record; Office of Management & Budget

SPACENEWS GRAPHIC

From Gruss, Mike. 2014. "Budget Bill Hits Military Satellite Programs." *SpaceNews.* http://spacenews.com/39096budget-bill-hits-military-satellite-programs/.

The difference between the president's military space budget request and what Congress approved for FY 2014 was a combined loss of approximately $600 million (Gruss 2014). The decreased budget is a troubling trend considering the U.S. military's reliance on space and adversary desires to disrupt U.S. capability. At the very least, the DOD must seek out solutions for more efficient use of the budget while maintaining its current space capabilities. At best, the DOD should look to expand and improve these capabilities in order to maintain the tactical advantage. U.S. adversaries are rapidly gaining ground in space, and the United States cannot afford to slow the evolution of its space systems.

The use of satellites has become such a crucial component of how the U.S. military conducts its operations that degrading this capability could severely diminish the strength of the U.S. military. The loss of key space systems would hamper U.S. military operations from the highest level down to the tactical systems that rely on satellites, potentially disrupting how the warfighter would perform his/her duties. Based on these threats, the DOD must consider new innovative solutions to maintain its space superiority while moving away from the traditional large and expensive satellites that take years to develop and build.

D. RESEARCH QUESTIONS

The following research questions were developed based on the background and problem statement previously discussed. These research questions drove the work completed in this thesis.

- How can model-based systems engineering (MBSE) develop a physical/synthesis model of a small satellite for use in trade space analysis?
- How can a model examine spacecraft design factors with respect to impacts on combat effectiveness?
- What information can we learn from a design model of a small satellite? How can that information assist spacecraft designers?
- Can a tool be developed to assist program acquisition decision makers in building a satellite that improves combat effectiveness?

E. CONTRIBUTION

The intent of this thesis was not to design a small satellite for the DOD or even develop potential alternative solutions. Instead, the intent was to develop a physical/synthesis model and tools that could support decision makers. These tools would respond to design factors chosen by the user (i.e., physical characteristics, cost) and allow the user to explore the trade space. The tools would then supply a graphical trade space depicting whether the inputs were physically feasible, and how much margin the user had in design factors for additional adjustments and fine-tuning.

This thesis will use accepted systems engineering (SE) practices, specifically focused on model-based systems engineering while attempting to solve the aforementioned real-world space problems. It is the author’s hope that the results are user-friendly design tools that allow acquisition professionals to trade design factor mission requirements and needs, and explore potential alternatives for feasibility using a graphical representation of the proposed satellite’s design trade space. The graphical trade space function should allow the acquisition professional to 1) assess feasibility in terms of preliminary physical designs, and 2) see how capabilities and programmatic considerations, like revisit time and cost, change when various design factors are modified within the bounds of the trade space.

The design tools are intended to be used very early in the satellite design process and by a DOD acquisitions professional who has some knowledge and experience with space and satellite design, but who is not necessarily the person designing or building the satellite (i.e., not the systems or design engineer). The tools will help DOD space acquisition professionals identify whether a proposed satellite program can physically meet the stated mission requirements. In addition to feasibility, they also provide an early estimate of a potential satellite's preliminary design factors to include mass, size, capability, and cost. Knowing and understanding these preliminary factors early in conceptual design will provide the acquisition professional a realistic expectation for the proposed satellite, which will save both time and costs later in the design and build process.

F. METHODOLOGY

This thesis used a SE methodology to address a space problem. Specifically, the work applied the SE process as defined in *Systems Engineering and Analysis* by Blanchard and Fabrycky (2011). This thesis did not need to consider the entire life cycle of a system because it did not involve design of an actual space system. Instead, the work is focused on the early steps of the SE process, specifically conceptual design. Like all SE processes, steps have been modified to address this thesis's specific problem. These steps included defining the problem, identifying stakeholder requirements and requirements analysis, conducting a functional decomposition of the system, and developing measures of effectiveness and key factors, which were used to build the synthesis model tool.

G. SCOPE

In accomplishing the SE tasks to meet the stated contributions, this thesis was scoped into four specific areas. First, this thesis focused on the use and design of small satellites as opposed to the typical larger satellites the DOD is using almost exclusively today as a solution to disaggregating large satellites. Small satellites provide a potential solution to the ASAT threat through disaggregation; a constellation made of many small satellites provides many smaller targets, forcing an adversary to expend more ASAT resources and/or diminishing the effects of an ASAT weapon on the capability. For this thesis, a “small satellite” is defined as any satellite with a mass less than 500 kilograms, and includes smaller size categories used by industry professionals such as microsatellites (10-100 kilograms) and nanosatellites (1-10 kilograms). While 500 kilograms was the defined upper limit for this thesis’s focus, more consideration was given to satellites within the microsatellite mass range. That range more closely met the masses and sizes of the small satellite designs currently emerging in both the U.S. government and commercial sectors.

Second, only DOD space programs were considered. Focusing on DOD programs provided a more realistic understanding of requirements for the thesis because those programs have made it through the DOD acquisitions process, rather than considering commercial or foreign alternatives that have not been approved for DOD use. This includes a literature review of past work investigating the DOD’s potential use of small satellites, stakeholder mission needs and requirements for a small satellite, and small satellite programs being developed and/or field tested by the DOD. Commercial small satellite designs, requirements, and needs were not included unless it was found the DOD also required those same considerations. Foreign small satellites also were not considered during the thesis work.

Third, only two space force enhancement components were examined in this work: satellite communications (SATCOM) and ISR. While other space components are important, the majority of DOD satellites have historically been built to provide force enhancement in these two mission areas. This is especially true for the U.S. Navy, which is more commonly seen as a space consumer rather than producer or operator. Other space force enhancement mission areas such as position, navigation, and timing (PNT) have produced satellite programs like the Global Positioning System (GPS), but the overwhelming majority of satellite programs reside in the SATCOM and ISR mission areas.

Last, considering the focus on small satellite design and use, low Earth orbit (LEO) was exclusively examined. This thesis will delve into more specific details in later chapters, but the focus on LEO is due to the technological limitations of small satellites used in SATCOM and ISR, and also DOD satellite requirements (likely for the same physics-based reasons). Constellations of small satellites operate more effectively in LEO than other orbits, as opposed to large satellites that possess more power and capability and thus can operate at higher altitudes.

H. THESIS ORGANIZATION

This thesis is organized into six chapters, with the forthcoming chapters going into greater detail regarding the work completed in an effort to solve the problem addressed in this chapter. Chapter II is the literature review, outlining the research conducted on the DOD's current catalog of large satellites, emerging space systems threats to DOD satellites, and the DOD's potential use of small satellites as a solution. The literature review discusses two specific areas of previous research: the design and use of small satellites within the DOD and the use of systems engineering in DOD capability design. Chapter III discusses the SE process and methodology used to provide the foundation for the model. Application of the SE process is also discussed, as are the results of applying that process to this problem, including identification of the primary DOD small satellite mission requirements, and defining the key factors based on those needs. Chapter IV discusses the development of the decision support tools, including the input and output design factors used, the mathematical equations used to produce those outputs, using the results of the tools to develop a model, and how the model was used to provide a trade space output. Chapter V provides a scenario simulation of how the tools may be used by DOD space acquisition professionals to assist in feasibility assessments on behalf of operational commands. Chapter VI summarizes this work and provides closing thoughts and recommendations for follow-on work.

II. LITERATURE REVIEW

It is important to review the history and work in the field of DOD space-based systems in order to provide a foundation for the work and contributions accomplished by this thesis. Understanding the DOD's historical use of space-based systems and additional research regarding their design will provide the context from which this thesis was established. This chapter discusses the DOD's current use of satellites, their capabilities, their disadvantages, the threat, and how emerging space capabilities can be used to mitigate operational risk. This chapter introduces the reader to work that has been done in the field of small satellite design, including commercial advances in small satellite design and DOD small satellite research and development programs. Also discussed are studies and research concerning the DOD space acquisitions process for new systems and the historical use of model-based systems engineering in DOD military systems design.

A. SATELLITES IN THE DOD

The DOD's current use of satellites predominantly falls into three broad areas: SATCOM, ISR, and PNT. SATCOM satellites allow warfighters to communicate with each other in-theater and around the globe without relying on ground-based telecommunication lines. ISR produces imagery and other products that provide information on allied and adversary locations and order of battle. The United States' intelligence community (IC) owns and manages most of the U.S. ISR satellites, though the DOD relies heavily on its products for intelligence and operations planning. PNT refers to the use of satellites to provide positional information for platforms and warfighters and timing to synchronize military systems for coordination. PNT is primarily provided by the Global Positioning System (GPS) constellation, which is owned by the DOD and managed by the U.S. Air Force (USAF), but this thesis will not concentrate on PNT beyond a short discussion.

The DOD is continuously replacing its older satellite systems with newer, more capable, and more robust satellites. Unfortunately, the latest generation of DOD satellites share many similarities with the legacy systems they are replacing and fail to account for emerging threats. These similarities include extremely large, complex, and capable satellites operating in constellations of a small number of satellites primarily in geosynchronous orbit. These factors allow for maximum support and capability to the warfighter and global coverage using fewer satellites. While these designs have many advantages, they also come with risk. Billions of defense dollars and decades of labor make the current generation of DOD satellites critical systems, which are expected to last for over a decade. However, the rapidly evolving realm of space technology and the emergence of space-capable nations like China put the current generation of DOD satellites at risk.

1. Military SATCOM

One critical space force enhancement component is military SATCOM (MILSATCOM). While early MILSATCOM systems provided the U.S. military the advantage of OTH voice and data communications, advances in telecommunication technology over the past 15 years has allowed more robust communications. These include the transfer of larger data files (i.e., emails, detailed imagery) and live streaming video, allowing more operationally essential information to be shared across greater distances. The DOD recognized the advantages of different bands within the electromagnetic frequency spectrum and divided its MILSATCOM systems into three primary categories: narrowband, wideband, and protected.

a. Narrowband

Mobile User Objective System (MUOS) is the DOD’s next generation narrowband tactical SATCOM system, replacing the older Ultra High Frequency (UHF) Follow-On (UFO) system to provide UHF band communications to the warfighter. MUOS is designed to provide cellphone-like communication services (i.e., voice and data) to small receiver terminals and mobile users who may be operating in disadvantaged areas (i.e., mountains, jungles, “urban canyons”) at data rates up to 384 Kbps (Space and Naval Warfare Systems Command 2014). The MUOS constellation is made of four satellites and a single on-orbit spare spaced in geosynchronous orbit, providing global SATCOM coverage. The MUOS satellites have a dry mass of 3,812 kilograms (Spaceflight101 2016b).

b. Wideband

Wideband Global SATCOM (WGS) is a DOD wideband SATCOM system, which replaced the older Defense Satellite Communications Systems (DSCS) to provide wideband SATCOM in the Super High Frequency (SHF) band. WGS's use of SHF allows it to provide more secure communication channels (i.e., low probability of intercept/detection, jam resistant) than UHF, and higher data rates ranging from 2.1 to 3.6 Gbps of total capacity (Spaceflight101 2016c). The current on-station WGS constellation contains seven satellites in geosynchronous orbit, each with a mass of approximately 5,987 kilograms (Air Force Space Command 2015b). WGS is viewed by the DOD as the "backbone of the U.S. military's global satellite communications," providing voice, data, video, and other telecommunication services to warfighters on the ground and ships at sea (Air Force Space Command 2015b).

c. Protected

Advanced Extremely High Frequency (AEHF) is the DOD's modern protected SATCOM system, replacing the older Military Strategic and Tactical Relay (MILSTAR) system. AEHF operates in the EHF band and provides survivable (i.e., nuclear) and protected (i.e., jam-resistant) communications for both strategic and tactical operations despite disadvantaged conditions (i.e., nuclear war) (Lockheed Martin 2016b). The AEHF constellation is composed of three satellites with an approximate mass of 6,170 kilograms, though Lockheed Martin is contracted to build a total of six satellites. AEHF can support a variety of data rates, ranging from compatibility with MILSTAR's low data rates of 75 bps to 2,400 kbps to higher data rates up to 8.191 Mbps (Spaceflight101 2016a).

2. ISR Satellites

The U.S. military has relied on satellites to collect ISR data since the 1960s when the Corona satellite was used to gather photographic imagery of the former Soviet Union

(Moltz 2011, 104). Since then, the DOD has expanded the ISR data it requests to include weather patterns, geological and terrain data, and intelligence on electronic signals emitted from ground and sea-based sensors. Gathering intelligence through space-based systems, especially satellite imagery, has become vital to the U.S. intelligence community and military operations planning.

The majority of ISR systems used by the DOD are classified programs, however, missile warning satellites offer a similar product to ISR, and conduct somewhat similar missions. Space-Based Infrared System (SBIRS) is a missile warning satellite system that uses short wave and mid-wave infrared (IR) sensors to conduct surveillance from space (Air Force Space Command 2015a). SBIRS' IR payload makes it a critical system for detecting missiles launches and providing early missile warning, missile defense, battle space awareness, and technical intelligence gathering. The SBIRS constellation uses four systems, two hosted payloads in a highly elliptical orbit (HEO) and two government-owned satellites in GEO, which are managed and operated by U.S. Air Force personnel. The two SBIRS payloads on host satellites have a mass of approximately 245 kilograms, less than 10% of the 2,540 kilograms total mass of the GEO satellites (Air Force Space Command 2015a).

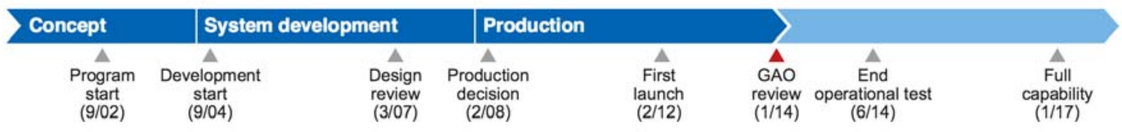
3. PNT Satellites

The DOD's PNT space force enhancement mission is achieved through the GPS constellation. The GPS constellation uses 24 satellites in medium Earth orbit (MEO) equally spaced across six different planes to provide PNT services around the world 95% of the time (National Coordination Office for Space-Based Positioning, Navigation, and Timing 2016). While the GPS constellation is maintained and operated by U.S. Air Force personnel, GPS provides precise navigation services to all civilians around the world in addition to the U.S. military. GPS satellites have a mass of approximately 3,680 kilograms (Los Angeles Air Force Base 2014). GPS is the premiere global navigation satellite system (GNSS) in the world though space near-peers like Russia and China are trying to field their own GNSS satellites, the Global Navigation Satellite System (GLONASS) and BeiDou, respectively.

4. Disadvantages of Current DOD Satellites

The most significant disadvantage of U.S. satellites is the number of key satellites in the DOD is quantifiably small yet the sizes of the satellites are large, escalating the cost of the systems. One of the DOD’s biggest challenges regarding the future of satellites is monetary cost and the time needed to develop, build, and launch these large satellites. For example, MUOS is one of the newest DOD constellations to be built and has taken more than 10 years to develop at a cost of $1.2 billion dollars per satellite as of September 2013, as shown in Figure 4 (Sullivan 2014, 97–98).

Figure 4. MUOS Program



Program Essentials

Prime contractor: Lockheed Martin Space Systems
Program office: San Diego, CA
Funding needed to complete:
R&D: $176.9 million
Procurement: $975.1 million
Total funding: $1,152.0 million
Procurement quantity: 1

Program Performance (fiscal year 2014 dollars in millions)

	As of 12/2004	Latest 09/2013	Percent change
Research and development cost	$3,836.4	$4,511.6	17.6
Procurement cost	$3,192.1	$2,867.4	-10.2
Total program cost	$7,069.1	$7,448.1	5.4
Program unit cost	$1,178.186	$1,241.345	5.4
Total quantities	6	6	0.0
Acquisition cycle time (months)	90	NA	NA

Latest acquisition cycle time could not be calculated because the most recent MUOS program baseline does not estimate dates for operational capability.

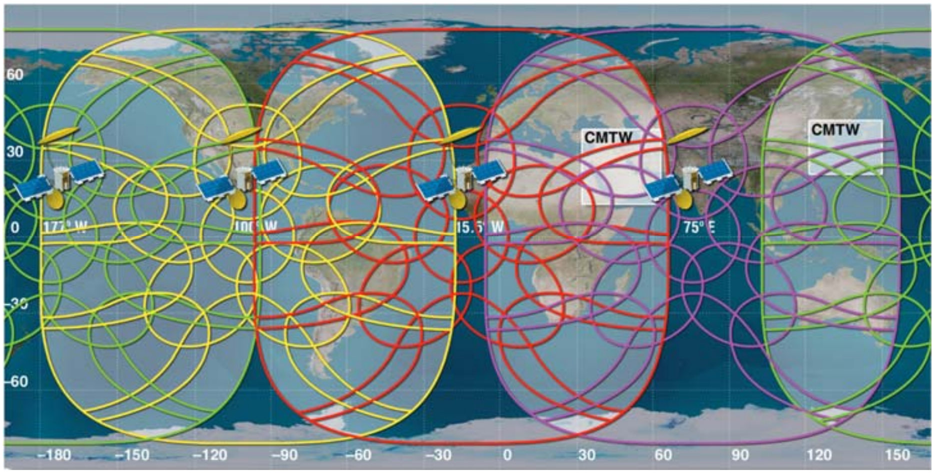
Source: Sullivan, Michael J. 2014. *Defense Acquisitions: Assessments of Selected Weapon Programs*. GAO-14-340SP. Washington, DC: U.S. Government Accountability Office. http://www.public.navy.mil/spawar/Press/Documents/MUOS/GAO_ASWP_March2014_MUOS_S.pdf.

As the figure shows, the MUOS program has taken 14 years to produce a satellite system and is still not projected to reach full capability until January 2017 despite a $1.2 billion dollar investment by the DOD. While these satellites provide a robust SATCOM capability and global coverage using only four satellites, the growth of small satellite technology and new trends in disaggregation suggest that a similar capability and effect could be had for much cheaper and much more quickly, while avoiding many of the risks faced by larger satellites.

In addition to cost, another disadvantage of U.S. military satellites is that they are vulnerable to ASAT technology developed by potential adversaries. ASAT technology can deny, degrade, disrupt, deceive, or destroy satellites in a number of ways. Non-destructive systems can include signal jammers or electro-optical countermeasures while more destructive methods include kinetic-energy weapons like guns and fragmented warheads, or directed-energy weapons like lasers or particle accelerators (U.S. Congress Office of Technology Assessment 1985). These provide adversaries a wide range of options for interfering with or destroying U.S. satellite capabilities. However, the U.S. military seems most concerned with kinetic kill vehicles (KKV), specifically the direct ascent ASAT weapons China is currently producing, due to their ability to completely destroy systems and put others at risk.

Direct ascent ASAT weapons are essentially ballistic missiles launched from Earth into space with the purpose of destroying satellites. Despite their destructive potential, direct ascent ASAT weapons are still a nascent technology, even for space-capable nations like China, and thus are a prized resource. As such, an adversary would likely seek to use that capability against a high value target at a time when its destruction would produce the greatest negative effects. In this case, the operational risk to larger satellites is much greater than the risk to small satellites because there are fewer targets that an adversary must attack to produce a proportional negative effect. As an example, the MUOS constellation is composed of four satellites providing global coverage with some overlap between each other. If an adversary deemed MUOS critical to the United States' war fighting capability during a conflict, it is likely they would use one or more ASAT weapons to destroy one or more of the MUOS satellites. As seen in Figure 5, the loss of one or two MUOS satellites (the satellite over Asia and China, for example) results in a gap in UHF SATCOM capability for the warfighters in that operating area. Other than the single on-orbit spare, which would still need time to reposition into the gap, the UH SATCOM loss is not easily recoverable due to the build and production timeline for MUOS.

Figure 5. MUOS Coverage



Source: Oetting, John D., and Tao Jen. 2011. "The Mobile User Objective System." *Johns Hopkins APL Technical Digest,* 30: 106. http://www.jhuapl.edu/techdigest/TD/td3002/Oetting.pdf.

Even if the adversary has limited counter-space capabilities, it is possible to effectively degrade U.S. space capability. However, that effect becomes much more difficult for the adversary to achieve as the number of targets (i.e., satellites) increases, as would be seen through implementation of the disaggregation concept. By comparison, a constellation of dozens of smaller satellites makes the constellation a less desirable target for limited high cost weapons systems like ASAT weapons, which would need to destroy many satellites to produce the same effect. Thus, the cost for the adversary is increased because of U.S. satellite disaggregation.

In 2014, the Government Accountability Office (GAO) conducted a study to learn more about the feasibility of disaggregating large satellite constellations in favor of constellations made of several smaller satellites (Chaplain 2014). The DOD's reported goals for disaggregating large satellites were reducing acquisition monetary cost and (operational/program sustainment) risk and improving U.S. space systems' resiliency against increased intentional and unintentional threats. The study listed potential benefits of disaggregation, which were

- Improved affordability and lower life-cycle costs
- Improved system resilience by spreading the capability across more satellites

- Increased ability to use commercial products, reduce build response time, and prevent systemic failures

- Increased advantages in the DOD acquisition process through the use of innovative business practices and more tailored acquisition

- Improved industrial base through more stable demand and higher production rates distributed over multiple contractors.

For every potential benefit, the study also listed potential limitations of disaggregation, which were

- Increased costs due to interoperability support, more complex ground systems, more satellites required to fulfill a capability, and duplication of effort in different programs

- Decreased system resilience due to increased protection for an increased number of ground stations and a more congested space environment

- Decreased capabilities due to some systems being unable to fit on smaller satellites, inability to support more frequent launches, lack of interoperability between legacy and new systems, and constraining available bandwidth

- Increased difficulty in the acquisitions process because of more rapid requirements development, the need to acquire more satellites, and complications in DOD program oversight

- Disrupted industrial base due to inability to support faster and more frequent production and interrupting the traditional providers in the current industrial base.

As shown, disaggregation into constellations of smaller satellites is not without its own operational challenges. The DOD’s potential disaggregation of large satellites also presents systemic barriers (Chaplain 2014). These include substantial changes to the space acquisition culture and process, gaps in delivery of the satellites, the ground stations, and the user terminals, which the DOD is still struggling with under the current space acquisition process. Additionally, the DOD would need to modify its practice of producing stove-piped satellite control networks and potentially incur costs associated with either building smaller launch vehicles or using the current launch vehicles that may be more capable and expensive than is needed. While the DOD is already pursuing research in disaggregation, the study stated it is too early to determine whether or not the

DOD's current analysis of alternatives (AOA) can efficiently assess disaggregation especially since the DOD lacks a standard assessment methodology to quantify resilience that can be used consistently in AOAs. Ultimately, the GAO suggested that the disaggregation of satellites was a potential solution to the DOD's goals of reduced cost and risk and improved resiliency, but confirmation would require additional research.

B. EMERGING DOD SPACE SOLUTIONS

As evidenced by the 2014 GAO study, the DOD has been looking for other space solutions that can minimize the risks associated with larger satellites, but still provide an effective capability to the warfighter. Two potential solutions that have emerged in the past decade are small satellites and high altitude airships (HAAS).

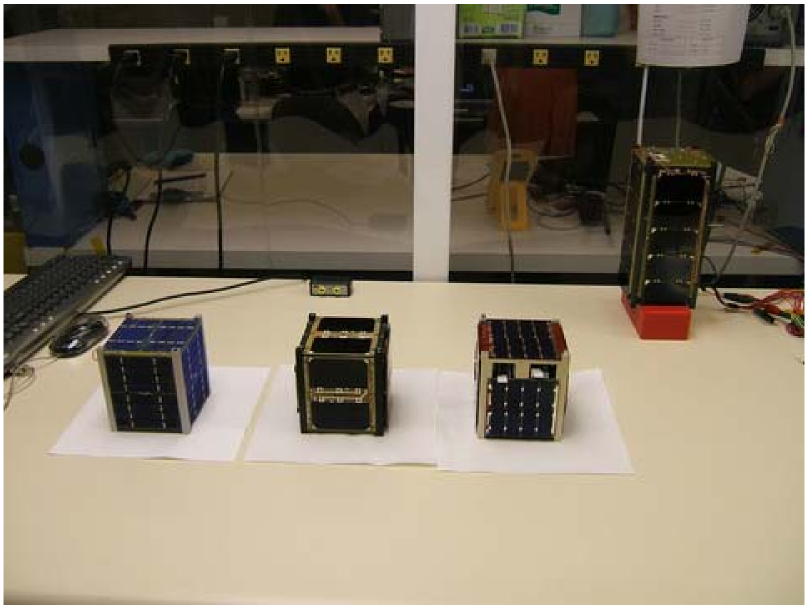
1. Small Satellites

Small satellites have captured the interest of many space professionals and enthusiasts over the past decade. Access to space was previously reserved for the wealthiest and most capable nations and companies, but advances in materials, circuitry, robotics, and information technology at the beginning of the 21st century has drastically decreased entry requirements for participation in space. Users outside of national space programs can now build satellites and arrange for their launch into space. Thanks to years of development, small satellites now provide the academic, commercial, and military space sectors a new vehicle to explore and/or use the space environment for their own benefit and purposes. The two prime areas of concern for this work are commercial and DOD use of small satellites.

a. Commercial Use of Small Satellites

As with most technology, the U.S. commercial sector is developing and producing new innovative space systems much faster than the U.S. government, primarily because companies are not as risk adverse, nor do they suffer from a bloated acquisitions process that slows innovation and development. One such innovation is the development of the CubeSat, a miniature satellite just 10 centimeters cubed with a mass of only a few kilograms (CubeSat Program 2014). These "1U" (one CubeSat unit) CubeSats, as shown in Figure 6, can be combined into larger, modular, more capable satellites, such as “2U” (two stacked CubeSat cubes) or “3U” (three stacked CubeSat cubes) designs. The CubeSat was a collaborative project between researchers at California State Polytechnic University (Cal Poly) and Stanford University who wanted to develop a standardized picosatellite design in order to minimize cost and development time. These reasons are exactly why CubeSat and other small satellite technology are beneficial to the DOD. As a result, the use of CubeSats as a cheaper solution for space systems has spread across the academic and commercial world, and has the potential to address many of the emerging threats facing U.S. military satellites.

Figure 6. CubeSats

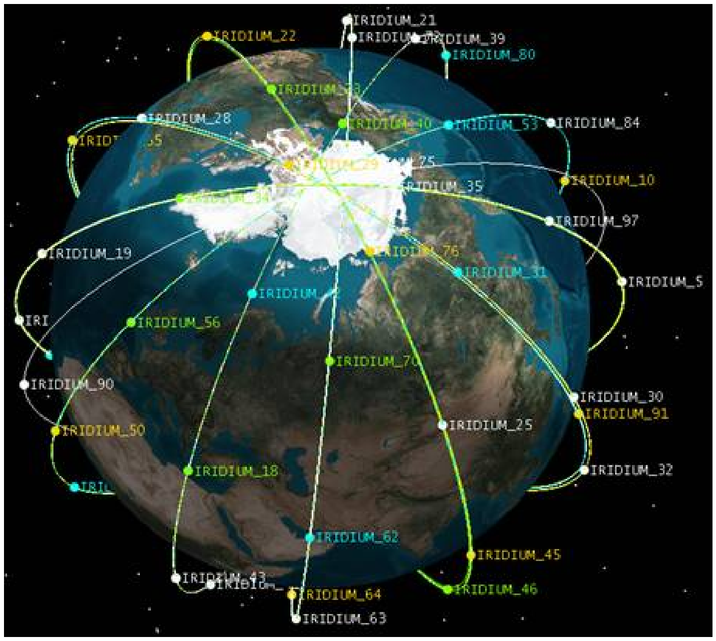


Source: CubeSat Program. 2009. “Dnepr 45 Integration.” Last modified November 8. http://htp.www.cubesat.org/index.php/media/pictures/48-dnepr-45-integration.

While the modular CubeSat is a relatively new design concept even in the commercial sector, large constellations of smaller satellites are not a new concept. Iridium has been successfully providing reliable SATCOM to mobile users in this manner for years. Iridium’s constellation is composed of 66 satellites cross-linked across six orbital planes in LEO, providing voice and data communications globally (Iridium 2015). Iridium’s satellites have a mass of only 698 kilograms, over five times less that the

DOD’s MUOS satellite, which serves a similar role (*Encyclopedia Astronautica* 2016). Figure 7 illustrates the Iridium constellation around the globe.

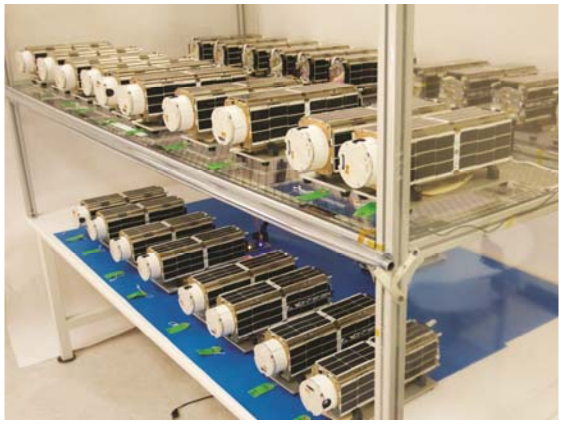
Figure 7. Iridium Constellation



Source: Jayne, Bob. 2007. “Effects of Satellite Constellation Deployment on Communication Networks.” ASEN 5050 Final Paper. University of Colorado. http://ccar.colorado.edu/asen5050/projects/projects_2007/jayne_proj/.

As shown, the Iridium constellation provides global coverage to users around the world thanks to the large number of satellites in orbit. Following in Iridium’s footsteps, U.S. companies are advancing the idea of disaggregation and building constellations of dozens of smaller satellites. Planet Labs is developing a constellation of over 100 nanosatellites (nanosats) that will provide worldwide imagery at three to five meter resolutions for use in multiple commercial, civil, and military applications (Planet Labs 2016). This is similar to services being provided by much larger commercial satellites. Figure 8 shows a rack of several Planet Labs’ nanosatellites.

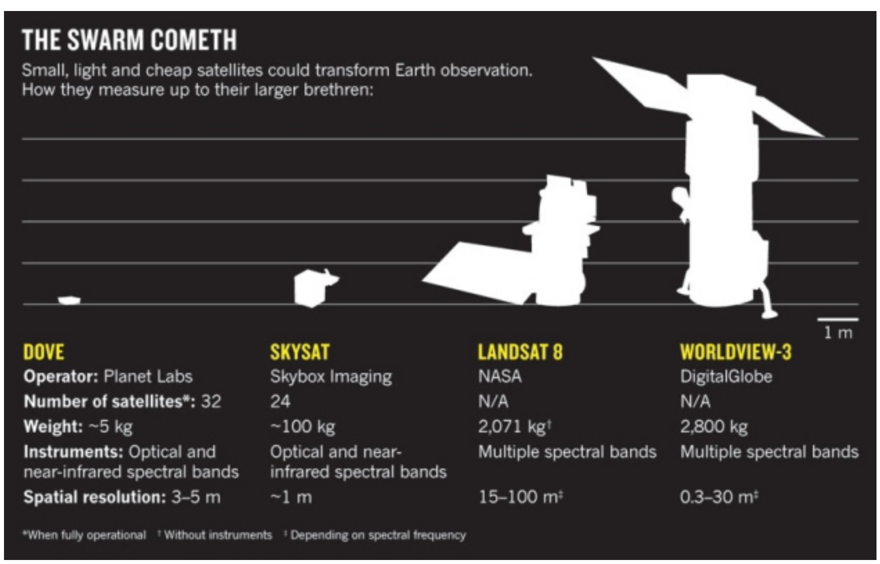
Figure 8. Planet Labs Dove Nanosat Design



Source: Werner, Debra. 2013. "Commercial Spaceflight: With 2 More CubeSats in Orbit, Earth-imaging Startup Planet Labs Ships Next Batch of 28 to Wallops." *Spacenews*, November 26. http://spacenews.com/38361commercial-spaceflight-with-2-more-cubesats-in-orbit-earth-imaging-startup/.

Planet Labs' Dove nanosats use a 3U CubeSat design and have a mass of approximately five kilograms, which is over 500 times smaller than DigitalGlobe's much larger WorldView-3 satellite (Earth Observation Portal 2016). As depicted in Figure 9, WorldView-3 has a mass of approximately 2,800 kilograms, but can provide sub-meter resolution.

Figure 9. Imaging Satellite Comparison



Source: Butler, Declan. 2014. "Many Eyes on Earth." *Nature, Volume 505, Issue 7482*. http://www.nature.com/news/many-eyes-on-earth-1.14475.

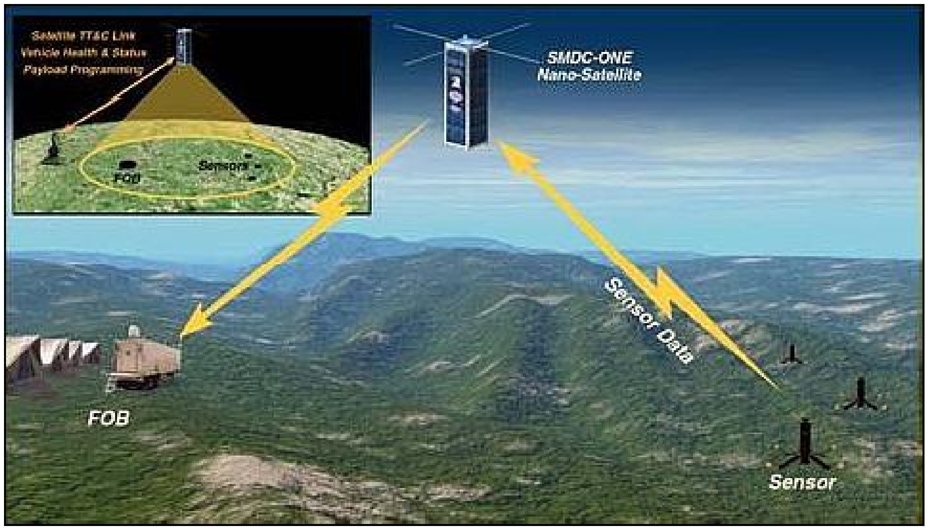
As the figure shows, Dove nanosats are 500 times lighter than WorldView-3 satellites, but Dove's resolution capability is only reduced by a factor of 10 (0.3 meters versus 3 meters, respectively). While Plant Labs' Dove satellite and "Flock 1" constellation may not be able to achieve the resolution of larger imaging satellites such as WorldView-3, it can still provide high-resolution images that may be good enough for certain applications, and do so with a significantly smaller satellite and potentially cheaper constellation.

b. DOD Use of Small Satellites

While the DOD does not currently have any small satellite programs of record, some of the DOD's space commands, such as the U.S. Army's Space and Missile Defense Command (SMDC) and the U.S. Navy's Space and Naval Warfare Systems Command (SPAWAR), have already begun research and development on the use of small satellites in military operations. This includes several operational test beds in both MILSATCOM and ISR. John London, the SMDC program manager for nanosatellite development, believes small satellites can fill a void in the DOD's current satellite arsenal. London envisions using nanosats to provide beyond line of sight (BLOS) communications and ISR for the tactical warfighter while also maintaining a relatively low monetary cost and responding quickly to operational needs (McCoy 2013).

One such program is the SMDC-Operational Nanosatellite Effect (SMDC-ONE), whose primary mission is "to demonstrate voice relay through a low-Earth-orbit satellite using military standard radios," as shown in Figure 10 (McCoy 2013).

Figure 10. SMDC-ONE OV-1



Source: Earth Observation Portal. 2016. "SMDC-ONE (Space & Missile Defense Command-Operational Nanosatellite Effect)." February 25. https://directory.eoportal.org/web/eoportal/satellite-missions/s/smdc-one.

As the OV-1 illustrates, SMDC-ONE is capable of receiving sensor data from U.S. military sensors in disadvantaged areas of operation and transmitting them to U.S. military operators located in distant forward operating bases (FOB). SMDC-ONE's maiden launch and demonstration occurred in December 2010, during which the satellite successfully received data from unattended ground sensors and spacecraft command and control (C2) commands from portable ground stations.

SPAWAR has also developed and tested a similar small satellite for the United States Navy, the Integrated Communications Extension Capability (ICE-Cap). ICE-Cap is a three-unit (3U) CubeSat planned for launch in 2016, as is shown in Figure 11.

Figure 11. SPAWAR's ICE-Cap Display

Source: Connor, Katherine. 2015. "SPAWAR Systems Center Pacific Celebrates 75 by Talking About Its Research." *The Daily Transcript*. June 9. http://www.sddt.com/News/article.cfm?SourceCode=20150609czg#.VpKMV3svpKo.

ICE-Cap's primary mission is demonstrating communication with users on secure networks using the Mobile User Objective System (MUOS), a system composed of four large satellites spaced out in geosynchronous orbit (Mroczek and Petrie 2015). SPAWAR also hopes to demonstrate ICE-Cap's ability to relay communications from users near the North Pole to other users positioned in other operational areas around the world, enhancing MUOS's global coverage to include the poles.

Another warfare community that has taken recent interest in using small satellites is special operations forces (SOF). The interest spawned from the United States Special Operations Command's (USSOCOM) desire to improve the responsiveness of space-based systems in providing tactical information to SOF operators who can be equipped with light and mobile SATCOM ground antennas as shown in Figure 12 (Mattox 2014).

Figure 12. SOF with SATCOM Ground Antenna

Source: Surviving in the city. 2016. "Current trends in special forces of foreign countries." February 25. http://survincity.com/2012/02/current-trends-in-the-special-forces-of-foreign/.

The first phase of USSOCOM's effort produced the Perseus CubeSat, a technology demonstration to prove CubeSats could be made cheaply and operated easily. The Perseus CubeSats were built for $25,000 each. In the fall of 2011, USSOCOM began its next phase, producing the Prometheus satellites with the help of the Pentagon's Office of Operationally Responsive Space (ORS). The Prometheus satellites are 1.5U CubeSats that are designed for a three to five year service life and cost less than $100,000 each. Their primary mission was to demonstrate a small satellite's ability to "transfer audio, video, and data files from man-portable, low profile, remotely located field units to deployable ground station terminals using over-the-horizon satellite communications." (Mattox 2014) Despite success with Prometheus, USSOCOM has said it does not expect Prometheus to replace services provided by current space-based systems. However, USSOCOM's CubeSat R&D efforts show a DOD command's interest in filling the capability gap of a low cost, rapidly deployable, short-term system that could still meet the warfighter's communications and ISR needs.

The DOD's research and development in small satellites does not just pertain to MILSATCOM, but includes forays into ISR payloads as well. Kestrel Eye is a nanosatellite demonstration developed by Quantum Research International, Inc. and SMDC (Keller 2014). The Kestrel Eye is a small, low-cost satellite designed to capture electro-optical images with 1.5-meter resolution and downlink those images directly to mobile and disadvantaged war fighter terminals within 10 minutes. The demonstration is meant to show that a tactical nanosat can be built relatively quickly and cheaply in large numbers in order to provide persistent surveillance coverage directly to war fighters without having to be routed to a central location for processing first (Keller 2014). While it has not been launched yet, SMDC continues to develop, test, and evaluate the Kestrel Eye nanosat as a potential ISR solution.

Ongoing R&D efforts from commands such as SMDC and SPAWAR closely mimic the commercial sector's aggressive research into the use of small satellites over the past decade. While the success of those command's efforts demonstrate the potential of small satellites as an effective capability and also the acceptance of this new technology within the DOD, there is still more work to be done before a DOD small satellite program is operational. Besides suggesting more research in small satellite technology, the GAO's 2014 study also stated transition from an R&D program into an operational one is not easy and would require potentially costly modifications to the acquisitions process. There are many aspects of the space acquisitions process that need to be addressed to make that transition, and this thesis seeks to address one of them. Specifically, this thesis seeks to improve decision making during the conceptual design phase of systems acquisition by presenting a model and tool that can provide design trade space analysis much earlier in the process. While the model and tool provided in this work are not a complete solution, they do offer a better method for supporting decision makers more effectively and efficiently, which should help improve the DOD space acquisitions process.

2. High Altitude Air Ships

High Altitude Air Ships (HAAS), also known as high altitude atmospheric satellites, are essentially unmanned blimps that are designed to operate autonomously in the stratosphere (i.e., 60,000+ feet) for extended periods of time (Lockheed Martin

2016a). The advantageous attributes of HAAS platforms are long endurance time on-station to provide persistent capability, large coverage areas (30,000+ square miles), capability of launch and recovery without the need of a runway, support for interchangeable mission payloads (i.e., communications, ISR, weather observation), and lower costs than other aircraft and satellites. While HAAS are relatively new and there has been limited work on the technology, the DOD, especially the U.S. Army, has shown recent interest in the platform.

The U.S. Army's first foray into HAAS platforms began in 2005 with the development of the Hi-Sentinel program, designed by the Southwest Research Institute (SwRI) (Southwest Research Institute 2005). SwRI worked with Aerostar International and the Air Force Research Laboratory (AFRL) to design and test the feasibility of blimps carrying communication satellites above enemy territories. The Hi-Sentinel tests proved successful remote control of unmanned blimps at an altitude of 74,000 feet by personnel on the ground, though these initial HAAS platforms could stay on-station only for five hours.

The U.S. Army followed up Hi-Sentinel with the Long Endurance Multi-Intelligence Vehicle (LEMV) in 2009 (Cummings 2009). The LEMV was designed by Hybrid Air Vehicles, a British firm, and meant to conduct surveillance missions in Afghanistan for up to 21 days at a time (Page 2014). In 2011, Lockheed Martin built a yet another HAAS platform for the U.S. Army named the High Altitude Long Endurance-Demonstrator (HALE-D) (Lockheed Martin 2016a). The HALE-D system successfully demonstrated launch and control, remote command and control, and communication links. Unfortunately for the HAAS programs, the end of the Iraq war eroded the U.S. Army's interest and thus their funding (Krisch 2014). While initially an interest area for this research and work, HAAS was not investigated further as a potential solution due to time and resource constraints. However, it is highly recommended that future work expand the work of this thesis to include HAAS as a potential solution.

C. THE CURRENT STATE OF DOD SMALL SATELLITE RESEARCH

Over the past decade, studies and research have been conducted regarding the use of small satellites in U.S. military operations. Unfortunately, there are still many unknowns that are slowing progress in this area, which are briefly addressed in this thesis. These major areas that require further research include analysis of small satellite design, constellation design, and improving the small satellite cost and acquisition process.

1. Analysis of Small Satellite Design

Research regarding small satellite design can fall into one of two general categories. The first category takes a top-down approach to the design of small satellites by extrapolating from large satellite designs and then focusing on concepts such as a standardized bus design and the trade-off between miniaturization and the loss of capability. The second takes a bottom-up approach, looking at very specific small satellite programs, discussing their design, potential deployment, and use, and factors that led to the initial requirement. While each category of research provides greater insight into the design and nature of small satellites, neither provides concrete, implementable recommendations to the DOD that can be used across multiple small satellite programs rather than a single, specific program.

a. Determining Small Satellite Design

In their conference paper titled, "Right-sizing Small Satellites," David J. Barnhart and Martin N. Sweeting discussed their attempt to optimize small satellite design. In their work, Barnhart and Sweeting examined the possibility of designing small satellites at the right size by using three top-down design factors: spacecraft utility, mission utility, and optimum cost (Barnhart and Sweeting 2014). For each of those design factors, the authors devised their own theoretical equations in an effort to score potential small satellite designs with the end goal of optimizing a specific satellite size that would meet the needs for any number of proposed missions. A "perfect" size is very desirable, but assumes that the same size can be used for any mission and any set of stakeholder requirements. In the world of DOD acquisitions, system standardization across numerous stakeholders can be very difficult if not impossible. It may be more valuable instead to focus on "robust design" by presenting a range of design alternatives with adjustable preferences in order to attempt to provide a decision maker with a trade space and allow him/her to meet as many of the requirement nuances of different stakeholders as possible.

b. Constellation Design for a Single Small Satellite Program

One example of small satellite research that looked at constellation design is Clayton Jarolimek's NPS thesis titled, "An Analysis of the Use of Nanosatellite Technology for Military Ultra-High Frequency Communications." In his 2014 work, Jarolimek looked at the Space and Missile Defense Command (SMDC) Nanosatellite Program (SNaP-3) and how a constellation of SNaP-3 satellites could be used to meet the needs of the stakeholder, United States Southern Command (USSOUTHCOM). USSOUTHCOM's primary mission requirement was to provide Ultra-High Frequency (UHF) communications to disadvantaged users (i.e., tactically deployed warfighters). Jarolimek used design information provided by the SMDC to build SNaP-3 constellation design models in System Toolkit (STK), a satellite-modeling program, and compared the different designs based on criteria such as coverage area, access duration, and revisit time. Jarolimek was able to show how the DOD could benefit from the use of decision support tools to design an efficient constellation of small satellites based on stakeholder requirements. However, it would have been better if the decision support tools were used pre-design so that the analysis and insight gained from the tools could have helped inform design. This thesis attempts to follow Jarolimek's reasoning, but provides tools to support the analysis of satellite design based on mission requirements earlier in the acquisitions process, rather than providing analysis post-satellite design as Jarolimek has done.

2. Small Satellite Cost Estimation and Acquisition

Another area of concentration for DOD small satellite analysis is cost estimation and acquisitions. This is an important consideration because cost savings are one of the proposed advantages for using small satellites as opposed to larger satellites. In their paper titled, "Microsatellites and Improved Acquisitions of Space Systems," authors Bille, Kane, and Cox (2000) introduced a conceptual approach for effectively acquiring microsatellites (microsats), which they named the Microsat Acquisition Paradigm (MAP). The authors' MAP approach is built on three pillars: 1) understanding the military's space requirements, 2) correlating those requirements with the physical capabilities of current microsat technology, and 3) the reality that microsats can be acquired with cost and time effectiveness in mind (a departure from larger satellites). The MAP approach conceptually fits with the intent of this thesis, but the authors do not offer an actual solution for implementing their approach. The MAP approach instead provides tenets to follow, which would make the use of microsats a desirable option for the DOD compared to continuing to acquire larger satellites. This thesis takes the MAP's ideology a step further by providing a tool to assist in implementing the MAP approach.

D. MODELING TO ILLUSTRATE TRADE SPACE

While the DOD and subordinate commands use various forms of the SE process during satellite design and acquisitions, new SE techniques may offer the DOD insight not previously gained. The use of modeling and simulations (M&S) in systems design is not a novel idea, but within the DOD and at NPS, its use has primarily been with regards to more traditional warfare areas such as naval ship design. An NPS thesis titled, "A Capability-Based Meta-Model Approach to Combatant Ship Design," written by Jason Fox in 2011, explored this idea. Fox used M&S to show how using combat/operational measures of effectiveness (MOE) as requirements early in the system design process rather than using physical constraints/factors (i.e., speed, stability, size, length) would produce a more effective naval ship for a specific mission (Fox 2011). Specifically, Fox used a design of experiments (DOE), a methodology used to determine the relationship between input design factors and the resultant output response of a process (SAS 2016a). By understanding the cause-and-effect relationship between input factors and output responses, output responses can be improved by manipulating the dominant input factors to maximize combat effectiveness. Fox used this process to understand the relationship between ship physical characteristics and combat effectiveness for the U.S. Navy's maritime interdiction operations (MIO). This thesis seeks to use a similar methodology by using the SE process to identify input factors and output responses based on stakeholder requirements, using DOE to identify the most dominant input factors that maximize satellite combat effectiveness, and presenting an interactive trade space that visualizes the relationships between the dominating factors and the responses the stakeholders desire.

E. CONCLUSION

As discussed, a gap exists within the DOD's current fleet of satellites. Despite a continuous evolution, DOD satellite design continues to cling to the outdated concept of a few large and expensive satellites. Unfortunately, that methodology faces new challenges that threaten to disrupt and degrade the DOD's SATCOM and ISR capabilities. New technologies like small satellites have emerged, providing a potential solution to these new threats. However, while research and development in small satellites as an alternative is ongoing, it requires additional tools to assist in the design and acquisitions process. This thesis seeks to address that gap. By using the methodologies of MBSE and DOE, this thesis provides tools that will assist decision makers early in conceptual design by allowing analysis of a small satellite's physical trade space.

III. APPLYING THE SYSTEMS ENGINEERING METHODOLOGY

This chapter discusses how early steps of the SE process were applied to the design of DOD small satellites for MILSATCOM and ISR missions. This process included defining the problem and need, conducting stakeholder, requirements, and functional analyses, and identifying the key factors that would inform and influence the design of a potential small satellite solution. While this thesis was not focused on designing any specific small satellite, the SE process used in this chapter was needed to identify the key design factors necessary to drive the modeling and development of the decision support tools this thesis produced. By using the SE process to set a foundation for tool development, this thesis was able to provide decision support tools that will assist in the early conceptual design of potential small satellite solutions. The results of this chapter justify the selection of the input factors and output responses used in model development by providing traceability to actual DOD requirements.

A. PROBLEM REFINEMENT

Before applying a SE process to the problem introduced in Chapters I and II, it is important to clearly delineate the efforts of this thesis versus those of the systems engineering process. The application of the SE process in this chapter is concerned with building a solution to the DOD's overall problem of satellite resiliency. If a complete and thorough SE process was being conducted, additional "system of systems" details would be needed, such as interoperability, ground stations, and user (i.e., a warfighter) equipment. However, those details are outside the scope of this thesis, which is focused on building a decision support tool to assist in the space acquisitions process. Thus, a modified version of the SE process is used in this chapter, and is limited to providing just the data needed to support tool development. Before the SE process can be addressed, the scope and assumptions of this thesis must be discussed. The scope and assumptions of this thesis provide the background and context in which the SE process is applied in this chapter.

1. Scope

Stating the scope helps to determine what aspects of the system should and should not be included within the body of work based on the limitations set by the project boundaries (Langford 2012, 41–42). Establishing scope ensures that one does not stray from the objectives of the effort when making decisions. While the scope can be no larger than the understood boundaries of the system, it can be minimized and focused further in an effort to solve a specific aspect of the problem. This thesis is concerned with developing decision support tools to be used during early needs refinement and conceptual design of a small satellite, an emergent system solution that can potentially resist emerging ASAT threats and budgetary constraints. This thesis was scoped in the following way.

- This thesis is focused on the prospects of a small satellite as a solution to the stakeholder's problem. Normally, the SE process does not focus on alternative system solutions until much later, but this thesis will focus only on small satellites as a solution. Other potential solutions, such as HAAS, hosted payloads on commercial satellites, or wholly relying on a commercial solution will not be investigated. Those alternatives should be examined, but remain outside the scope of this thesis.

- This thesis will focus primarily on the physical characteristics of a small satellite, and not on other factors such as political or operational considerations. Typically, those concerns are considered during the design phase of the SE process, which is assumed to be future work. Thus, this thesis will not focus outside of the system boundary.

- While elements of the decision support tools introduced later will touch on the number of satellites desired, the context is from a mass, sizing, and cost perspective and not on operational employment. This thesis is only concerned with conceptual design and not details, production, or operations. Thus, the design of a constellation is not within the scope of this work either, with the understanding that the proposed satellite would likely operate in a constellation.

- Similar to the design of a constellation, ground stations and user segments are outside the scope of this thesis. Obviously they are important factors and are necessary for completing the satellite system as a whole, but this thesis is not concerned with their design or deployment. These considerations would come later in the SE process if every step of the SE process was being applied.

- The life cycle and disposal of the small satellite at end of life are not within the scope of this thesis. The only considerations given to life cycle in this work are the realization that a small satellite solution will have a much shorter lifespan (i.e., one to five operational years) compared to the DOD's larger satellites (i.e., 10 to 15 operational years), and the idea that small satellites should be capable of reconstitution much faster compared to larger satellites.

- This thesis is not focused on any particular unit, command, or branch of service within the DOD. While small satellites may offer greater optimization for specific missions compared to large satellites designed to satisfy multiple missions that may conflict, that was not an area of focus for this thesis. This thesis maintained a broader view of the DOD's need for small satellites rather than what the U.S. Navy, Army, or Air Force needed for their own respective warfare areas.

The scoping of this thesis serves to focus the work in this chapter by providing clear delineation of the concentration areas. Due to the limitations of time and resources, assumptions must also be stated to serve as justification for liberties taken over the course of the thesis work. Similar to scoping the effort, stating the assumptions identifies which details the thesis concentrated on and which details were ignored. Listing the assumptions allowed this thesis to disregard details that are critical considerations for implementing a system solution in the real world but are also details that would detract from the intent of this work.

2. Assumptions

This thesis focused on a specific solution to a large problem, namely, small satellites. As such, assumptions must be stated so that the focus of the effort can be understood and realized. To pare down the problem to a manageable size, the following assumptions were made:

- The design and build of the system solution (i.e., the small satellite) will come after the use of the tools developed by this thesis.

- This thesis did not consider ground stations or user terminals and assumes that a proposed satellite design will be interoperable with the current system.

- Monetary costs will only consider research and development costs, build costs, and launch costs.

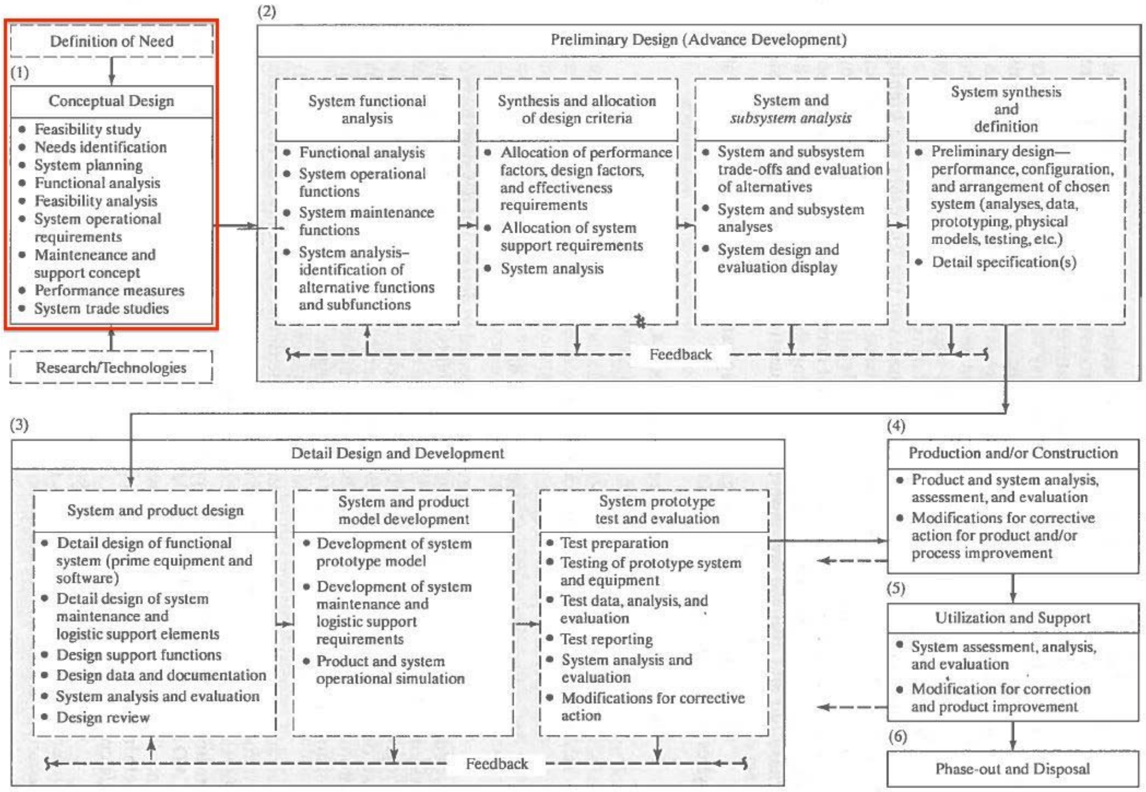
- Acquisition time will include the time needed to design a satellite, build a satellite, and launch a satellite.
- The DOD has in place a small satellite acquisitions process that can be improved with the creation of decision support tools.
- Any procedural, programmatic, or other problems within the DOD's acquisitions process will not affect satellite design.
- The mission requirements guiding conceptual design of a system solution (i.e., a small satellite) will not change during the course of the satellite's acquisition and build.

These stated assumptions serve to clarify the focus of this thesis and identify the context in which the SE process was applied. Because of the refined scope of this thesis, not all steps of the SE process were applied to the problem. Instead, only the SE steps pertinent to the thesis were applied, specifically, the definition of need and the conceptual design phase.

B. OVERVIEW OF THE SE PROCESS

Unlike other engineering disciplines, SE is a methodology that can be applied to nearly any field of industry or study. SE is concerned with solving problems by clearly identifying the current gaps causing the problem, stating requirements of a proposed solution, and using those requirements to design and build a system solution, ensuring that the system solution efficiently and effectively solves the stated problem. To ensure consistent results and application across all disciplines, the SE process was created. The SE process contains principles and objectives of SE that are generally agreed upon, but can vary in implementation from one system to the next based on the nature of the system (Blanchard and Fabrycky 2011, 33). Within the DOD, there is a particular desire to ensure the SE process encompasses and is applied to the entire system life cycle. The system life cycle process is defined by six phases, illustrated in Figure 13.

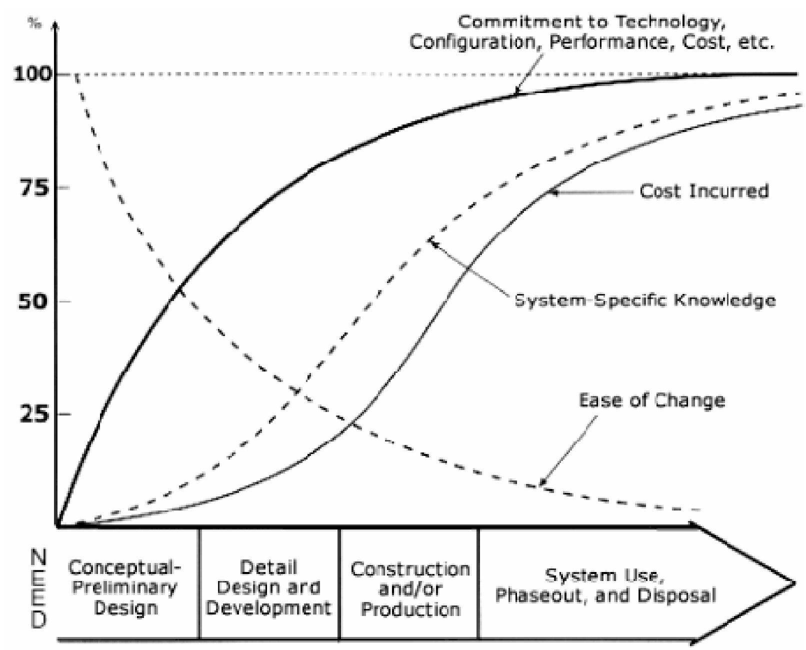
Figure 13. System Life Cycle Process



Adapted from: Blanchard, Benjamin S., and Wolter J. Fabrycky. 2011. *Systems Engineering and Analysis*. 5th ed. Upper Saddle River, NJ: Prentice Hall.

As the figure illustrates, these phases include conceptual design, preliminary design, detail design and development, production and/or construction, utilization and support, and phase-out and disposal. All of these steps are needed to develop a system solution; however, the focus of this thesis is to provide DOD decision makers with a decision support tool to evaluate the feasibility of a potential system solution (i.e., a small satellite). Therefore, this thesis is not concerned with the development of an actual space system or its life cycle. Rather, this thesis only focuses on definition of the need and the conceptual design phase, highlighted in red in Figure 13. While Blanchard and Fabrycky's system life cycle process diagram does not expand on the definition of need, this step is both the most difficult and the most important step to complete. Defining the need is characterized by defining the problem on hand, which facilitates identification of the gap (i.e., the need) that must be filled in order to solve the problem. Improperly or insufficiently defining the need indicates a lack of understanding of the true problem in question, and thus can produce a less effective system solution for the problem. This step is closely followed in importance by the conceptual design phase. The conceptual design phase expands on defining the need by turning the need into requirements, functions, and performance measures for the system solution. This phase begins to define what the system must be, what it must do, and how to measure its effectiveness. Similar to defining the problem, poor execution of this phase produces an inaccurate system solution, which can prove costly in the long term. Figure 14 illustrates the life cycle commitment throughout the SE process phases.

Figure 14. Life-Cycle Commitment during the Systems Engineering Process



Source: Blanchard, Benjamin S., and Wolter J. Fabrycky. 2011. *Systems Engineering and Analysis*. 5th ed. Upper Saddle River, NJ. Prentice Hall.

As the figure shows, over 50% of the commitment to technology, configuration, performance, and cost is achieved upon completing the conceptual design phase, yet less than 5% of the costs have been incurred. Thus, it is easy to understand why the ease of change quickly diminishes from 100% to 50% just during conceptual design. Any large changes to the chosen technology, configuration, or performance past that point will likely produce large cost and schedule overruns. It is apparent that an accurate definition of need and a conceptual design set the foundation for a successful design and development process, and thus are the primary focus of this thesis's application of the SE process.

As Figure 13 shows, the first step is to define the need that must be fulfilled, which spawns from understanding the problem. Once the problem is identified and understood, the needs for a potential solution/system can be identified. Identification of needs explicitly state the requirements of the system, which are primarily defined and stated by the key stakeholders. Thus, stakeholder analysis must also be conducted, which will produce a list of stakeholder needs, limitations, and constraints for the system solution. After completing the stakeholder analysis, an exploration of the system solution's boundary conditions can be completed. This step can help refine the understanding of the problem by further defining the context and space of the problem despite not being a formal step within the conceptual design phase. This thesis will also conduct a requirements and functional analysis, allocate functions to satellite subsystems, and identify performance measures during the latter steps of the conceptual design phase. Those final steps will identify the key factors that will be used to build the synthesis model, and thus are critical steps to accomplish. Tracing the key factors identified by this chapter back to DOD requirements ensures that the models and the decision support tools developed by this thesis are accurate.

C. PROBLEM DEFINITION

Defining system need begins with identifying a problem or deficiency for which the system will provide a solution (Blanchard and Fabrycky 2011, 32–33). By first identifying the problem to solve, capabilities and requirements the system must satisfy in order to solve the dilemma can then be identified. Failure to appropriately define the problem can lead to a "design-it-now-fix-it-later" mentality that often results in an overrun in cost for a system. The Space Mission Analysis and Design (SMAD) process defines this step as "define objectives" for space systems (Wertz and Larson 2010, 2). During this phase, it is imperative the systems engineer understands as much as possible regarding the problem and the context in which the system solution will be used. Developing an operational concept to describe how the system will operate as well as producing a context diagram to illustrate the relationships and interactions of the system sharpen the understanding of the problem, ensuring the appropriate factors are considered when developing a system to solve the stated problem. These products allow the systems engineer to see the larger "picture" so that critical aspects of the proposed system solution are not lost.

1. Operational Concept

An operational concept is a narrative that describes the characteristics of a system based on its functions and how a user will operate the system. The operational concept used for this chapter focuses on the following:

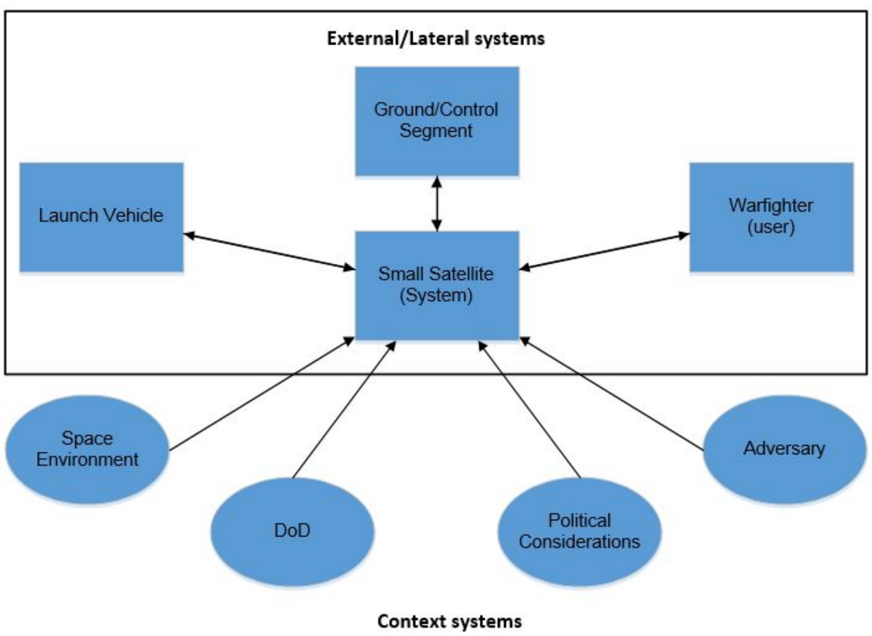
- System solutions that acquire a satellite at a relatively cheaper price than the cost of current large DOD satellites. Cost savings can possibly be achieved through cheaper parts and/or a reduction in spacecraft mass.
- A satellite that is rapidly built and launched into an advantageous orbit.
- A satellite that provides a capability (MILSATCOM or ISR collection in this case) to benefit the warfighter.
- A satellite that is managed and operated by an assigned DOD command that ensures the satellite is functioning as intended or conducts repairs as needed.
- A satellite that communicates with ground stations globally, transmitting down its mission data and receiving new commands. The satellite may also be designed to communicate with individual units or personnel who are forward deployed and not tied into the DOD's land-based communications infrastructure. These units can range from a single U.S. Navy vessel steaming in the middle of the ocean to a SOF unit with a small, portable antenna operating in the mountains.
- Forward-deployed units will not have any control over the satellite's operations; only use of the products (i.e., imagery) or capability (i.e., communications channel) it provides.

These considerations describe the context in which the proposed system solution is to be operated. This further illustrates areas on which this chapter focused when applying the SE process. The operational concept of the system can be enhanced further by the context diagram, which will illustrate the interactions.

2. Context Diagram

A context diagram enhances the operational concept by providing a broader understanding of the system, and allowing stakeholders to visualize how a proposed system solution may be used in a larger system of systems as well as how it may interact with other systems or objects. This thesis will focus on the proposed system solution of a small satellite. Figure 15 is a context diagram for the small satellite system, depicting the general relationships between the satellite and other systems and objects with which it will interact.

Figure 15. Context Diagram



The square cells at the top of the figure represent external and lateral systems that have a two-way interaction with the small satellite, denoted with the double-sided arrows. These objects have an influence on the satellite, but are also influenced by the satellite, either through physical, functional, or behavioral means. In the case of the launch vehicle and ground segment, decisions made in their design or selection are likely influenced by the satellite's own design and vice versa. For the warfighter, his/her behavior (i.e., operating procedures, CONOPs) is modified by the presence of the satellite, but user preferences may modify aspects of the satellite's design as well. The elliptical cells at the bottom of the figure represent context systems that impose an influence on the satellite's design and operations, but are not affected by the satellite's design. The actions, behaviors, and/or conditions of these systems likely influenced the system's functionality and design. While a deeper consideration for how these systems affect each other can be made, that examination remains outside the scope of this thesis, which will focus solely on physical considerations.

3. Definition of the Problem

Developing the operational concept of the system and illustrating the system's context diagram provide a foundation of understanding with regards to the problem. Combined with the research conducted in Chapter II, there is ample understanding to accurately define the DOD's problem, which is as follows: the DOD wants to continue improving its space force enhancement capabilities by using satellites to provide over-the-horizon communications as well as collecting and supplying ISR products to the tactical warfighter. The issue the DOD faces is that large, highly capable satellites are very expensive and take many years to design, develop, and launch before becoming operational. Large satellites are becoming a less enticing solution considering the DOD's reduction in budget, the rapidly growing threat of ASAT weapons, and the time and money it takes to develop large satellites. To this end, the DOD is searching for innovative solutions that provide "enough" capability to enhance and support the warfighter but at a fraction of the cost and time needed for larger satellite programs.

D. STAKEHOLDER ANALYSIS

Once a foundational understanding of the system is achieved and the problem identified, the needs of a system solution can be defined. While a general idea of the needs now exists as a result of the problem definition, conducting a stakeholder analysis will further refine the system needs. A stakeholder analysis allows more introspective analysis with regard to not only what a system solution must do but also what the stakeholders need the system to do in order to solve the problem. This also affords the stakeholders an opportunity to voice any limitations or constraints of the system, which will inform the system requirements and design. Typically, a stakeholder analysis includes stakeholder interviews and meetings with stakeholders, however, due to time and resource constraints as well as the breadth of programs, this thesis primarily relied on extensive research, and in some cases, the author's expertise as a military space professional, to conduct the stakeholder analysis. This research focused on exploring the boundaries of the defined problem to elucidate conditions that may not have been initially understood during the problem and needs identification phase. Once the stakeholder analysis has been completed and the boundary conditions have been studied, a requirements analysis can be completed with confidence.

1. Definition of Need

Once the initial or originating problem has been defined, the stakeholders can be approached in order to gain insight into their needs and wants for the system. In this case, this was accomplished by researching the stakeholder needs of numerous DOD programs. Typically, stakeholders' needs can be represented in risk, consequential opportunity, influence, or essential support from the system (Langford 2012, 259). Examples of needs can include the risk of a stakeholder's reputation or monetary investment, an opportunity to profit or benefit from the system, the influence a system may have on a stakeholder's business or behavior, or that a system is necessary for the stakeholder to conduct business. While a system may have a wide range of stakeholders with needs at different levels of the system's functionality and life cycle, conducting a detailed stakeholder analysis can identify the key stakeholders whose needs should outweigh others, and thus have greater influence on the system. Key stakeholders are likely organizations or people who are investing time, money, and effort to build the system, people who directly benefit from the resolution of the problem, or people who will be operating or using the system. For the purposes of this thesis, the key stakeholders are the DOD, which provides the budget to space and acquisition commands; the space acquisition professionals, who acquire space systems; and the warfighters, who will use the space-based capability.

For this problem, research was conducted to collect stakeholder needs of numerous DOD space programs to build a base of knowledge. While the research was not optimal due to the number of varied DOD space programs examined, it identified a wide sample of stakeholder mission needs and allowed confident determination of the primary and most common needs across space and small satellite programs. The following stakeholder needs were the most common among the various programs researched.

- Supporting the warfighter during combat operations.
- Meeting DOD MILSATCOM and/or ISR mission requirements.
- Minimizing system and life cycle costs.
- Minimizing the time needed to design, build, and launch.
- Improving resiliency to deter and mitigate adversary attack.

In addition to these primary needs, the research uncovered the following gaps that, if addressed, could also support the stakeholder needs.

- A method for determining whether a spacecraft program or a spacecraft design will meet the mission needs.
- A method of identifying key factors that are driving a spacecraft's design based on the stated stakeholder requirements.
- A method for analyzing trade-offs based on stated stakeholder requirements early in spacecraft conceptual design.

Based on the research, it is evident the DOD warfighter needs satellite communications and ISR imagery to conduct mission operations. This is especially important for disadvantaged warfighters who operate in areas without reliable communications due to lack of infrastructure or environmental obstacles. Space offers a potential solution through satellites, but for space to be operationally feasible, the DOD needs to minimize the cost and time needed to create and launch these satellites while validating their benefit to operational effectiveness.

2. Limitations and Constraints

Another aspect of identifying stakeholder needs is identifying the limitations and constraints of a system solution. Both limits and constraints are consequences of decisions made by people within the system design process. Limits are "conditions of boundaries," given by the domain of the problem, and are unchangeable (Langford 2012, 361). They are the physical lack of capability of a system due to design, material, or operational decisions. The physical limitations of the small satellite are listed below.

- Shall fit in a launch vehicle approved for DOD-use.
- Shall have a mass no greater than 500 kilograms.
- Shall operate in a space environment and obey the laws of physics and orbital mechanics.

Constraints, on the other hand, are "conditions of allocations" that can be changed even once established (Langford 2012, 355). Constraints are restrictions placed on the system by someone, typically someone from a decision-making place of power such as the stakeholder or a program director. In terms of the proposed small satellite solution, the major constraints would be communicated by the DOD and would restrict the small satellite design even before a concept is brainstormed. The constraints for small satellites are listed below.

- Shall be built and launched in less than one year.
- Shall cost less than current DOD satellite programs.

These lists of limitations and constraints are not intended to be all-inclusive, but instead present the more significant and most influential limits and constraints on a proposed small satellite system in this scenario. Due to time constraints, this thesis focused on the immediate limitations and constraints, but future work may expand these lists given more time.

3. Boundary Conditions

In his 2012 book "*Engineering Systems Integration*," Langford (2012) defined boundaries as a limit "predicated on a perspective," marking the end of one factor so as to delineate the extent of that factor (354). Langford further describes three types of boundaries, two of which were applied to this thesis. A physical boundary is characterized as the physical limits of a single object's matter without consideration of interaction with a second object (365). A functional boundary is determined by the interaction of two objects and the resultant action from their interaction (358). In these cases, boundaries are pre-determined limits of the system, established by the nature and function of the system, and not set by a stakeholder or an engineer. Understanding a system's boundaries enhances understanding of the system's purpose and its relationship with other systems and objects, and thus the requirements of the system.

a. Physical Boundary

The primary physical boundaries associated with this system are the small satellite to be designed, the launch vehicle, and low Earth orbit where the satellite will operate. Physical boundaries for the small satellite are primarily focused on its size, though the physical boundary considerations may include numerous others, but they were determined to be outside the scope of this thesis. The launch vehicle's physical boundary is based on the size of its fairing, the compartment where the satellite will be stowed for launch into orbit. The fairing has a specific size into which the satellite(s) must fit. The physical boundary of LEO is the total altitude range, which was defined by the scope of this thesis. Orbits and any space objects operating within them are obviously bounded by the laws of physics, particularly orbital mechanics. Physical boundaries that will be considered are as follows:

- Satellite mass
- Satellite linear length
- Launch vehicle fairing volume (height and diameter)
- LEO altitude range of 200–1000 kilometers

As will be shown later, the physical boundaries listed here will be important considerations during the development of the decision support tools as both input factors and output responses. This thesis is primarily concerned with the physical feasibility of a small satellite, so the physical boundaries provide quantifiable measurements for analysis.

b. Functional Boundary

Since requirements inform the functionality of the system, the system's functional boundary is defined by the stakeholder's requirements. A more detailed assessment of system requirements will be completed after consideration of the boundaries, but enough information has already been gathered through research to provide a basic definition of the system's functional boundaries. The functional boundaries that will be considered are as follows:

- Perform its mission. The system shall perform the function of capturing ISR imagery or receiving and transmitting communications, but it cannot be expected to perform a function for which it was not designed.
- Perform functions inherent of a satellite, such as power generation, attitude determination and control, survive the space environment, communication, orbital maintenance, and possibly maneuvering.

While the first functional boundary is obvious, the second is not, and it is important to capture because it's not addressed in any requirements analysis, but does have a significant impact on success. As expected, the functional boundaries of the system are entirely tied to the capabilities that will be designed into the system, based on the requirements of the specific mission the system solution will perform. A general idea of those capabilities can be imagined, but details cannot be listed until requirements analysis for specific missions are conducted.

E. REQUIREMENTS ANALYSIS

After completing a stakeholder analysis and consideration of the problem's boundary conditions, requirements analysis can now be conducted. As stated during stakeholder analysis, research was conducted on multiple DOD SATCOM and ISR small satellite programs, many of which were proof of concepts or test and evaluation programs. The programs were separated based on their mission payload (i.e., SATCOM versus ISR), and the mission objectives from the programs were used as the basis for this thesis's system requirements. Furthermore, the requirements for the systems were sorted into two categories: functional and non-functional. Functional requirements state what the system must do; non-functional requirements state the quality of the system's performance (Langford 2015). Within each specific mission payload, there were many requirements shared by the different programs, many of which focused on functionality and capability. However, the programs also shared multiple non-functional requirements, such as a lower cost and increased response time (i.e., shorter build time). These shared functional and non-functional requirements highlight that different commands and services within the DOD often share the same needs and wants for a space-based solution.

Five DOD ISR small satellite programs and eight DOD MILSATCOM small satellite programs were researched. Two charts detailing the DOD programs researched and the mission requirements found for each program can be seen in the appendix. The charts in the appendix were then screened and quantified through numeration of common requirements. In addition to the stakeholder requirements, there are system design requirements of a satellite that must be addressed in order for the satellite to operate in space. These system design requirements were based on common satellite design knowledge and added to the list of functional and non-functional requirements if they were not already covered by stakeholder requirements. Table 1 shows a list of the initial functional and non-functional requirements.

Table 1. Functional and Non-functional Requirements

Functional	**Non-Functional**
To provide power	To fit in the launch vehicle fairing
To regulate power	To survive the launch environment
To store power	To lower program costs
To transmit spacecraft health data	To lower spacecraft weight
To receive telemetry	To fit a CubeSat structure/reduce size
To navigate position	To achieve the reliability threshold
To launch to LEO	To pass usability testing
To determine spacecraft attitude	To rapidly develop and launch
To control spacecraft attitude	To be a non-nationally tasked system
To maintain spacecraft operational and survivable temperature	To be interoperable with current DOD networks
To maneuver	To easily reconstitute/replenish
To maintain orbital position	
To provide OTH/BLOS communications	
To collect mission ISR	

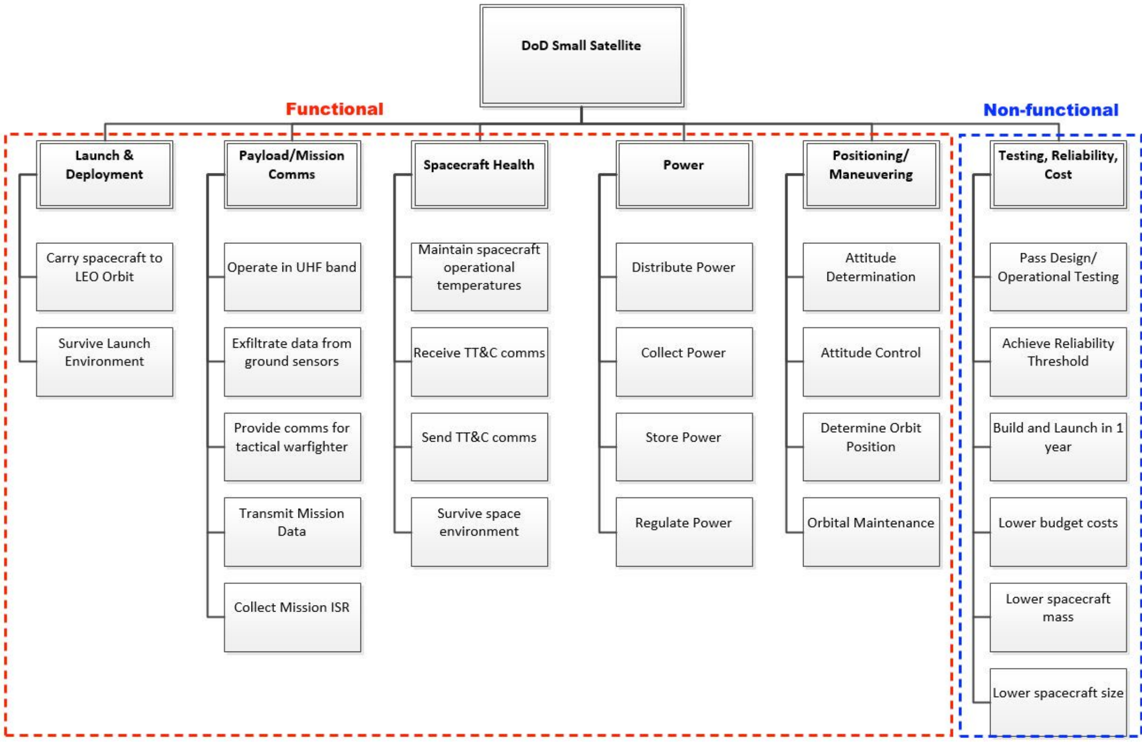
To operate in UHF band	
To secure communications	
To provide timely communications	
To support disadvantaged users	

As the table shows, most of the functional and non-functional requirements refer to the satellite bus (the body or structure of the satellite that houses the payload) or common satellite subsystems rather than a specific mission payload, further suggesting that multiple shared commonalities exist between different DOD command requirements of small satellites. The requirements highlighted in yellow represent categorized requirements that came from the DOD, as compared to non-highlighted design requirements that focus on satellite functionality as described by the functional boundary. While this initial requirements list does not separate the functional and non-functional requirements by spacecraft payload, the next step of functional analysis and allocation will separate them to allow for more detailed analysis.

F. FUNCTIONAL ANALYSIS AND ALLOCATION

After completing requirements analysis, functional analysis could be conducted based on the requirements, followed by allocation of functions to spacecraft subsystems. The functional and non-functional requirements identified were divided among broader function areas for the satellite, producing a functional hierarchy, which provided organization for the many specific functions and non-functional requirements the spacecraft must possess. The functional hierarchy prevented the thesis from going outside its scope by becoming too granular in detail, and also provided a foundation for allocating functions to spacecraft subsystems. Figure 16 shows how functions were organized into broader function areas.

Figure 16. Functional Hierarchy Chart



As the figure shows, the functional hierarchy chart was developed based on the mission requirements identified in the appendix and the functional decomposition displayed in Table 1. The functional hierarchy chart organizes the specific functions of the spacecraft system into broader functional categories. The area outlined in red represent the functional requirements and the area outlined in blue represent the non-functional requirements. While most of the functions and terms used are common concepts, "TT&C" may need explanation. Telemetry, tracking, and command (TT&C) refers to communication between the satellite and the ground station responsible for monitoring the satellite's position at all times and managing its operation and use.

The next step is to allocate the functions from broad functional categories into specific spacecraft subsystems through a functional requirements matrix. This step provides traceability of requirements, identifying which subsystems will provide which functions, and also ensures that all functions deemed important are accounted for in preliminary conceptual design. A functional requirements matrix was made for each of the space force enhancement mission areas, ISR and MILSATCOM. Table 2 illustrates the ISR functional requirements matrix.

Table 2. ISR Functional Requirements Matrix

	ISR Subsystems							
Functions	**Payload**	**Propulsion**	**EPS**	**Thermal**	**TT&C&DH**	**ADCS**	**Launch Vehicle**	**Structure**
F1.0 Launch and Deployment								
F1.2 Fit in launch vehicle fairing	X	X	X	X	X	X	X	X
F1.3 Survive launch environment	X	X	X	X	X	X	X	X
F2.0 Payload/Mission Communications								
F2.2 Collect tasked high resolution (1.5m) mission ISR	X							
F2.3 Provide mission ISR to tactical warfighter	X				X			
F2.4 Transmit mission data					X			
F2.5 Store mission data					X			
F3.0 Spacecraft Health								
F3.1 Maintain spacecraft operational temperatures				X				
F3.2 Receive TT&C communications					X			
F3.3 Send TT&C communications					X			
F3.4 Survive space environment	X	X	X	X	X	X	X	X
F4.0 Power								
F4.1 Distribute power			X					
F4.2 Collect power			X					X
F4.3 Store power			X					
F4.4 Regulate power			X					
F5.0 Positioning/Maneuvering								
F5.1 Determine spacecraft attitude						X		
F5.2 Control/Correct spacecraft attitude		X				X		
F5.3 Determine spacecraft orbital position						X		
F5.4 Maintain spacecraft orbital position		X				X		
F6.0 Non-Functional Requirements								
F6.1 Lower program costs	X	X	X	X	X	X	X	X
F6.2 Build and launch spacecraft in 1 year	X	X	X	X	X	X	X	X
F6.3 Pass design and operational tests	X	X	X	X	X	X		X
F6.4 Achieve reliability threshold	X	X	X	X	X	X		X
F6.5 Lower spacecraft weight	X	X	X	X	X	X		X
F6.6 Minimize spatial size	X	X	X	X	X	X		X
F6.7 Interoperability with current DOD networks and systems	X				X			

As the ISR figure shows, eight subsystems were identified. Payload refers to the mission hardware; ISR in this case. Propulsion refers to the satellite's ability to maneuver. Electrical power system (EPS) refers to the production, maintenance, and use of electrical power. Thermal refers to the regulation and control of the satellite's temperature during operation. Telemetry, tracking, command, and data handling (TT&C&DH) refers to communication with the ground control station responsible for managing and operating the satellite, as well as the satellite's ability to store data when unable to immediately transmit data to the ground. The attitude determination and control system (ADCS) controls the orientation of the satellite (i.e., which way the satellite is facing) while in orbit. Launch vehicle refers to the rocket chosen to carry the satellite to orbit. Structure refers to body of the satellite that protects its internal subsystems, and performs load bearing and appendage support. This thesis did not assign functions below the subsystem level due to the scope of the thesis, but all functions are accounted for and allocated. Very few of the functions are performed or shared by multiple subsystems, which is desired. The functions that are shared by subsystems are either non-functional requirements or are involved with the launch. A functional requirements matrix for MILSATCOM was also developed, illustrated by Table 3.

Table 3. MILSATCOM Functional Requirements Matrix

	SATCOM Subsystems							
Functions	Payload	Propulsion	EPS	Thermal	TT&C&DH	ADCS	Launch Vehicle	Structure
F1.0 Launch and Deployment								
F1.1 Operate in LEO orbit	X	X			X	X	X	
F1.2 Fit in launch vehicle fairing	X	X	X	X	X	X	X	X
F1.3 Survive launch environment	X	X	X	X	X	X	X	X
F2.0 Payload/Mission Communications								
F2.1 Operate in UHF band	X				X			
F2.2 Exfiltrate data from ground sensors	X				X			
F2.3 Provide communications for tactical warfighter	X				X			
F2.4 Transmit mission data	X				X			
F3.0 Spacecraft Health								
F3.1 Maintain spacecraft operational temperatures				X				
F3.2 Receive TT&C communications					X			
F3.3 Send TT&C communications					X			
F3.4 Survive space environment	X	X	X	X	X	X	X	X
F4.0 Power								
F4.1 Distribute power			X					
F4.2 Collect power			X					X
F4.3 Store power			X					
F4.4 Regulate power			X					
F5.0 Positioning/Maneuvering								
F5.1 Determine spacecraft attitude						X		
F5.2 Control/Correct spacecraft attitude		X				X		
F5.3 Determine spacecraft orbital position						X		
F5.4 Maintain spacecraft orbital position		X				X		
F6.0 Non-Functional Requirements								
F6.1 Lower program costs	X	X	X	X	X	X	X	X
F6.2 Build and launch spacecraft in 1 year	X	X	X	X	X	X	X	X
F6.3 Pass design and operational tests	X	X	X	X	X	X		X
F6.4 Achieve reliability threshold	X	X	X	X	X	X		X
F6.5 Lower spacecraft weight	X	X	X	X	X	X		X
F6.6 Minimize spatial size	X	X	X	X	X	X		X
F6.7 Interoperability with current DOD networks and systems	X				X			

As the figure shows, the SATCOM payload functions are dominated by the payload subsystem as well as the TT&C&DH subsystem, highlighted in red, which is obvious because of the MILSATCOM mission. Comparison between the ISR and MILSATCOM functional requirements matrixes show that there are a number of identical functional requirements shared between an ISR satellite and a MILSATCOM satellite. The primary differences can be found within the payload, which is the subsystem that will produce the specific capability desired of the designed satellite. These payload capabilities will be important in key factor analysis because they drive the satellite’s effectiveness in a specific mission area rather than the other common subsystems shared by all satellites.

G. KEY FACTORS ANALYSIS

The intent of this thesis is to build decision support tools to support decision makers and assess the feasibility of small satellites early in the conceptual design phase. In order to streamline the tools to ensure ease of use especially in initial development, complexity must be reduced. Thus, it is imperative to focus on the key factors that will drive a satellite’s mission effectiveness. Key factors are those that help determine a system’s operational effectiveness and can serve as indicators as to how well a system can solve the problem for which it was designed. For a DOD small satellite program, operational effectiveness stems from the functionality of the payload for a particular mission as well as physical characteristics of the spacecraft and the orbit in which it operates. Key factors will determine and measure how well a spacecraft system is able to solve the problem defined by the DOD stakeholder. The best way to quantify key factors is by developing a list of measurements or metrics. There are two forms of metrics used to determine the success or failure of a system: Measures of Performance and Measures of Effectiveness.

Measures of Performance (MOPs), or technical performance measures (TPMs), are quantified measures of attributes and/or characteristics inherent within the system design (i.e., measures within the system boundary) (Blanchard and Fabrycky 2011, 40). Table 4 lists all MOPs generated during the ideation process for a DOD small satellite system, divided into ISR and MILSATCOM mission areas. These MOPs are common measurements for SATCOM and ISR satellite performance within the DOD, to include additional considerations for cost and time.

Table 4. DOD Small Satellite MOPs

Comms	ISR
Amount of bandwidth available (data rate)	Resolution achieved at nadir
Frequency used	Size of field of regard
Size of coverage area	Size of field of view
Length of access time per pass	Amount of bandwidth available (data rate)
Eb/No achieved during communications	Frequency used
Length of time between transmission to receive (time late)	Length of access time per pass
Number of users supported simultaneously	Eb/No achieved during communications
Length of time link is available	Length of time between transmission to receive (time late)
Length of time link is unavailable	Number of images captured per pass
Average amount of power used	Number of users supported simultaneously
Maximum amount of power needed at one time	Length of time link is available
Mass of system	Length of time link is unavailable
Linear dimensions of system	Average amount of power used
Operational lifetime	Maximum amount of power needed at one time
	Mass of system
	Linear dimensions of system
	Size of coverage area
	Timeliness of image delivery after tasking
	Operational lifetime
	Length of time from tasking to delivery (Total response time)

As Table 4 shows, the MOPs can vary depending on the payload and the measures of system effectiveness. To further reduce the complexity of the analysis, the highlighted MOPs were considered more important based on the stakeholder statements of needs gathered during the program research and MOPs common during spacecraft design.

Measures of Effectiveness (MOEs) are top-level technical performance measures that determine whether or not or how well a characteristic of the system achieves its functional objective (i.e., measures outside the system boundary) (Blanchard and Fabrycky 2011, 41). MOEs are typically concerned with high-level measures of operational effectiveness that focus on the system's impacts on the warfighter. However, due to this thesis's need to develop requirements based on a broad array of systems rather than focusing on one, many of the MOEs listed relate to prioritized MOPs, ranked by level of importance. Table 5 divides the MOPs for each mission area into MOEs categories, which were taken from SMAD (Wertz, Everett, and Puschell 2011, 93).

Table 5. DOD Small Satellite MOEs

	Comms MOP	ISR MOP
	How well does the system provide communications?	*How well does the system collect/provide ISR?*
Accuracy (Comm: ability to tx/rx intended message, ISR: ability to capture intended ISR)	Frequency	Likelihood of capturing actionable ISR
	Bit Error Rate	Resolution achieved at nadir
	Eb/No achieved during tx	% of time system captures tasked AOI
	Gain	Gain
Capacity (Comm: available bandwidth, ISR: # of images able to capture)	Bandwidth available	Number of images captured per pass
	Interoperability with other DOD comms systems	Data size of single image
		Size of onboard storage
Survivability/Vulnerability (Probability s/c can survive adversarial attack)	Probability of surviving hostile/adversarial attack	Probability of surviving hostile/adversarial attack
Coverage (Comm: area of Earth able to tx/rx from, ISR: area of Earth able to image)	Geographic access area per pass	Size of FOV
	Usability in a geographic region	Size of FOR
	Observations per day	% of AOI system can image
		Number of observations per day
Reliability (Probability system lasts duration of designed operational lifetime)	Operational lifetime	Operational lifetime
	Mean Time Between Failure	Mean Time Between Failure
Responsiveness (Time late: time from action to receipt by intended receiver)	Time (sec) from message is transmitted until it is received by intended party (Total response time)	Time (sec) from observation to delivery to operator (Total response time)
		Time (sec) needed to acknowledge tasking
Maintainability (Probability system can be repaired in operational environment)	Average time system is down for repair/upgrade (min out of day)	Average time system is down for repair/upgrade (min out of day)
Availability (Probability payload is available for use)	Time (sec) per day link is available	Time (sec) per day imaging is available
	Length of access per pass	Length of access per pass
Cost (reduction in budget for this mission area)	Cost to build one system	Cost to build one system
Time (reduction in time to build)	Time to build one system	Time to build one system
	Ease of use of the system	Ease of use of the system
	Average amount of power needed	Average amount of power needed
	Maximum amount of power needed	Maximum amount of power needed
	Mass of the system	Mass of the system
	Linear dimensions of the system	Linear dimensions of the system
	Revisit of a point in 24 hours	Revisit of a point in 24 hours

As Table 5 shows, the MOE categories are initially broad, but can have very specific definitions within the context of a specific mission area. The number of MOPs for each MOE category is also dependent on the mission areas being examined and also the MOPs that have the most importance to the stakeholders. While not always accurate, the MOE categories that possess the most MOPs can be assumed to be the MOEs most important to the stakeholders, and thus, can drive design decisions during trade off analysis.

The MOPs and MOEs listed were derived from the thesis's research, which examined mission and program requirements of numerous DOD commands that are exploring small satellite technology. While some of the commands stated more specific requirements, many of the requirements overlapped or were similar enough to be grouped into general categories. The overlapped requirements indicated shared needs from the system regardless of service affiliation or program, and thus were used in identification of the key factors that would be used in development of the decision support tools. Table 6 lists the key factors derived from the work conducted in this chapter.

Table 6. Key Factors

ISR Payload Factors	Comms Payload Factors	Shared Factors
Resolution at nadir	Data rate	Spacecraft mass
Resolution off nadir	Frequency	Propellant mass
Size of field of view (FOV)	Antenna diameter	Linear dimensions
Size of field of regard (FOR)	Satellite transmit power	Altitude
Wavelength	Receiver's antenna diameter	Number of accesses (revisit)
	Signal-to-Noise ratio	Length of access per pass
		Inclination
		Number of satellites per launch
		Cost

As Table 6 shows, each payload has very specific factors based on the particular mission it is designed to perform. However, there are also shared factors that are common to all small satellites regardless of mission, most of which are tied to satellite bus characteristics. This suggests the potential for a common satellite bus with interchangeable payload modules; however, this analysis is outside the scope of this thesis. The purpose of this chapter was to justify the selection of factors for use in the decision support tools by using a well-executed systems engineering process. Although not fully executed, the steps of the SE process described in this chapter successfully derived the key factors listed in Table 6, which will inform the input factors and output responses of the decision support tools developed. The relationships between these key factors were analyzed to build the synthesis model detailed in the next chapter, providing the foundation for the development of the tools needed to conduct feasibility analysis of small satellites and assist decision makers during conceptual design.

IV. BUILDING THE SYNTHESIS MODEL

The SE process discussed in chapter three provided a methodology for identifying the key factors with the greatest influence on early satellite design. However, the SE process does not present a means for analyzing the relationship between the key input factors and the output responses, which is critical to assessing the feasibility of the satellite design. MBSE and DOE were used to analyze the relationship between input factors and output responses. The analysis provided insight on how changes to input factors would constrain or expand the satellite design's trade space. This chapter will discuss the use of MBSE and DOE techniques, as well as describe the tools developed to analyze the relationship between the key input factors and output responses, which will allow for the exploration of the satellite design trade space.

A. MODEL-BASED SYSTEMS ENGINEERING

Model-based systems engineering (MBSE) is a systems engineering methodology that has gained momentum over the past decade. As defined by INCOSE, MBSE is a methodology that uses models to "support system requirements, design, analysis, and verification and validation activities beginning in the conceptual design phase." (INCOSE 2007) MBSE uses models to provide a visual context for the systems engineering process, allowing a view of the relationships between a system's requirements, structure, and behavior, rather than solely relying on documents to track the SE process (Haduch 2015). A key component of MBSE is system synthesis. System synthesis (also known as "system design") "translates the system functional architecture into a physical architecture. It creates a 'how' for every 'what' and 'how well.'" (Guerra 2008, 3). Essentially, system synthesis translates functions the system must perform into physical components of the system. As U.S. military systems begin to coalesce into larger, more complex systems of systems, MBSE becomes an attractive analysis methodology for DOD research.

Paul Beery, a faculty associate within the NPS Systems Engineering Department, has been applying MBSE to DOD systems analysis for over four years. In a November

2014 presentation given at NPS titled, “Modeling and Simulation in Support of Model-Based Systems Engineering (MBSE),” Beery discussed his efforts to use a model-based approach to design large and complex DOD systems. Specifically, Beery used MBSE to analyze the operational effectiveness of a DOD system by gaining insight on its response to input factors. To do this, Beery developed an operational simulation model to look at the system concept of operations (CONOPs) and a physical synthesis model to look at physical characteristics. Ultimately, Beery developed a “dashboard” as a decision support tool that illustrated those effects and relationships for visual trade space analysis. While Beery’s work focused on a naval vessel conducting anti-surface warfare, this thesis sought to apply the same techniques to DOD satellite systems.

This thesis attempts to apply Beery’s MBSE methodology to satellite design in order to analyze the relationship between input factors and output responses. However, due to the scope of the effort, this thesis focused only on the physical characteristics of a satellite and was not concerned with operational modeling. Using MBSE, a physical synthesis model was developed that demonstrated the cause and effect relationships between input factors and output responses. The synthesis model was then used to graphically illustrate a satellite’s design trade space based on input factor changes. The result is a pair of tools that will serve decision makers in the DOD space acquisitions process by providing better trade space analysis earlier in satellite conceptual design.

B. DEVELOPING THE MS EXCEL TOOL FOR INPUT RESPONSES

For the physical synthesis model to function as a tool, input factor data and output response information need to be collected from the user. A simple user interface tool was developed based on the “SMAD worksheet,” a Microsoft Excel spreadsheet built by David Cloud, a former professor within the U.S. Air Force Academy’s Department of Astronautics. Cloud’s SMAD worksheet is fairly complex and allows the user to design a spacecraft and calculate detailed subsystem parameters in high detail. The SMAD worksheet is currently used in both Naval Postgraduate School (NPS) and USAF space educations courses. Figure 17 shows an example of the thermal control subsystem design page from the SMAD worksheet.

Figure 17.   SMAD Worksheet Example

Return to Navigator	Thermal Control Subsystem Analysis						
(All information on this sheet is contained in the block from Cell A1 to Cell I30)							
[NOTE: References on pp 445-447 refer to the 4th Printing of the 3rd Edition of SMAD]							
Orbit altitude		35785.000	km	Solar flux		1418.0	W/m^2
Planet angular radius		8.70	deg	Albedo	23.0%	23.0%	
Albedo reflection factor		0.738		Maximum Planet IR emission		258.0	W/m^2
				Minimum Planet IR emission		216.0	W/m^2
Available surface area		63.061	m^2				
Diameter of equivalent sphere		4.48	m	Solar energy absorbed		21237.4	W
				Albedo energy absorbed		82.5	W
Absorptivity of spacecraft surface	95.00%	95.00%		Maximum Planet IR energy absorbed		82.8	W
Emissivity of spacecraft surface	89.00%	89.00%		Minimum Planet IR energy absorbed		69.4	W
Maximum power dissipation on spacecraft		3371.6	W	Maximum equilibrium temperature		24.0	deg, C
Minimum power dissipation on spacecraft		3371.6	W	Minimum equilibrium temperature		-91.7	deg, C
Upper temperature limit for spacecraft		35.0	deg, C				
Lower temperature limit for spacecraft		5.0	deg, C				
Possible changes to reduce maximum equilibrium temperature to specified upper limit:							
Additional surface area		N/A	m^2	New absorptivity of spacecraft surface		N/A	
				New emissivity of spacecraft surface		N/A	
Heater requirements during eclipse:							
Radiator area to accommodate s/c power dissipation		7.424	m^2	Maximum eclipse time		69.4	min
Minimum temperature for given radiator area		35.0	deg, C	Duty cycle (per orbit period)		4.8%	
Required heater power (during eclipse)		0.0	W	Average heater power		0.0	W

As the figure shows, the SMAD worksheet requires a lot of input from the user in order to calculate design outputs. While the SMAD worksheet is a helpful tool for satellite design, its focus on detailed design of satellite subsystems makes its resolution too high for the intent of this thesis. The SMAD worksheet has 47 worksheets and requires an understanding of satellite subsystems and engineering practices that will likely be outside the expertise of a typical space acquisition professional. Additionally, the SMAD worksheet does not provide a visualization tool of the trade space of a theoretical satellite design, which can be helpful for users. Therefore, a new tool was developed that captures the essence of the worksheet, but at a reduced level of complexity to support early conceptual design of a satellite without "getting into the weeds."

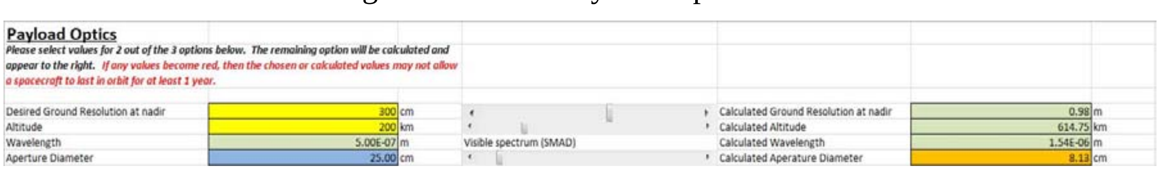
To reduce complexity, the MS Excel tool developed in this thesis focused on minimizing the number of key factors analyzed, which then required fewer inputs from the user and fewer outputs to be calculated. For this, the key factors identified in Chapter III were used and would need to be collected by the MS Excel tool. To collect these inputs, a draft tool was built to accept a user's (i.e., a space acquisition professional) desired input design factors and capabilities. The draft tool then took these inputs and calculated outputs using common spacecraft design equations from SMAD. These inputs and outputs were later used in a DOE and later plugged into the JMP program to build the meta-models used in the final trade space analysis worksheet, which will be discussed later in this chapter.

For all the worksheets in this tool, a yellow cell represents an input field that was deemed a key input factor in Chapter III, and included in development of the synthesis model. A blue cell represents an input field that is not necessarily key, but necessary to maintaining the tools functionality. An orange cell represents a calculated output response that was deemed a key output response and was thus included in development of the synthesis model. Pale green cells are cells that the user should not tamper with or modify. They were provided to support future expansion. The values in these cells are locked for the sake of simplicity and do not need user interaction. The following worksheets were developed for the MS Excel tool.

1. Synthesis Model: ISR Payload Worksheet

The ISR payload worksheet collected information regarding the desired capabilities of a proposed ISR payload. Globally accepted orbital mechanics and physics equations from the SMAD textbook were used to calculate all of the output responses displayed in this section. This worksheet was broken into five parts based on the outcome of Chapter III, and organized for clarity and usability. The first part is the payload optics section, which examined ground resolution at nadir, the altitude of the satellite, wavelength used, and aperture diameter. Figure 18 shows the payload optics section.

Figure 18. ISR Payload Optics



As the figure shows, the desired resolution and altitude were key input factors in the synthesis model along with the calculated aperture diameter value, which was a key output response. Desired ground resolution at nadir was given a value range of 0.5 to five meters, the resolution range where imagery is most useful to military operations. Altitude was given a range between 200 and 1000 kilometers to represent LEO, the orbit specified by the researched DOD small satellite programs. Wavelength was locked at 50 micrometers, based on SMAD's visible spectrum value (Wertz and Larson 2010, 265). Ultimately, calculated aperture diameter was fixed as a key output response in order to support model development within JMP, which is justified by the belief that a typical space acquisition professional would prioritize ground resolution and altitude over aperture diameter.

Figure 19 shows the off-nadir resolution section, the second part of the sheet. This was first included based on the possibility of a user's interest in the resolution achieved at the farthest boundary of the camera's footprint, understanding that resolution decreases as a point moves farther from the nadir angle (i.e. 90 degrees/directly below the satellite). This is an additional usability tool and was not used in generating meta-models.

Figure 19. Off-nadir Resolution

Off-nadir Resolution						
To find ground resolution off of nadir for the same optical parameters, please select a number of degrees off of nadir you want to image.						
Cone Half Angle/Degrees off of nadir	45	deg		Calculated Ground Resolution off nadir	1.40	m
Altitude	200.00	km				
Slant Range	287.37	km				

As the figure shows, the user-inputted altitude from earlier is carried down, and once combined with a cone half-angle value to produce a slant range distance, a resolution can be calculated for a small satellite angled in that manner. While this section may be useful in some cases, it was deemed far less important than resolution at nadir because it was believed that a space acquisition professional would be primarily concerned with a small satellite's resolution at nadir. For this reason, the off-nadir resolution section was not used in the final draft of either decision support tool.

The third section of the ISR payload worksheet was the calculated maximum access area. For this thesis, maximum access area is defined as the maximum footprint size on Earth a satellite could see from horizon to horizon, regardless of resolution. Figure 20 shows the maximum access area section.

Figure 20. Maximum Access Area


Maximum Access Area

Access area uses the S/C's altitude to calculate λo, the angular radius measured at the center of the Earth of the region seen by the S/C.

Altitude	200.00	km	Calculated diameter of access area	1575.13 km

As the figure shows, the only input value used was altitude, which was pulled from an earlier cell filled out by the user. Similar to the off-nadir resolution section, maximum access area for an ISR payload was assumed to be low priority because imaging small satellites commonly have a very restricted ability to image off nadir. This section was not included in the meta-model development, but was maintained in the MS Excel tool to offer additional information to the user in case it was desired.

Figure 21 shows the field of regard (FOR) section, the fourth part of the ISR payload worksheet, which calculates the maximum possible area in which a satellite could capture imagery if it were to move its view over that area. This is a reduction of the maximum access area and is constrained by the maximum slew angle defined by the user. The inputs for this calculation are altitude and cone half angle, and used Earth geometry equations from SMAD (Wertz and Larson 2010, 111–113).

Figure 21. Field of Regard (FOR)


Field of Regard (FOR)

Please select a nadir angle (up to 75 degrees max) to calculate a FOR.

Cone Half Angle/Degrees off of nadir	45	deg	Calculated diameter of FOR	203.06 km
Altitude	200.00	km		

As the figure shows, the cone half-angle/degrees off of nadir input was identified as a key input factor and included in the synthesis model. While the output of this section, calculated diameter of FOR, was not selected as a key output response, the cone half-angle input on this worksheet was carried over to the orbital period/revisit time worksheet and used to calculate the number of accesses in 30 days and mean access duration, which are key output responses. The input value for the cone half angle was limited to a maximum value of 75 degrees for two reasons: 1) based on the range of values set for altitude, a cone half angle greater than 75 degrees could not be calculated because the footprint would stretch beyond the horizon; and 2) this value was within the typical maximum of DOD systems researched.

Figure 22 shows the field of view (FOV) section. This final section of the ISR worksheet calculates the maximum diameter of the area that the satellite's camera can view at one time. This is again a distillation of the FOR based on constraints by the diameter of the FOV.

Figure 22. Field of View (FOV)

Field of View						
Please input either desired FOV or desired focal length, and the other option will be calculated to the right.						
Diameter of FOV	20	km		Calculated Object size	125.00	km
Focal plane width	0.03	m	*Pitch 5-10 micrometers...4096x4096 pixels?	Calculated Detector size	0.00	m
Altitude	200.00	km				
Focal Length	4	cm		Calculated Focal Length	0.2500	m

As the figure shows, the initial draft of the FOV section was more flexible and allowed the user to choose the inputs he/she wanted to submit in order to get the calculated output he/she desired, but this flexibility was removed to reduce the complexity of the DOE, thus, pixel plane width was fixed. Desired FOV diameter was limited to a maximum size of 100 kilometers and pixel plate size was set to 0.03 meters based on values from Raytheon research on focal plane array sizing (Raytheon 2008). Future work can modify this setting as necessary in order to meet future needs of the tool. This thesis sought to keep the calculations used as simple as possible and did not focus on values for specific pieces of hardware that may be used.

When the key input factors were decided, diameter of FOV was determined to be important because of its effect on operational capabilities, and thus it was believed that a space acquisition professional would want to set the field of view for the satellite. However, calculated payload focal length, the output response for this section, was not included in the synthesis model. Thus, calculated focal length's effect on the linear dimension of the satellite was not introduced into the tool. As such, FOV had no effect on the outputs included in the synthesis model despite being submitted as a key input factor. By the time the omission was discovered, there was no time to rectify the error, so this thesis did not correct the issue, but recommends future work address this concern.

The ISR payload worksheet captured information deemed significant to a space acquisition professional who was beginning feasibility analysis of a small ISR satellite. As shown, accepted space design and physics equations were used to produce estimated output responses based on the user's inputs. While this is a distillation of the SMAD worksheet, its simplicity and ease of use make it an optimal tool for addressing early conceptual design. The same process was used to develop a MILSATCOM payload worksheet, which focused heavily on the link budget equation.

2. Synthesis Model: MILSATCOM Payload Worksheet

The MILSATCOM payload worksheet collected information regarding the desired capabilities of a proposed communications payload. This worksheet is broken into three parts based on the outcome of Chapter III, and is again organized for clarity and usability. The first part is the payload communications section, which used the link budget equation to determine data rate based on user inputs. Figure 23 shows the payload communications section.

Figure 23. Payload Communications

Payload Communications

Please enter a satellite altitude, then enter values for either desired data rate or satellite's antenna diameter and power output below. The remaining option will be calculated and appear to the right.

Altitude	200	km			
Data rate	8.909690	Mbps	Calculated data rate	356.387868	Mbps
Satellite's antenna diameter	1	m	Calculated satellite antenna diameter	0.16	m
Satellite's power output	10	W	Calculated satellite power output	0.25	W
Frequency band	305	MHz			
Wavelength	0.984	m			
Receiver's antenna diameter	0.61	m			
Receiver's power output	20	W			
Gain of the receiver	2.09				
Eb/No	9.6	dB			

As the figure shows, altitude, the satellite's antenna diameter and power output, and frequency band were key input factors in the synthesis model. Calculated data rate was identified as a key output response. For this spreadsheet, antenna efficiency for both the satellite and receiver antennas was calculated using the equation for parabolic antennas. Parabolic antennas may not be appropriate considering the desire for using small satellites and the UHF band, so this represents an area that can be improved in future work. Wavelength was automatically calculated based on the user's submitted frequency value. The gain of the receiver was locked and calculated from the receiver's antenna diameter and power output as per the gain equation (Wertz and Larson 2010, 553). For the purposes of this thesis, the AN/PRC-117F user terminal was used as the example receiver system because of its common use as a UHF SATCOM terminal for U.S. armed forces, but this is another design choice that can be modified in the future (*Wikipedia* 2016). The values for antenna diameter and power output were taken from a specifications sheet for the AN/PRC-117F system (Harris Corporation 2007, 3–13). The signal-to-noise ratio (i.e., Eb/No) value was locked at 9.6 decibels, the default value from the SMAD design worksheet (Cloud 2016). Similar to the ISR payload optics section, the payload communications section was more flexible in the initial MS Excel tool, allowing the user to decide if he/she wanted to calculate data rate, satellite antenna diameter, or satellite power output. However, this flexibility was removed to support the DOE. Based on research, it was assessed that the space acquisition professional would prioritize data rate available over antenna diameter and power output, so data rate was set as the output response.

Figure 24 shows the off-nadir SATCOM pointing section, the second part of the MILSATCOM worksheet. This was first included based on the possibility of user interest in the data rate available at the farthest boundary of the satellite's FOR, understanding that data rate may decrease as the point moves farther from the sub-satellite point. As with ISR, this is an additional usability tool and was not used in generating the meta-models.

Figure 24. Off-nadir SATCOM Pointing

Off-nadir SATCOM Pointing						
To find data rate off of nadir for the same link budget parameters, please select a number of degrees off of nadir you want to slew.						
Degrees off of nadir, η	20	deg		Calculated data rate	313.49	Mbps
Altitude	200	km				
S/C distance to off-nadir point	213.24	km				

As the figure shows, the user-provided altitude from earlier is carried down, and once combined with a degrees off-nadir value to produce a slant range distance, a data rate can be calculated for a small satellite angled in that matter. While this section may be useful in some cases, it was deemed far less important than data rate achieved at nadir because it was believed that a space acquisition professional would be primarily concerned with a data rate achieved at nadir. For this reason, the off-nadir SATCOM pointing section was not used in the final draft of either decision support tool.

The final section of the MILSATCOM payload worksheet was the half-power beamwidth, which determined gain and bandwidth available at the edge of the satellite's beam rather than down its bore sight. Figure 25 shows the half-power beamwidth section.

Figure 25. Half-power Beamwidth

Half-power Beamwidth						
To find the gain and bandwidth available at the edge of the satellite's beam, rather than down the boresight.						
Satellite antenna diameter	1	m		Antenna base power gain	5.610733024	
				Antenna half-power gain -3dB	4.490	dB
				Converted antenna half-power gain	2.812027763	
				Calculated data rate	178.6170498	Mbps

As the figure shows, the only input used was the satellite's antenna diameter, which was carried down from an earlier cell filled out by the user. The antenna diameter was used to calculate the base power gain of the satellite, which was used to calculate the half-power gain after being converted to decibels. After subtracting three decibels of loss at the edge of the beam, the gain was converted back to its unit-less value and used to calculate the data rate available at the edge of the satellite's beam using the link budget equation.

The MILSATCOM payload worksheet captured information deemed significant to a space acquisition professional who was beginning a feasibility analysis of a small MILSATCOM satellite. As shown, accepted space design and physics equations were used to produce estimated output responses based on the user's inputs. Similar to the ISR payload worksheet, the MILSATCOM worksheet's simplicity and ease of use make it an optimal tool for addressing early conceptual design. While both worksheets addressed design considerations for specific payload subsystems, they did not consider common subsystem design factors, which have a large impact on the overall satellite functionality. The following satellite bus worksheets were developed to address those factors.

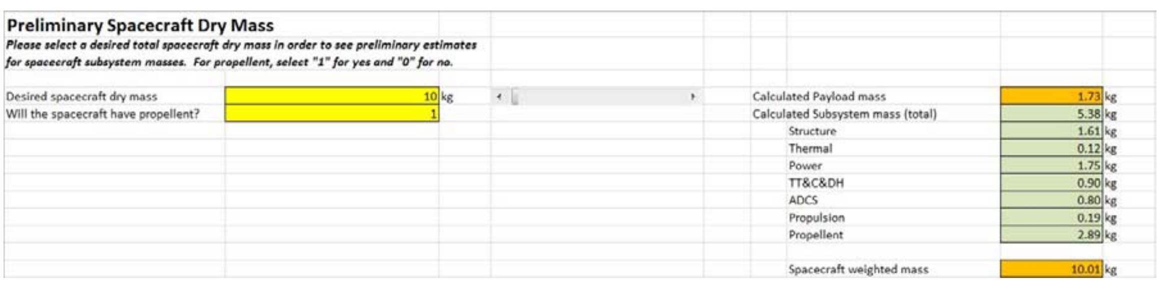
3. Synthesis Model: Satellite Bus Worksheets

This thesis looked at two different mission payloads, ISR and MILSATCOM. Each payload had its own characteristics and needs that did not relate to the other and thus were separated into two different worksheets. However, both payloads would share similar satellite bus designs, therefore worksheets were designed based on common satellite bus features. The following three worksheets account for the shared satellite bus features and were developed for the tool.

a. Mass and Size Worksheet

Figure 26 shows the preliminary spacecraft mass section of the mass and size worksheet. This section calculates the payload mass and the mass of the major subsystems based on a desired spacecraft mass submitted by the user. The subsystem masses were calculated based on the averages for light satellites listed in SMAD's Appendix A (Wertz and Larson 2010, 896).

Figure 26. Preliminary Spacecraft Mass



As the figure shows, the user is asked to input the desired mass of the proposed small satellite. The desired mass was then used to calculate estimated subsystem masses using average subsystem percentages taken from SMAD. This section also allows the user to decide whether to include propellant to enhance the satellite's performance. The inclusion of propellant required a modification to the original percentages used to calculate the subsystem masses and was calculated as 28.9% of the satellite's total mass on average when included based on the average propellant mass of light satellites from SMAD's Appendix A (Wertz and Larson 2010, 895). The summation of all these subsystem masses produced the total spacecraft weighted mass as an output. Based on Chapter III, the key input factors in this section are desired spacecraft mass and the inclusion of propellant, and the key output responses are calculated payload mass and spacecraft weighted mass.

The mass and size worksheet also calculated some spacecraft preliminary sizing data, which can be seen in Figure 27. This section calculates a minimum, maximum, and expected value for the satellite's volume, body area, and linear dimension based on the satellite's weighted mass.

Figure 27. Preliminary Spacecraft Sizing

Preliminary Spacecraft Sizing

Estimated spacecraft sizing is based on the desired spacecraft dry mass.

	Minimum		Expected		Maximum	
Volume	0.05003555	m^3	0.1000711	m^3	0.5003555	m^3
Body area	0.104	m^2	0.290	m^2	0.418	m^2
Linear dimension	0.323	m	0.539	m	0.646	m

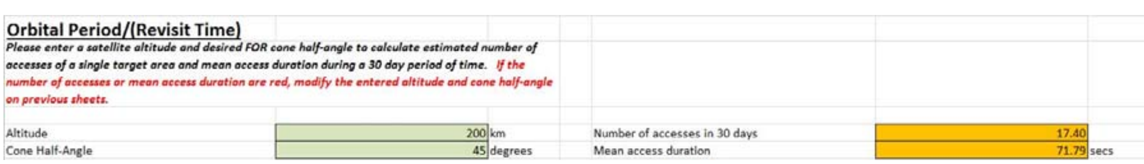
As the figure shows, all of the sizing values are calculated based on user inputs from previous sections and the sizing equations in SMAD (Wertz and Larson 2010, 337). Volume and body area were also included as additional information for future users, but ultimately determined to be too detailed for the purposes of this thesis. The most important of the six sizing calculations with regards to the synthesis model was the expected linear dimension, which presented an accurate predication for the satellite's length and width based on the satellite's mass. This key output response was important because it was a primary factor used to determine a launch vehicle's ability to carry the satellite.

b. Orbital Period/Revisit Time Worksheet

The next worksheet was the orbital period/revisit time worksheet. The purpose of this worksheet was to determine the satellite's period and revisit time, which are critical in determining the satellite's access to a particular location for capturing imagery or providing communications. This section produced two output responses based on user inputs from previous worksheets: number of accesses in 30 days and the mean duration of a single access. Unlike the other worksheets, the relationship between the inputs and outputs in this section were based on data from an STK simulation, which used a satellite orbit scenario to provide organized data more quickly than if the calculations were completed by hand. To minimize variance, all the STK scenarios were set for 30 days, which provided a reliable number of data points without requiring STK to spend hours calculating results.

Each scenario contained a satellite at a defined sun-synchronous orbit in increments of 100 kilometers. A variety of cone half angle options were defined for each satellite scenario; the cone half angles were defined as 1, 2, 3, 4, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, and 75 degrees, respectively. Cone half angle directly affects the width of FOR. A wider cone half angle will produce a wider FOR, allowing for a larger area of potential access, and potentially better revisit times. The STK-generated 30-day access reports for each satellite altitude and cone half-angle combination, and the number of accesses achieved during the scenario timeline and the mean access duration in seconds were recorded. All of these data points were entered into JMP, which produced meta-model equations for the two output responses. The meta-model equations were then placed into the MS Excel tool under the orbital period/revisit time worksheet and used to calculate the number of accesses in 30 days and the mean access duration. Figure 28 shows the orbital period/revisit time section.

Figure 28. Orbital Period/Revisit Time


Orbital Period/(Revisit Time)

Please enter a satellite altitude and desired FOR cone half-angle to calculate estimated number of accesses of a single target area and mean access duration during a 30 day period of time. If the number of accesses or mean access duration are red, modify the entered altitude and cone half-angle on previous sheets.

Altitude	200	km	Number of accesses in 30 days	17.40	
Cone Half-Angle	45	degrees	Mean access duration	71.79	secs

As the figure shows, the number of accesses in 30 days and mean access duration are reliant on only two inputs: altitude and cone half-angle. While both of those inputs were determined to be key input factors, the cells for altitude and cone half-angle are green because the values are taken from an earlier worksheet that requests those same inputs from the user. The two output responses, number of accesses in 30 days and mean access duration, were determined to be key output responses because of their effect on satellite mission effectiveness.

c. *Cost Worksheet*

The development of the cost worksheet was divided into two tasks: 1) determining the cheapest launch vehicle available that could carry the satellite and then estimating the price of that launch vehicle, and 2) calculating an estimated program cost for a single satellite based on user inputs. Those two estimations are added together to produce the total estimated cost per satellite. Figure 29 provides a screenshot of a portion of the cost worksheet.

Figure 29. Cost

Cost

Please select a desired altitude and orbit inclination to determine a launch vehicle. Spacecraft mass and linear dimension is taken from Mass-Size spreadsheet.

Altitude	200	km
Mass	10.01	kg
Linear Dimension	0.539	m
Inclination	98	degs
# of satellites per launch	3	
Total Mass	30.02	kg

Once you have set your parameters, look for any rows highlighted in green. These are vehicles that meet your needs. Enter the cost value for your chosen launch vehicle below.

Lowest Launch Vehicle Cost	56.3	$ million USD	Total Cost	$ 62,892,821.31	USD
# of launch vehicles that meet lowest cost	9				
Bus Development Cost	4081.40	$K USD			
Payload Development Cost	1632.56	$K USD			
Integration, Assembly, & Testing Cost	567.31	$K USD			
Program Level Cost	311.55	$K USD			

Launch Vehicle	Payload Fairing Height (m)	Payload Fairing Diameter (m)	Usable Mass Allowance (kg)	Altitude (km)	Inclination (deg)	Cost ($M)	Usable
Pegasus XL	2.13	1.15	208	800	90	56.3	No
Pegasus XL	2.13	1.15	182	900	90	56.3	No
Pegasus XL	2.13	1.15	155	1000	90	56.3	No
Pegasus XL	2.13	1.15	345	100	98.7	56.3	No
Pegasus XL	2.13	1.15	328	200	98.7	56.3	Yes
Pegasus XL	2.13	1.15	307	300	98.7	56.3	Yes
Pegasus XL	2.13	1.15	283	400	98.7	56.3	Yes
Pegasus XL	2.13	1.15	262	500	98.7	56.3	Yes
Pegasus XL	2.13	1.15	242	600	98.7	56.3	Yes
Pegasus XL	2.13	1.15	221	700	98.7	56.3	Yes
Pegasus XL	2.13	1.15	190	800	98.7	56.3	Yes
Pegasus XL	2.13	1.15	172	900	98.7	56.3	Yes
Pegasus XL	2.13	1.15	143	1000	98.7	56.3	Yes
SpaceX Falcon 9	13.1	5.22	10704	100	28.5	61.2	No
SpaceX Falcon 9	13.1	5.22	10454	200	28.5	61.2	No
SpaceX Falcon 9	13.1	5.22	10202	300	28.5	61.2	No

Adapted from: (Orbital Sciences 2007; SpaceX 2015; United Launch Alliance 2010; United Launch Alliance 2013).

As the figure illustrates, the majority of the input fields are carried over from earlier worksheets. The two yellow fields are new and represent the desired inclination and the number of satellites to be launched at one time. These inputs drove the calculations seen in the center of the worksheet and were used to calculate the build costs of a small satellite as well as launch vehicle cost. The equations used to calculate the cost of building a single satellite came from the newest edition of "Space Mission Engineering: The New SMAD" and depended on the calculated payload mass from the mass and size section. (Wertz, Everett, and Puschell 2011, 300–301). This included equations for calculating the individual costs of bus development, payload development, integration, assembly, and testing (IA&T), and program level costs which include factors like systems engineering, program management, and software development. The sum of these costs represents the estimated cost to build a single satellite, which was multiplied by the number of satellites. This assumes no savings from efficiencies gained from building multiple satellites.

The bottom of the cost worksheet is a launch vehicle selection matrix programmed to highlight launch vehicles that meet the user input parameters in bright green. The lowest cost from the highlighted options is added to the calculated satellite build costs to determine the total estimated cost of building and launching the small satellite (highlighted in orange). This thesis assumed that the user would want the cheapest feasible launch vehicle, but the user has the option to scroll through the launch vehicle matrix and choose his/her own launch vehicle and its associated cost. Determining the cheapest launch vehicle and the price of that launch vehicle began with research on available launch vehicles. Particular attention was paid to any launch vehicles and companies that had been previously used by the DOD and/or the U.S. government because this indicated a successful, working relationship between the DOD and the contracted launch company.

The research of this thesis also focused on smaller launch vehicles for two reasons. First, the thesis is focused on small satellites versus large ones. Second, it was assumed that smaller launch vehicles would be cheaper than larger ones, and using smaller launch vehicles prevents potentially wasting space due to small satellites filling more of the available space in the fairing. Thesis research into the current launch vehicle market discovered only a few smaller launch vehicle options that had been proven through operational use and had literature on vehicle specifications and capabilities. DOD launch vehicle programs such as Super Strypi and the Soldier-Warfighter Operationally Responsive Deployer for Space (SWORDS) were researched, but ultimately left off the model because they were still unproven R&D programs and no cost data were available. Once cost data is available, these launch vehicles should be added because they will provide a significant cost savings over the current available launch vehicles.

Ultimately, four launch vehicles were chosen: Orbital ATK's Pegasus XL rocket, SpaceX Falcon 9 rocket, United Launch Alliance's (ULA) Atlas V 401 rocket, and the ULA Delta IV Medium rocket. Launch-relevant information for each launch vehicle option was recorded, including payload fairing height, payload fairing diameter, usable mass allowance, altitudes used, inclinations used, and listed cost. The rocket parameters were taken from each launch vehicle's user guide, provided by the respective company's online websites. The resultant table provided over 200 variations across the four launch vehicles, dependent on the desired satellite mass, size, orbit altitude, and inclination.

Together, the mass and size, orbital period/revisit time, and cost worksheets represented design factors that were common to any small satellite design, regardless of the payload. Each worksheet examined aspects of a small satellite bus that are important to a space acquisition professional based on this research and the outcomes of previous thesis chapters. The key input factors and output responses highlighted in these worksheets as well as the payload-specific worksheets were determined to be significant and would be used in the DOE and assist in the production of the synthesis model.

C. DOE

Once the MS Excel tool was completed, it was sent to the NPS SEED Center for Data Farming, a research center within NPS that is researching how decision makers can use M&S effectively to assist in their decisions and subsequent policies (Simulation Experiments & Efficient Design Center for Data Farming 2016). Mary McDonald, a faculty associate in the Operations Research Department, used a 2nd Order Nearly

Orthogonal Latin Hypercube (NOLH) design tool developed by Alex MacCalman to build the DOE. Figure 30 shows a screen shot of the ISR factors and responses used in the design.

Figure 30. ISR Factors-Responses Macro

FACTORS (8)				Responces	
Input Name	**Design Column**	**Sheet/Cell**		**Output Name**	**Sheet/Cell**
Desired GSD	A	ISR!B4		Calculated Aperature Diameter	ISR!B7
Altitude	B	ISR!B5		Calculated Payload mass	Mass-Size'!H4
FOR cone half angle	C	ISR!B24		Spacecraft weighted mass	Mass-Size'!H14
Diameter of FOV	D	ISR!B30		Linear dimension	Mass-Size'!D22
Desired mass	E	Mass-Size'!B4		Number of accesses in 30 days	Orbits-Size'!F19
Propellent	F	Mass-Size'!B5		Mean access duration	Orbits-Size'!F20
Inclination	G	Cost!B7		Total cost	Cost'!G13
# of satellites per launch	H	Cost!B8			

Output should include all input factors as well as responces

Set Ranges of Interest

Factor Settings	A	B	C	D	E	F	G	H
Factor Name	GSR	Altitude	FOR Ang	FOV Diameter	Mass	Prop?	Inclination	# sats
Type	C	C	C	C	C	Cat/D	C	D
Min	50	200	1	1	10	1	0	1
Max	500	1000	75	100	500	0	180	12
unit	cm	km	deg	km	kg	n/a	deg	#
levels	100	100	100	100	100		100	

As the figure shows, the "Factors" section at the top left of the worksheet lists the eight ISR key factors, and the cells of the MS Excel tool from which those inputs were originally displayed (highlighted in yellow). The seven desired output responses were listed in the "Responses" section, with the cells of the MS Excel tool from which those calculated outputs were originally displayed highlighted in orange. The bottom of the worksheet displays the minimum and maximum values for each of the input factors for use in building the DOE. Based on those settings, McDonald built a 465-point 2nd order NOLH design with a pairwise correlation, which would ensure limited 1st and 2nd order confounding. Using this design, McDonald created a macro in the MS Excel spreadsheet that executed the DOE within the model directly, and recorded the output responses directly into the worksheet next to the design input factors. This table can be seen in Figure 31

Figure 31. Partial DOE Output Table

1	GSR	Altitude	FOR Ang	FOV Diameter	Mass	Prop	Inclination	# sats	Calculated Aperature	Calculated Payload mass	Spacecraft weighted mass	Linear dimension	Number of accesses in 30 days	Mean access duration	Total cost
2	195	352	10	6	342	0	22	12	22.02	83.45	342.34	1.749	0.16	-0.03	$ 813,828,891.83
3	136	715	52	5	477	1	154	4	64.14	116.39	615.33	2.126	63.47	360.47	$ 387,456,787.89
4	293	840	64	88	11	0	139	7	34.98	2.68	11.01	0.556	94.21	545.32	$ 17,361,173.11
5	207	650	39	21	86	1	54	5	38.31	20.98	110.94	1.201	40.57	227.37	$ 124,095,855.46
6	322	910	3	80	473	1	70	8	34.48	115.41	610.17	2.120	-10.24	-60.98	$ 814,319,769.99
7	289	429	35	2	258	1	118	6	18.11	62.95	332.82	1.733	23.94	124.91	$ 269,994,526.02
8	446	919	33	89	445	1	111	5	25.14	108.58	574.05	2.078	45.16	263.18	$ 441,238,556.16
9	164	764	2	65	377	1	94	12	56.83	91.99	486.33	1.966	-10.53	-61.30	$ 909,620,535.50
10	211	664	37	17	437	1	27	10	38.39	106.63	563.73	2.065	38.64	217.11	$ 911,631,447.22
11	312	692	42	14	340	0	147	5	27.06	82.96	340.34	1.745	47.30	267.37	$ 316,684,367.67
12	226	353	39	46	237	0	172	6	19.06	57.83	237.24	1.548	23.26	116.13	$ 243,605,128.96
13	148	324	22	21	343	1	95	6	26.71	83.69	442.47	1.905	8.95	43.13	$ 443,491,441.29
14	127	214	33	59	295	1	92	8	20.56	71.98	380.55	1.812	11.93	50.09	$ 482,436,374.93
15	76	217	72	70	291	1	72	10	34.83	71.00	375.39	1.803	33.25	143.28	$ 577,151,929.19
16	369	675	30	57	315	1	42	7	22.32	76.86	406.35	1.852	29.47	165.78	$ 461,601,622.00
17	69	534	33	79	255	0	9	1	94.42	62.22	255.26	1.586	27.01	146.81	$ 110,932,886.60
18	188	361	52	86	354	1	146	7	23.43	86.38	456.66	1.925	34.27	172.44	$ 462,038,338.16
19	166	440	4	88	198	0	3	12	32.34	48.31	198.20	1.458	-5.20	-28.13	$ 448,913,311.58
20	395	293	11	3	301	1	123	2	9.05	73.44	388.29	1.824	0.59	1.76	$ 113,843,868.21
21	464	243	21	84	252	0	166	5	6.39	61.49	252.25	1.580	6.20	26.70	$ 219,721,069.24
22	280	758	11	30	57	1	10	4	33.03	13.91	73.53	1.047	3.48	19.08	$ 89,220,508.04
23	500	830	48	65	112	1	155	4	20.25	27.33	144.48	1.312	66.22	382.55	$ 68,027,704.21
24	159	381	68	53	350	1	103	1	29.23	85.40	451.50	1.918	49.49	252.54	$ 73,219,052.16
25	337	267	63	43	277	0	27	12	9.67	67.59	277.28	1.630	33.51	155.17	$ 642,797,164.83
26	421	852	70	1	429	1	49	11	24.69	104.68	553.41	2.053	105.82	613.53	$ 974,333,565.29
27	416	430	1	44	404	0	178	4	12.61	98.58	404.40	1.849	-7.95	-42.46	$ 315,521,668.88
28	358	595	24	13	128	1	144	4	20.28	31.23	165.12	1.372	18.67	102.97	$ 79,257,410.92
29	355	274	17	11	338	0	5	12	9.42	82.47	338.34	1.742	4.37	19.37	$ 803,038,659.96
30	298	564	51	58	195	1	82	1	23.09	47.58	251.55	1.578	49.82	273.72	$ 97,199,198.97
31	437	816	1	4	217	1	9	8	22.78	52.95	279.93	1.635	-12.74	-74.59	$ 351,477,541.56
32	276	901	53	53	453	0	174	5	39.83	110.53	453.45	1.921	80.63	469.87	$ 451,073,072.01
33	286	905	14	80	492	1	171	11	38.60	120.05	634.68	2.148	9.86	56.51	$ 1,081,916,326.83
34	363	562	56	91	41	0	176	1	18.89	10.00	41.04	0.862	55.59	305.29	$ 6,656,125.45
35	172	706	1	85	324	0	125	6	50.08	79.06	324.32	1.718	-11.37	-65.43	$ 356,481,770.35
36	287	317	60	68	29	0	177	11	13.48	7.08	29.03	0.768	36.47	177.64	$ 48,200,731.29
37	443	604	8	18	428	0	172	11	16.63	104.43	428.43	1.885	-1.27	-7.74	$ 910,503,968.55
38	91	256	10	44	186	0	131	9	34.32	45.38	186.19	1.428	-0.25	-2.45	$ 270,973,321.10
39	144	612	50	82	261	0	17	4	51.85	63.68	261.26	1.598	52.42	291.51	$ 245,949,723.23
40	134	408	58	77	424	0	141	2	37.15	103.46	424.42	1.879	43.53	225.41	$ 173,464,589.34
41	232	583	10	78	390	0	167	7	30.66	95.16	390.39	1.827	1.17	5.78	$ 520,535,727.66
42	492	640	30	50	39	0	24	5	15.87	9.52	39.04	0.848	28.02	156.46	$ 84,824,154.93
43	293	966	45	82	129	0	29	6	40.22	31.48	129.13	1.264	70.62	414.06	$ 179,723,917.49
44	423	515	24	31	41	0	80	6	14.85	10.00	41.04	0.862	16.24	87.46	$ 91,926,083.22

As the figure shows, for each set of input factors there is a corresponding set of output responses highlighted in orange. Since some combinations of the input values might produce an infeasible design, some of the output response values came out as negative values, highlighted in red. Despite producing some infeasible small satellite design outputs, the output response values were tied to the original input factors, so meta-models could still be developed that would preserve the relationship between the inputs and outputs. These meta-models would allow for a deeper exploration of the relationships between the factors and responses.

To develop these meta-models, the data table was exported into JMP in order to explore the relationship between input factors and output responses in more depth. The JMP software is a program comprised of multiple statistical tools designed to provide data analysis with a visual medium such as interactive graphs and charts (SAS 2016b). Paul Beery used JMP to develop his meta-models used to drive his “dashboard,” which he used to visualize the trade space for his operational and physical synthesis models. This thesis sought to use JMP for the same purpose.

D. DEVELOPING THE JMP TOOL

The JMP program was used to explore the relationship between the input factors and output responses from the DOE data produced by Mary McDonald's macro. The output data from the DOE provided hundreds of data points, presenting an opportunity to discover how certain factors influence certain responses. JMP's statistical functions correlate the factors and the responses based on the type of regression analysis the user wants to conduct. Initial regression analysis used seven output responses and eight input factors, as well as their higher order interactions using second-degree factorial and second-degree polynomial relationships. The standard least squares estimate method was initially used for data screening, which JMP applied to each of the seven responses individually. For the purposes of this thesis, the output response "total cost" will be used to illustrate the products created by the JMP software, although similar analysis was done for all seven responses. The resultant statistical products include a predicted plot showing the fit of the model to the data points, a summary of fit reporting the R-squared value, sorted parameter estimates showing the amount of influence each input factor had on the overall model, and a predicted expression, which is the meta-model that used all the input factors as well as the factorial and polynomial relationships up to the second degree. Figure 32 shows some of these initial regression analysis products for total cost.

Figure 32. Initial Regression Analysis Products for Total Cost

Summary of Fit

RSquare	0.995735
RSquare Adj	0.995288
Root Mean Square Error	17625034
Mean of Response	3.156e+8
Observations (or Sum Wgts)	465

Analysis of Variance

Parameter Estimates

Effect Tests

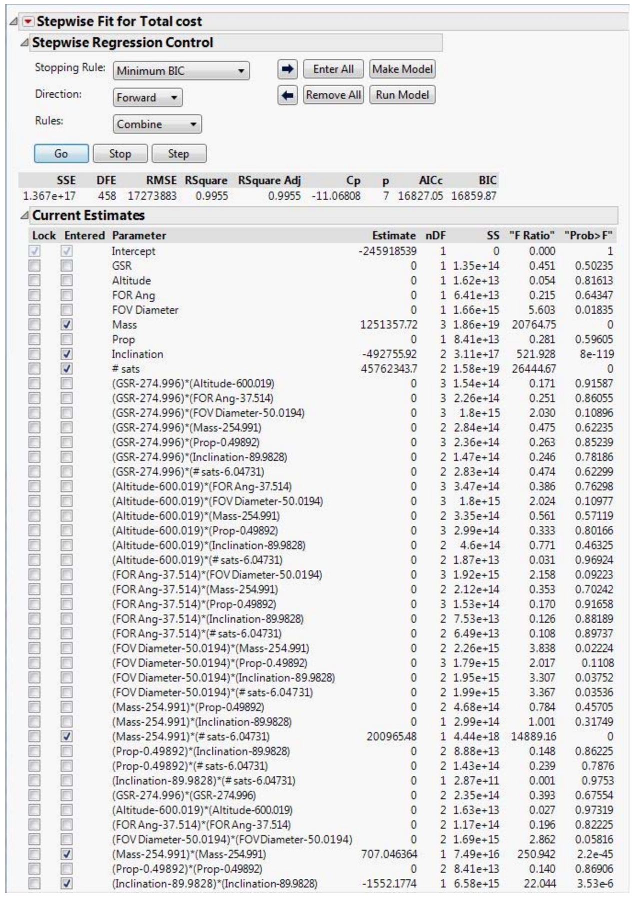
Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Mass	12523349	5821.19	215.13	<.0001*
# sats	45733942	244272.6	187.22	<.0001*
(Mass-254.991)*(# sats-6.04731)	201509.85	1716.559	117.39	<.0001*
Inclination	-495325.2	15976.37	-31.00	<.0001*
(Mass-254.991)*(Mass-254.991)	709.53418	45.8964	15.46	<.0001*
(Inclination-89.9828)*(Inclination-89.9828)	-1528.402	341.7909	-4.47	<.0001*
FOV Diameter	-68014.24	28462.54	-2.39	0.0173*
(FOV Diameter-50.0194)*(Mass-254.991)	274.06338	201.148	1.36	0.1738
(Mass-254.991)*(Prop-0.49892)	-14470.04	11736.19	-1.23	0.2183
(Altitude-600.019)*(Inclination-89.9828)	-75.12948	68.80549	-1.09	0.2755

As the figure shows, the R-squared value, also known as the “coefficient of determination” in statistics, was 0.995735, indicating a near-perfect fit of the data to the model. This is not surprising considering how many input factors (including the second degree relationships) were used to build the model as well as the deterministic nature of mathematical models. Under the “sorted parameter estimates” section, the chart shows only six of the 40 possible interactions (highlighted in orange) that were significant and responsible for the majority of the effects on total cost. All seven output responses showed similar results; their behaviors were primarily affected by six or fewer input interactions. As a result, the next step sought to simplify the regression analysis by removing all the insignificant factors that had minimal influence on the output response.

For ease of analysis, each of the seven output responses were run individually. The first analysis used stepwise regression to simplify the model by identifying the factors that had the greatest influence on the response. Figure 33 shows the stepwise regression analysis for total cost.

Figure 33. Stepwise Regression Analysis for Total Cost


Stepwise Fit for Total cost

Stepwise Regression Control

Stopping Rule: Minimum BIC

Direction: Forward

Rules: Combine

Enter All | Make Model | Remove All | Run Model | Go | Stop | Step

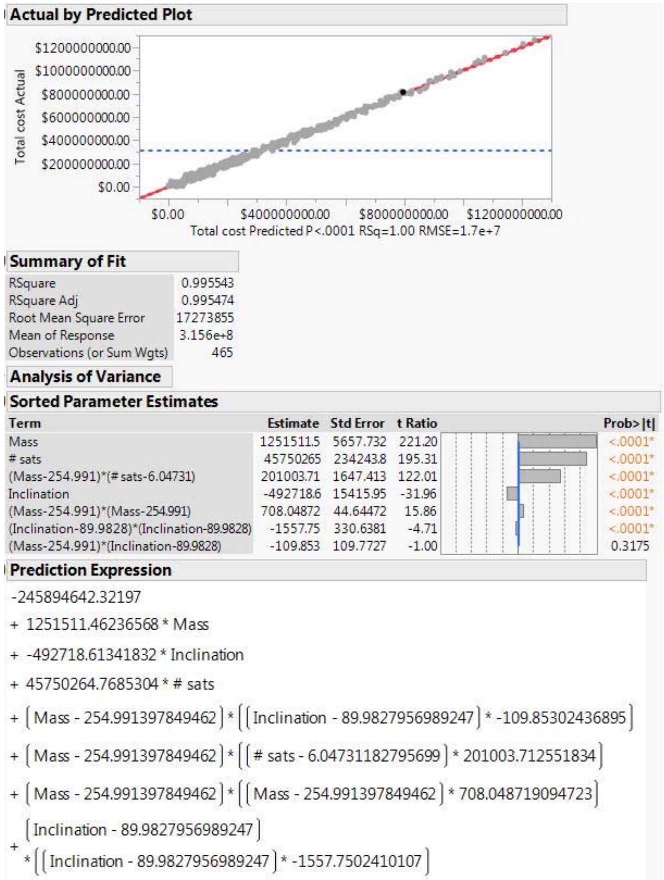
SSE	DFE	RMSE	RSquare	RSquare Adj	Cp	p	AICc	BIC
1.367e+17	458	17273883	0.9955	0.9955	-11.06808	7	16827.05	16859.87

Current Estimates

Lock	Entered	Parameter	Estimate	nDF	SS	"F Ratio"	"Prob>F"
✓	✓	Intercept	-245918539	1	0	0.000	1
		GSR	0	1	1.35e+14	0.451	0.50235
		Altitude	0	1	1.62e+13	0.054	0.81613
		FOR Ang	0	1	6.41e+13	0.215	0.64347
		FOV Diameter	0	1	1.66e+15	5.603	0.01835
	✓	Mass	1251357.72	3	1.86e+19	20764.75	0
		Prop	0	1	8.41e+13	0.281	0.59605
	✓	Inclination	-492755.92	2	3.11e+17	521.928	8e-119
	✓	# sats	45762343.7	2	1.58e+19	26444.67	0
		(GSR-274.996)*(Altitude-600.019)	0	3	1.54e+14	0.171	0.91587
		(GSR-274.996)*(FOR Ang-37.514)	0	3	2.26e+14	0.251	0.86055
		(GSR-274.996)*(FOV Diameter-50.0194)	0	3	1.8e+15	2.030	0.10896
		(GSR-274.996)*(Mass-254.991)	0	2	2.84e+14	0.475	0.62235
		(GSR-274.996)*(Prop-0.49892)	0	3	2.36e+14	0.263	0.85239
		(GSR-274.996)*(Inclination-89.9828)	0	2	1.47e+14	0.246	0.78186
		(GSR-274.996)*(# sats-6.04731)	0	2	2.83e+14	0.474	0.62299
		(Altitude-600.019)*(FOR Ang-37.514)	0	3	3.47e+14	0.386	0.76298
		(Altitude-600.019)*(FOV Diameter-50.0194)	0	3	1.8e+15	2.024	0.10977
		(Altitude-600.019)*(Mass-254.991)	0	2	3.35e+14	0.561	0.57119
		(Altitude-600.019)*(Prop-0.49892)	0	3	2.99e+14	0.333	0.80166
		(Altitude-600.019)*(Inclination-89.9828)	0	2	4.6e+14	0.771	0.46325
		(Altitude-600.019)*(# sats-6.04731)	0	2	1.87e+13	0.031	0.96924
		(FOR Ang-37.514)*(FOV Diameter-50.0194)	0	3	1.92e+15	2.158	0.09223
		(FOR Ang-37.514)*(Mass-254.991)	0	2	2.12e+14	0.353	0.70242
		(FOR Ang-37.514)*(Prop-0.49892)	0	3	1.53e+14	0.170	0.91658
		(FOR Ang-37.514)*(Inclination-89.9828)	0	2	7.53e+13	0.126	0.88189
		(FOR Ang-37.514)*(# sats-6.04731)	0	2	6.49e+13	0.108	0.89737
		(FOV Diameter-50.0194)*(Mass-254.991)	0	2	2.26e+15	3.838	0.02224
		(FOV Diameter-50.0194)*(Prop-0.49892)	0	3	1.79e+15	2.017	0.1108
		(FOV Diameter-50.0194)*(Inclination-89.9828)	0	2	1.95e+15	3.307	0.03752
		(FOV Diameter-50.0194)*(# sats-6.04731)	0	2	1.99e+15	3.367	0.03536
		(Mass-254.991)*(Prop-0.49892)	0	2	4.68e+14	0.784	0.45705
		(Mass-254.991)*(Inclination-89.9828)	0	1	2.99e+14	1.001	0.31749
	✓	(Mass-254.991)*(# sats-6.04731)	200965.48	1	4.44e+18	14889.16	0
		(Prop-0.49892)*(Inclination-89.9828)	0	2	8.88e+13	0.148	0.86225
		(Prop-0.49892)*(# sats-6.04731)	0	2	1.43e+14	0.239	0.7876
		(Inclination-89.9828)*(# sats-6.04731)	0	1	2.87e+11	0.001	0.9753
		(GSR-274.996)*(GSR-274.996)	0	2	2.35e+14	0.393	0.67554
		(Altitude-600.019)*(Altitude-600.019)	0	2	1.63e+13	0.027	0.97319
		(FOR Ang-37.514)*(FOR Ang-37.514)	0	2	1.17e+14	0.196	0.82225
		(FOV Diameter-50.0194)*(FOV Diameter-50.0194)	0	2	1.69e+15	2.862	0.05816
	✓	(Mass-254.991)*(Mass-254.991)	707.046364	1	7.49e+16	250.942	2.2e-45
		(Prop-0.49892)*(Prop-0.49892)	0	2	8.41e+13	0.140	0.86906
	✓	(Inclination-89.9828)*(Inclination-89.9828)	-1552.1774	1	6.58e+15	22.044	3.53e-6

As the figure shows, the stepwise regression identified six interactions that were considered significant and most influenced the total cost output response. This included the primary input factors of mass, inclination, and number of satellites as well as the second-degree factorial relationship between mass and the number of satellites, and the second-degree polynomial relationship between mass and itself, and inclination and itself. Following this screening, secondary analysis returned to least squares estimate regression to analyze only the six interactions identified by stepwise analysis rather than using all eight input factors and the additional second-degree factors. This produced a more simplified model that was nearly as accurate, as shown in Figure 34 for the total cost response.

Figure 34. Refined Regression Model for Total Cost



As the figure shows, the R-squared value dropped from 0.995735 to 0.995543, a marginal decrease when considering the reduction in complexity from 40 input interactions to just six, proving that the six input interactions identified by stepwise regression analysis were indeed responsible for nearly all of the effects on the model. The “sorted parameter estimates” section shows all six input interactions highlighted in orange, indicating their importance to the model. The key product from this analysis report is the prediction expression, which is the meta-model that is used to calculate the total cost output response based on the user-submitted values for the relevant input factors. The initial least squares regression analysis, which included over 40 input interactions, yielded a prediction expression that was dozens of lines long. The refined prediction expression for total cost, shown in Figure 34, only requires input values for mass, inclination, and the number of satellites, making the prediction expression much simpler while still maintaining a near-perfect fit. The refined meta-models for each of the seven output responses were then reinserted into the final, stream-lined iteration of the MS Excel tool (named the "trade space analysis worksheet"), completing the tool and making it ready to provide decision support to DOD space acquisition professionals.

E. FINALIZING THE DECISION SUPPORT TOOLS

The initial MS Excel tool introduced earlier in this chapter served two purposes. The first was to develop a functional tool that would accurately calculate design responses based on user-selected values for a variety of input factors. The second purpose of the initial MS Excel tool was to produce output data through the execution of a DOE for use in statistical analysis and meta-model development. The data produced by Mary McDonald and then analyzed in JMP resulted in refined meta-model equations for each of the seven key output responses that produced very precise fits (over 90% for all output responses). The model equations provided an opportunity to streamline the MS Excel tool even further into the trade space analysis worksheet, which is shown in Figure 35.

Figure 35. Trade Space Analysis Worksheet

Trade Space Analysis

Please submit input values for each of the blue cells below. The outputs will be calculated and presented in the green cells.

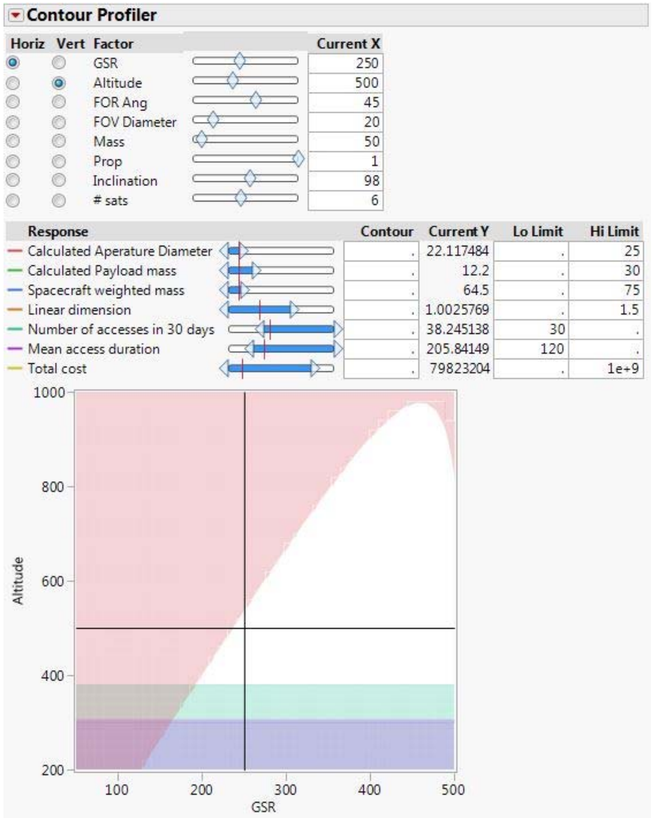
Inputs		Units
GSR	250	cm
Altitude	200	km
Cone Half-Angle	20	deg
Spacecraft Mass	10	kg
Propellant	1	0="No", 1="Yes"
Inclination	50	deg
# of Satellites	4	

Outputs		Units
Total Cost	$ 64,735,118.21	USD
Aperature Diameter	0.87	cm
Linear Dimension	0.815	m
Number of Accesses (in 30 days)	4.617	
Mean Access Duration	17.755	secs
Payload Mass	1.73	kg
Spacecraft Weighted Mass	10	kg

As the trade space analysis worksheet shows, the only inputs required are the seven key input factors that influenced the seven key output responses identified at the end of chapter three. The only key input factor that was not included in the final trade space analysis worksheet was FOV diameter due to the oversight previously mentioned. A user can now use this worksheet for quick feasibility analysis of potential small satellite designs by inputting values for the seven inputs without needing to search through the earlier worksheets or using JMP. A trade space analysis worksheet was produced for both the ISR and MILSATCOM payloads, which are very similar. If the user is interested in other variables that are not included on this worksheet, he/she can choose to use the earlier worksheets of the MS Excel tool that include those additional variables.

While the trade space analysis worksheet provides a faster and simpler analysis tool for examining the relationship between key inputs and outputs, it is still limited in the support it provides because it does not possess a visual component. As discussed earlier, a visual component adds another layer of understanding to the information being presented. While the trade space analysis worksheet presents estimated values for the key output responses, it does not tell the user how much “wiggle” room he/she has in the design. Adding a visual component to the decision support tools enhances the understanding of the user by providing an additional dimension to explore. That information can be important to a DOD space acquisitions professional who may be interested in how much margin is available for trade-offs in each of the input responses, especially during the early portions of conceptual design. Unfortunately, MS Excel did not possess a graphical function capable of displaying the desired visual so this thesis used the JMP contour profiler as a supplemental tool to help visualize the trade space of a small satellite. JMP provided an interactive contour plot that would respond and change its display features based on user inputs. The visuals of the JMP program used in combination with the trade space analysis worksheet provide different analysis options for a decision maker to use during satellite conceptual design. The contour profiler provides a reactive graph that responds to changes in input factor values carried over by the user from the trade space analysis worksheet. Figure 36 shows a screen shot of the contour profiler.

Figure 36. Contour Profiler



As the figure shows, there are three sections to the contour profiler: the input section at the top, the response limits section in the middle, and the profiler graph at the bottom. The input section at the top lists the eight key input factors determined in chapter three, including FOV diameter, which was excluded on the trade space analysis worksheet. The user should take the input values from the trade space analysis worksheet and enter these values in the appropriate box under the "Current X" column. This provides a foundational starting point for exploring the trade space of a feasible small satellite design. One limitation of JMP is that it can only display two input factors at a time, represented by the "Horiz" and "Vert" columns in the input section. The user will have to jump between factors while exploring the trade space of the small satellite to gain more insight.

The response limits section is where the user can set the lower and upper limits of the output responses in the “Lo Limit” and “Hi Limit,” respectively. These limits set the shaded areas of the profiler graph based on the values submitted in the input section. The user can choose to set both lower and upper limits based on their needs, but it’s more likely that one or the other will be set for each output response. For example, the user will want the lightest feasible satellite possible, and thus will set a maximum limit for spacecraft weighted mass. Conversely, the user will want as many accesses in 30 days as possible, but may not want any less than 30 accesses during that time frame. Therefore, the user would set a minimum limit for number of accesses in 30 days. The “Current Y” column represents the current value for each of the output responses based on the input factor values submitted by the user in the input section. This is similar to the calculations provided by the trade space analysis worksheet.

Finally, the profiler graph at the bottom provides the visual element of the trade space analysis worksheet. The x-axis and y-axis are set based on the input factors selected under the “Horiz” and “Vert” columns in the input section. The values submitted for the two input factors being explored produce the black, intersecting lines seen in Figure 36, and represent where your design sits in the trade space. If the crosshair sits in a white area, the values that were selected for all inputs and the constraints set in response limits section generate a feasible synthesis design option. The entire white area, no matter how small or large, represents trade space for a feasible small satellite design. If the crosshair falls into a colored, shaded area, the design is not feasible due to an input setting or constraint of at least one output response. Each output response is represented by a specific color that appears on the profiler graph. For example, the output response “calculated aperture diameter” is pink, as shown in Figure 36. While the black crosshair currently sits in a white area, if desired altitude was increased, the calculated aperture diameter would increase, eventually moving the crosshair into the pink “calculated aperture diameter” area of infeasibility. To alleviate infeasibility, the user must modify either the input factors or the limits of calculated aperture diameter.

F. CONCLUSION

Despite some limitations, JMP's contour profiler provides a powerful tool for exploring the trade space of a small satellite design, presenting both a numerical and a visual component. The contour profiler and the interpretation of its results are not easily intuitive, but practice and understanding of how to manipulate the profiler settings will allow a user to see how a small satellite design can be modified and trade-offs made, while still maintaining feasibility. When the trade space analysis worksheet is used in concert with the JMP contour profiler (referred to hereafter as the "trade space exploration tool"), they provide decision support tools for a DOD space acquisition professional, allowing him/her to not only determine feasibility of a conceptual small satellite design but also to explore the design's trade space and where trade-offs can be made. The next chapter will present an example of how the DOD may apply these tools by using them in a fictional stakeholder scenario.

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V. SCENARIO ANALYSIS

Chapter IV presented a detailed discussion of the two decision-support tools developed in this thesis, but it may still be difficult to understand the usability of the tools without applying it to an example scenario. This thesis did not approach or consult with any DOD stakeholders to test the usability of the decision support tools but conducted testing through a simulated scenario created by the author based on his professional military space knowledge and experience. This chapter will demonstrate the application of the trade space analysis worksheet and the trade space exploration tool. This chapter will discuss the test case scenario used, which was based on an informed yet fictitious account of real-world DOD stakeholders and their needs, and provide a step-by-step demonstration of using the tools in that scenario.

A. TEST SCENARIO

The scenario developed for this chapter is fictional and should not be mistaken as an authentic request from any DOD command or personnel. However, this scenario is informed by the author's experience as a U.S. military space professional. The following scenario is inspired in part by the DOD's concerns of China's expanding counter-space capabilities as introduced in Chapters I and II.

U.S. Pacific Command (USPACOM) J5 planners are developing plans to retake control of the Spratly Islands from China in the event of a conflict in that area of responsibility (AOR). Over the past year, the commander of USPACOM has been receiving reports detailing China's ASAT capabilities, particularly their direct ascent weapons systems. The commander of USPACOM understands that satellites are a significant force enhancement capability needed for executing operations, but has concerns about the potential of China taking out critical ISR satellites early in a potential conflict. He has tasked USPACOM J3 and the space operations professionals to explore the feasibility of potential solutions to the threat before formally requesting the capability on his integrated priority list (IPL). One course of action (COA) involves developing ISR small satellites that may be resilient against the direct ascent ASAT threat while still *providing acceptable capabilities. USPACOM J3 has reached out to SPAWAR's Program Executive Office (PEO) for Space Systems to conduct a preliminary design feasibility analysis based on PACOM's stated requirements. USPACOM J3's requirements are a mixture of mission requirements and system requirements.*

- *PACOM J3 needs to image objects of interest in the Spratly Islands AOR. This may include but is not limited to Chinese maritime vessels, ground-based systems, and infrastructure.*
- *PACOM J3 suggested a resolution of at least one meter, but is willing to trade this off for other capabilities.*
- *PACOM J3 recommends using LEO orbit to support resolution and also minimize launch costs.*
- *While PACOM J3 is interested in small satellites, it has no specific mass or size dimensions that need to be met; though they believe smaller is better.*
- *PACOM J3 needs to collect ISR of activity in the Spratly Islands area of operations (AO) at least once a day, though more access is preferred.*
- *PACOM J3 understands that this is an initial investigation on feasibility, therefore the focus will be on a single small satellite design though a constellation will likely be needed to achieve better access and revisit times to the Spratly Islands AO.*
- *PACOM J3 did not present a budget constraint since this is only a preliminary analysis, but it is interested in an estimated cost with the intent of minimizing the program's cost. A lower cost may help in the DOD's approval of the program if the small satellite is selected as a solution.*

This fictional scenario will guide a demonstration of the trade space analysis worksheet and the trade space exploration tool developed by this thesis. For this scenario, it is assumed that any administrative tasks or obstacles that may arise in the real world have been overcome so that analysis can focus solely on the feasibility of a proposed small satellite design. While these tools and the subsequent analysis are intended to be used by space acquisition professionals who may work for a command similar to SPAWAR PEO Space Systems, the discussion in this chapter will be from the perspective of the author rather than a space acquisition professional.

B. USING THE TOOLS

Discussions with USPACOM J3 produced both broad and contextualized requirements that provide a foundation for analysis. The major requirements as understood include:

- One-meter resolution to image
- LEO orbit
- “Small” satellite
- Access to Spratly Islands AO per day
- Lowest cost possible

These requirements spark a few initial considerations and assumptions at the beginning of the feasibility analysis. First is that an imaging small satellite is desired for deployment in LEO orbit. While it was not specified, it is assumed that an electro-optical (EO) satellite that collects imagery in the human visible spectrum is desired. Since an EO satellite is desired, it is more beneficial to design the small satellite for a sun-synchronous orbit. This will allow the satellite to access the region at the same time every day, ensuring there will always be sunlight at the time of image collection. This setting is subject to stakeholder preference and trade-offs because an orbital inclination closer to the latitude of the area of interest can produce better revisit times and may be better suited for the mission requirements. LEO altitudes are still achievable from a sun-synchronous inclination, but the differences between the assumed circular LEO and a sun-synchronous orbit must be understood.

Second, altitude was set to 200 kilometers for this initial assessment with the intent of maintaining as low an altitude as possible to support resolution and minimize launch costs. Third, cone half-angle (i.e., FOR angle) was set to 20 degrees, which is a common value for imaging satellites. Fourth, the stakeholder did not provide an exact mass or size requirement, only the general term “small.” This analysis will define “small” to be a mass under 100 kilograms based on assumptions of the stakeholder’s intent for and needs of the satellite. The addition of propellant was selected to maximize mission flexibility, but this will also maximize the spacecraft’s weighted mass during initial assessment, though that option can be removed in the future. Fifth, the stakeholder requires access (i.e., imaging) of the area at least once a day, however, the stakeholder did not specify the length of time needed. This analysis will assume a mean access time of one to two minutes is desired, which should be enough time for the small satellite to capture sufficient ISR data. Finally, the stakeholder understands that this initial analysis will only consider a single small satellite, but knowing that a constellation is likely desired, cost analysis will consider multiple small satellites. This analysis used a constellation of six satellites, but they factor only into cost and not performance of the small satellite system.

After accounting for the stakeholder's requirements and the subsequent associated considerations, these inputs were entered into the trade space analysis worksheet. Figure 37 shows the application of the stakeholder's requirements with the aforementioned considerations.

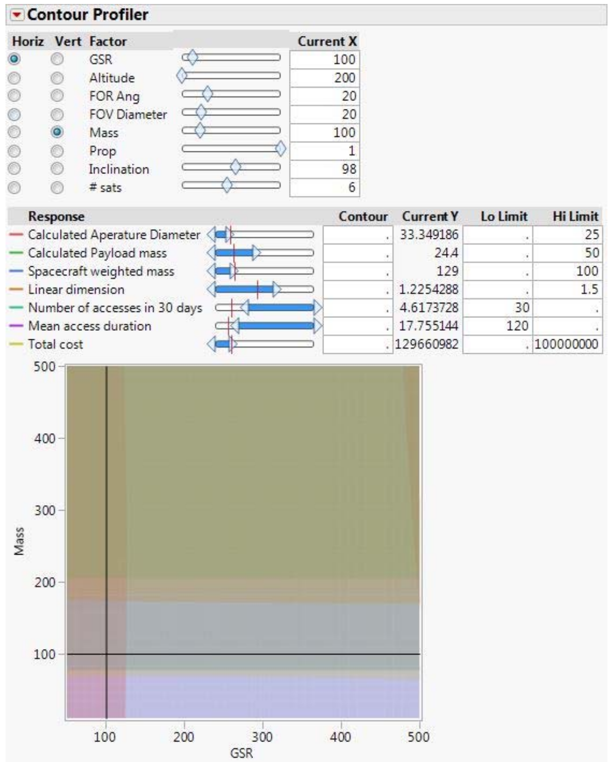
Figure 37. Scenario Trade Space Analysis Worksheet

Trade Space Analysis		
Please submit input values for each of the blue cells below. The outputs will be calculated and presented in the green cells.		
Inputs		**Units**
GSR	100	cm
Altitude	200	km
Cone Half-Angle	20	deg
Spacecraft Mass	100	kg
Propellant	1	0="No", 1="Yes"
Inclination	98	deg
# of Satellites	6	
Outputs		**Units**
Total Cost	$ 123,990,974.07	USD
Aperature Diameter	33.88	cm
Linear Dimension	1.218	m
Number of Accesses (in 30 days)	4.617	
Mean Access Duration	17.755	secs
Payload Mass	17.3	kg
Spacecraft Weighted Mass	100	kg

As the trade space analysis worksheet shows, the resultant output values are not surprising and are consistent with the parameters of small satellites researched earlier in this thesis, given the input values. The estimated cost of the six satellites is under $124 million, which includes the cost of the launch vehicle. Based on the desired mass, the satellite will be just over one meter long. Initial analysis indicates the outputs that warrant further exploration for potential trade-offs are the number of accesses in 30 days and the mean access duration. The current estimation predicts just four visits to a particular area of interest in a single month with each visit being just under 18 seconds long. This adds up to approximately 71 seconds of access to an area of interest in a 30-day timespan. This is a concern even when multiplied by six satellites because it is far less than the stakeholder requested and needs to be addressed. Thus, the analysis will now move to the trade space exploration tool to see if trade-offs can be made to improve the number of accesses in 30 days and the mean access duration while meeting the rest of the requirements.

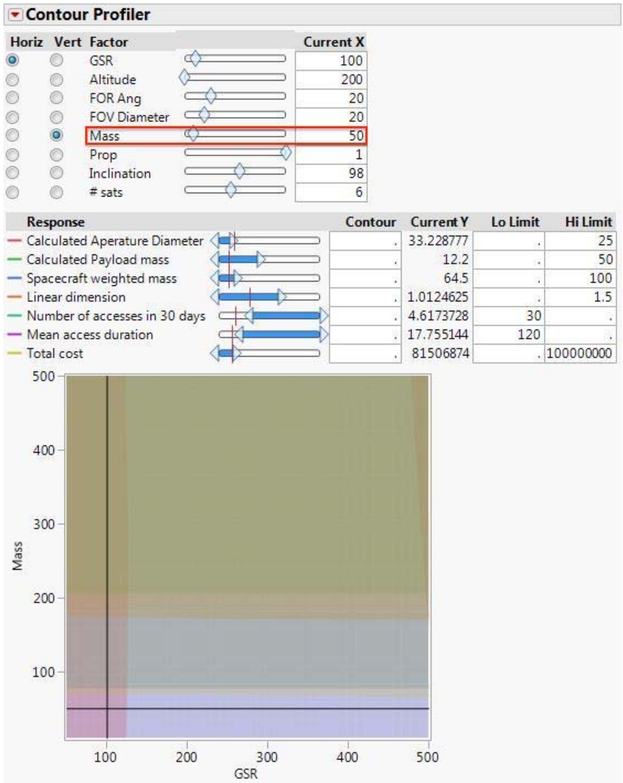
The input values from the trade space analysis worksheet are then entered into the trade space exploration tool. FOV diameter, an input factor not included on the trade space analysis worksheet, was set to 20 kilometers based on common values for ISR satellites. The upper (‘Hi Limit’) and lower (‘Lo Limit’) bounds in the response section were chosen based on either stated stakeholder requirements, assumptions based on their needs and intentions, and/or military experience. A maximum aperture diameter of 25 centimeters, a maximum payload mass of 50 kilograms and a maximum spacecraft weighted mass of 100 kilograms, and a maximum linear dimension of 1.5 meters all serve to keep the satellite relatively small as requested by the stakeholder. The minimum values for number of accesses and mean access duration were based on the stakeholder’s access requirement. The total cost limit was set to a maximum of $100 million based on knowledge of costs for larger DOD satellite programs, which are more expensive, as described in Chapters I and II. Figure 38 shows the output of the trade space exploration tool after entering the initial inputs from the trade space analysis worksheet.

Figure 38. Scenario Trade Space Exploration Tool Initial Input



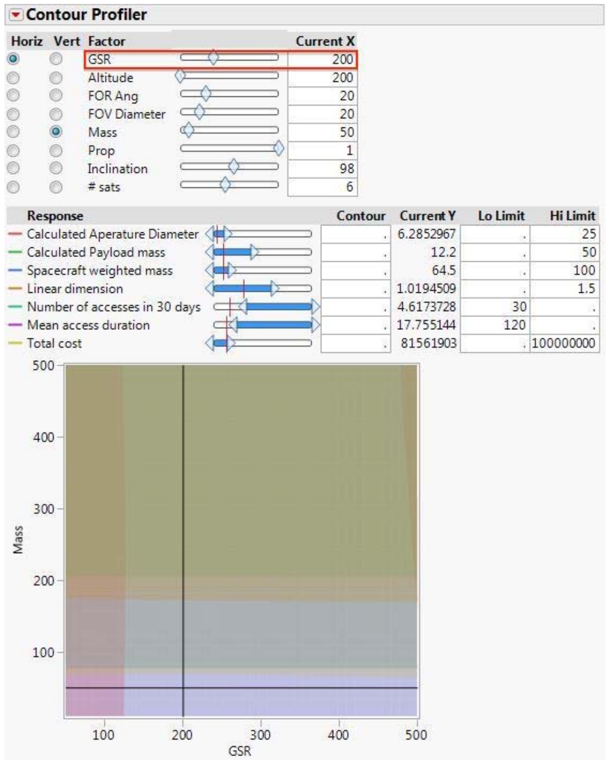
As the figure shows, both the response limits section and the profiler graph show that the initial small satellite design is infeasible. The response values under the "Current Y" column show five out of seven of the output responses are infeasible and outside either the upper or lower limits set based on the stakeholder's requirements. The output responses limiting feasibility are calculated aperture diameter, spacecraft weighted mass, number of accesses in 30 days, mean access duration, and total cost. Thus, modifications must be made to the input factor values or the upper and lower limits in order to produce a feasible small satellite design. To do this, the mass value will be modified first because of its direct relationship to spacecraft weighted mass and total cost. Figure 39 shows the trade space exploration tool after the input mass has been changed.

Figure 39. Scenario Trade Space Exploration Tool with Mass Reduced



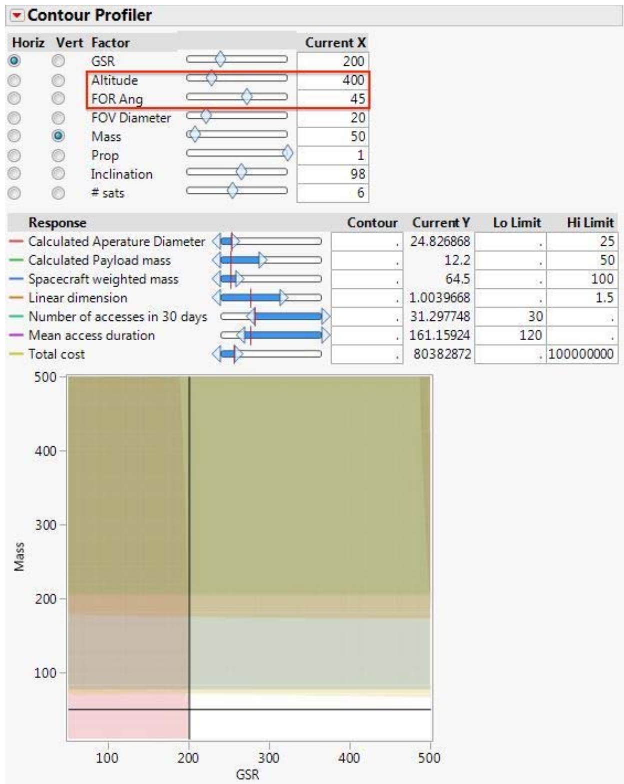
As the figure shows, by reducing the input mass from 100 kilograms to 50 kilograms, the spacecraft weighted mass dropped from 129 to 64.5 kilograms and the total cost dropped from approximately $130 million to $81.5 million, making both of these output responses feasible. While these two output responses no longer limit the satellite's feasibility, there are still three other output responses that are causing an infeasible design, as can be seen on the profiler graph. The black crosshair on the profiler graph shifted outside of the shaded regions of the spacecraft weighted mass and total cost, but the black crosshair is still located in a region of infeasibility, necessitating further modifications to the small satellite's input factor values or limits. The output responses still preventing feasibility are calculated aperture diameter, number of accesses in 30 days, and mean access duration. To modify these responses, a change is required in either desired resolution, altitude, FOR angle, and/or FOV diameter because those are the input factors that affect the limiting output responses. While a resolution of one meter was initially desired, relaxing that requirement could produce increased feasibility of design, as shown in Figure 40.

Figure 40. Scenario Trade Space Exploration Tool with Decreased Resolution



As the figure shows, by decreasing the desired resolution from one meter to two meters, the number of output responses causing infeasibility decreased from three to two. While two meters is not as precise, it still allows detection of targets of interest like Chinese naval vessels or aircraft operating near the Spratly Islands, thus can be a legitimate trade-off for feasibility. This modification produced another shift in the black crosshair out of the calculated aperture diameter's shaded area (pink), indicating the calculated aperture diameter value is now feasible within the stakeholder's limit. However, the current small satellite design remains infeasible, still limited by the number of accesses in 30 days and the mean access duration. The two input factors that most affect the number of accesses and the mean access duration are spacecraft altitude and the cone half-angle, listed as FOR angle in the trade space exploration tool. In order to produce a feasible small satellite design, those two input factors need to be modified. The results of those changes are shown in Figure 41.

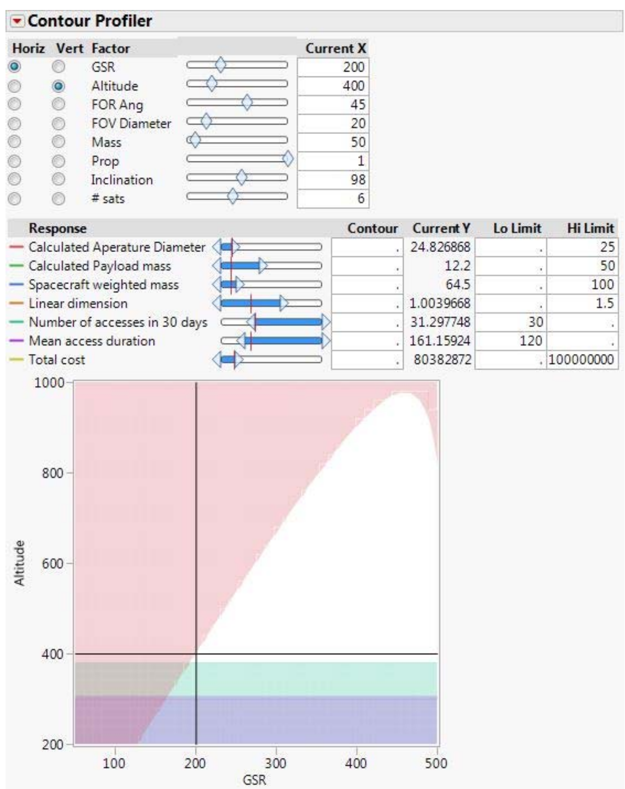
Figure 41. Scenario Trade Space Exploration Tool with Increased Altitude and FOR Angle



As the figure shows, by increasing altitude from 200 kilometers to 400 kilometers and the FOR angle from 20 degrees to 45 degrees, a feasible solution is achieved. While the black crosshair did not move since mass and resolution were not modified, the shaded areas of infeasibility for the number of accesses and the mean access duration shrank. As the profiler graph shows, the black crosshair is now located in a non-shaded, white area, which represents the area of feasible design and potential further design trade-offs. The white strip above the crosshair indicates margin for the desired mass input factor. The spacecraft weighted mass value is 64.5 kilograms, which is 35.5 kilograms under the 100-kilogram stakeholder limit, providing feasible trade space for the desired mass of the small satellite. The trade space for desired resolution is not as generous. The black crosshair is on the right-most edge of the calculated aperture diameter response's shaded area. The calculated aperture diameter's value is 24.83 centimeters, just barely under the set limit of 25 centimeters, making improved resolution impossible under the current limits and inputs. The white space to the right of the black crosshair indicates a large amount of flexibility in the positive x-axis direction, but further decrease in resolution is not a desired trade off.

Thus, far, this analysis has only explored the visual responses based on the desired mass and resolution input factors. Changing the selected input factors under the "horiz" and "vert" columns can provide more in-depth analysis on the effects of other input factors, which is dependent on the needs and priority of the user. To give an example, Figure 42 shows the trade space exploration tool looking at the desired resolution and altitude input factors instead of desired resolution and mass.

Figure 42. Scenario Trade Space Exploration Tool with GSR-Altitude Comparison



As the figure shows, the values in the response limits section did not change because no changes were made to the values of the input factors. However, the profiler graph contours changed due to the switch from desired mass to desired altitude along the y-axis. The calculated aperture diameter region now has a curved edge rather than a linear edge and engulfs more of the graph space, indicating the output response's more robust relationship with desired altitude compared to desired mass. Despite the change in contour, the small satellite design is still feasible. While the black crosshairs are again just outside the limits of the calculated aperture diameter, there is more margin in the trade space for these two input factors, providing an opportunity to increase the satellite's altitude and decrease its resolution, though both of those changes are likely undesirable.

Based on the findings of this initial analysis, SPAWAR PEO Space Systems should inform the PACOM J3 that if it is willing to reduce its desired ground resolution from one meter to two meters, a feasible design is possible that meets PACOM's other mission requirements. PACOM J3 did not provide any other specific requirements that could not be met by the trade-offs made during analysis, thus SPAWAR can offer a feasible small satellite design based on the input values. Ultimately, it is up to PACOM to decide whether or not the design input values are acceptable and whether or not to fund the requirement as an IPL, but PACOM now has estimates for a feasible small satellite design that it can choose to explore in further detail.

C. CONCLUSION

The intent of this chapter was to demonstrate the usability and functionality of the trade space analysis worksheet and the trade space exploration tool developed by this thesis in a simulated scenario. The scenario offered a hypothetical set of space requirements and design considerations that a DOD command may request, and produced insight into how the tools may be used to support an initial feasibility assessment. The tools provide a method for assessing system feasibility and analysis and present compelling data that can be used in judging the design value of potential small satellites. By quantitatively and graphically describing the relationship between user inputs and output responses, the tools allow a user to explore potential small satellite design in much more depth and consider the potential trade-offs that can be made in order to achieve a feasible design. The tools are designed to be used in early conceptual design to assess feasibility and are not designed to provide concrete design specifications and parameters. These tools provide an opportunity to explore the design trade space of a proposed small satellite that can provide insight for stakeholders, acquisitions professionals, and engineers to design considerations that may save all parties money, time, and effort down the road. This thesis presented evidence that MBSE may be used to help assess some of the DOD's space acquisition problems. By building and applying a physical synthesis model that can assess the feasibility of a small satellite design, the tools included in this thesis provided an initial operating capability for decision makers that can have an immediate impact, but also have the potential to be refined and enhanced further by future work.

VI. FUTURE WORK AND CONCLUSIONS

This chapter reviews the problem introduced in chapter one and discuss how this thesis sought to solve that problem. This chapter discusses areas of potential follow-on work. Specifically, recommendations will be made with regard to pertinent areas to explore further and questions that were not addressed by this thesis so that future researchers may expand and enhance this research. In addition, this chapter reviews the key ideas, themes, and conclusions that emerged as a result of this work, summarizing the contributions this thesis made to research on DOD small satellites.

A. RECOMMENDATIONS FOR FOLLOW-ON WORK

Due to the limited amount of time and resources available, the goals of this thesis were significantly constrained. As such, this thesis was unable to explore all the relevant research areas or produce decision support tools beyond an initial proof of concept. Despite these limitations, the following areas of concern are important to the improvement of the research and are recommended as areas of future work.

1. Increase the Number of Key Factors Analyzed

This thesis applied the systems engineering process to screen the number of key factors included in the model to eight input factors and seven output responses. This was done to simplify model development, DOE, and analysis. By increasing the number of key factors included, the model may offer more accurate analysis on the relationship between inputs and outputs and on the trade space of the small satellite design. However, it should be cautioned that increasing the number of key factors used may also make the tool too cumbersome to use by a DOD space acquisition professional, as seen in the SMAD worksheet. Future work can strive to find an appropriate balance between accurate information and ease of use.

2. Refining the Data Used in Models

In addition to minimizing the number of key input factors and output responses used to build the model, assumptions and constraints were applied to some of the data used to build the meta-models. One example of this was the use of an STK simulation to gather data and build the meta-models for the number of accesses in 30 days and the mean access duration. While a range of altitudes and cone half-angles were used in the STK simulation, the inclination remained the same (98 degrees/sun-synchronous). This restricted the meta-models for the output responses to be dependent on only two factors, altitude and cone half-angle. In future work, the STK scenario can be improved to include a range of values for inclination, providing more robust data and thus more robust meta-models for the number of accesses in 30 days and the mean access duration. More robust models can improve the quality of the analysis performed by the trade space analysis worksheet and the trade space exploration tool.

3. More Data on Launch Vehicles

Due to time constraints and the state of current small launch vehicle R&D, this thesis primarily focused research on active launch vehicles with an established record of launching DOD systems. While that research provided an accurate snapshot of the launch vehicle services currently available, it does not address the movement toward smaller and more affordable launch vehicles like Super Strypi and SWORDS. Considering this thesis's focus on the disaggregation of large satellites in favor of constellations of small satellites, the development and emergence of small launch vehicles is an important area of future research.

4. Other Emerging Space Capabilities

This thesis focused on small satellites as a system solution to the DOD's problem, but small satellites are one of many alternatives. Another alternative is high altitude airships that were briefly discussed in Chapter II. The steps performed in this thesis and the decision support tools developed can easily be adapted to account for HAAS to better inform the DOD space community of its potential as an option.

5. Refining the DOE

The DOE macro used produced some questionable values for the key input factors based on the set minimum and maximum values because of low fidelity STK models, which in turn affected the output response data points. The effects were minimal since they appeared as outliers during the statistical analysis of the model, but refining the DOE could produce more accurate data, especially for the cost and revisit time output responses, which in turn would produce more accurate models and better information from the analysis.

6. Improve Usability and Functionality of the Tools

The decision support tools developed in this thesis serve as a proof of concept to show that MBSE could be used beneficially to solve a spacecraft design problem. However, future work can strive to improve the tool by increasing and streamlining its functionality. For example, rather than flipping between multiple worksheets, all of those fields can be added to a single worksheet. The single worksheet may be capable of determining earlier which fields the user will need (i.e., choosing between payloads), and remove or hide the non-pertinent fields. In addition, it may be possible to add the visual component provided by the JMP program to MS Excel. JMP is not used widely, especially in the DOD, whereas Excel is common. Adding in a version of the contour profiler to Excel would make a complete tool that can be used by nearly all DOD commands.

B. CONCLUSION

The DOD relies more than ever on space-based capabilities to maintain its advantage in modern warfare. Satellites have been critical space force enhancement tools for over two decades, whose support has been particularly important in the mission areas of MILSATCOM and ISR collection. While the DOD’s large satellites provide a robust capability, they are ill designed to combat emerging threats and concerns like ASAT weapons and the DOD’s shrinking defense budget. If the DOD wants to maintain its military advantage, it must seek out innovative solutions to protecting its space-based capabilities. One solution is the disaggregation of large satellites in favor of constellations of smaller satellites. Unfortunately, small satellites are still a relatively new technology whose application needs further exploration before deployment, especially by the DOD. The DOD needs further exploration of small satellites as a potential solution to emerging threats and concerns. This thesis sought to fill that need by using the SE process and the MBSE methodology to develop a set of decision support tools that provide exploration of small satellite designs early in the conceptual design phase of the DOD space acquisition process.

MBSE provides a method for graphically exploring and analyzing the relationships between input factors and output responses. As this thesis proved, the MBSE methodology can be useful in feasibility analysis of nascent technology like small satellites by providing insightful and accurate information earlier in the acquisitions process. Understanding how input factors like a small satellite's mass affect output responses like a the cost to build a small satellite provide DOD space acquisition professionals an opportunity to determine whether or not resources should be allocated to a small satellite design. It also provides an opportunity to further explore that relationship to determine if trade-offs can be made in order to achieve a feasible design. This thesis used early phases of the SE process to convert DOD mission requirements into key factors, then used MBSE to accurately relate key input factors to key output responses in small satellite design. The analysis of those relationships culminated into meta-models that can be used to predict design values for a small satellite and also explore how different design changes in a small satellite's physical components may impact combat effectiveness. The meta-models accurately depict how changing the value of an input factor like desired resolution or spacecraft mass can effect change in an output response like cost. Information on the cause and effect relationship between design factors can assist in assessing feasibility of small satellite designs. Knowing the feasibility of a small satellite design and seeing where trade-offs can be made in its physical components can result in a more effective small satellite design and a more efficient space acquisition process.

This thesis used the meta-models, which can be traced back to DOD small satellite mission requirements gather through extensive research, to build decision support tools to assist in the space acquisition process. The two decision support tools produced in this work should help fill a gap identified within the DOD. With the analysis and information provided by the decision support tools, DOD decision makers now have a capability to conduct quick feasibility assessments on proposed small satellite designs very earlier in the conceptual design phase rather than discovering problems later in the process. By receiving the feasibility analysis earlier, decision makers may have an opportunity to more accurately apply resources to small satellite programs that best meet mission requirements. Additionally, the decision support tools can be used in conjunction with a utility assessment method. In the case of equally feasible designs, the two decision support tools can provide a means for space system design adjustments during utility analysis. In the long run, more informed decision-making in the space acquisition process might preserve valuable DOD resources that would have otherwise been wasted. This thesis was a proof of concept that now sets a foundation for future work. With additional analysis and expansion of the scope and focus, the products of this thesis can be enhanced and possibly one day operationally deployed to the benefit of the DOD.

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APPENDIX. REQUIREMENTS OF SMALL SATELLITE PROGRAMS

Figures 43 and 44 catalog the multiple DOD small satellite programs that were researched in support of Chapters II and III, and their mission requirements. In some cases, the mission requirements found for each program were slightly different (e.g., some were vague while others offered a specific performance parameter), but the intended needs of the programs were similar enough that they could be grouped together as summarized mission requirements. The grouping was a subjective interpretation of the researched mission requirements for each program meant to minimize the size of the graphic and simplify the figures. These summarized mission requirements are listed in red under the “mission requirements” column. If research showed that a program stated a mission requirement, an ‘x’ was placed under that program for that mission requirement. The “Totals” column indicates the percentage of programs researched that shared the same mission requirement. Figure 43 shows the mission requirements matrix for the ISR programs that were researched.

Figure 43. Mission Requirements Matrix for ISR Programs

	ISR PROGRAMS					
Mission Requirements	Kestrel Eye	NanoEye	Small Agile Tactical Satellites (SATS)	TacSat-1	TacSat-2	TOTALS
Collects multiple forms of ISR	X	X	X	X	X	100%
Low cost	X	X		X	X	80%
Low weight	X	X		X		60%
Resolution better than or equal 1.5 m	X	X			X	60%
Fast production cycle		X		X	X	60%
Built with existing hardware (lowers cost)	X	X		X		60%
Product delivery in less than or equal to 10 min	X	X				40%
In-theater tasking/Tactical usage	X	X				40%
Utilize established tactical networks				X	X	40%
Persistent coverage	X	X				40%
Direct delivery to disadvantaged/mobile users	X					20%
Short operational life time	X					20%
Low cost constellation	X					20%
Small satellite size		X				20%
Live streaming video			X			20%
Onboard data storage			X			20%
Ability to collect multiple images on same pass			X			20%
Cross platform interoperabilty				X		20%
Launch with low cost commercial vehicle				X		20%
Autonomous tasking					X	20%
Use VMOC network for tasking/product dissemination					X	20%

Adapted from: (Citizens in Space 2012; Duffey and Hurley 2005; London 2015; USASMDC/ARSTRAT 2015; Wertz, Van Allen, and Barcley 2010).

As the figure shows, five DOD ISR programs were researched. Across those five programs, 21 mission requirements were found. However, only six of the mission requirements were shared by more than half of the programs. A similar result was found in the researched MILSATCOM programs. Figure 44 shows the mission requirements matrix for the MILSATCOM programs that were researched.

Figure 44. Mission Requirements Matrix for MILSATCOM Programs

	MILSATCOM PROGRAMS								
Mission Requirements	SNaP-3	SMDC-ONE	ICE-Cap	TacSat-4	Prometheus	Colony-1	ORSES	PERSEUS (PEO-SRSE)	**TOTALS**
Lower program costs	X	X	X	X	X	X		X	88%
Provide comms for disadvantaged users	X	X		X	X	X	X		75%
Data comms	X	X		X	X	X		X	75%
LEO Orbit	X	X	X	X	X				63%
Fit a CubeSat structure	X	X	X		X	X			63%
Rapid development	X	X			X	X			50%
Low data rate	X	X	X	X					50%
Voice comms	X	X		X	X				50%
Exfiltrate data from ground sensors	X	X		X					38%
Over-the-Horizon/Beyond line-of-sight comms	X	X			X				38%
Text comms	X	X		X					38%
Smaller mass			X	X					25%
Secure communications	X		X						25%
Non-national system	X							X	25%
Systems interoperability	X								13%
Short orbital life (less than 24 months)		X							13%

Adapted from: (Anderson and Raynor 2013; Earth Observation Portal 2015; Jarolimek 2014; Mattox 2014; Spaceflight101 2016; Weeks, Marley, and London 2009; Yoo, Obukhov, and Mroczek 2015).

As the figure shows, eight DOD MILSATCOM programs were researched compared to five ISR programs. This may suggest one of two things; the DOD has a greater need for MILSATCOM small satellites and thus has developed more MILSATCOM research, development, test, and evaluation (RDT&E) programs, or there is simply more unclassified documentation of MILSATCOM small satellite programs in the public domain compared to ISR small satellite programs. The research produced 16 summarized mission requirements for MILSATCOM programs. None of the mission requirements were shared by all of the researched programs, but eight mission requirements were shared by at least half of the programs.

The data gathered and displayed in these figures provides a quantitative foundation for the identification of key factors for DOD small satellites. However, the data must be taken with a grain of salt. These mission requirements were gathered from unclassified, open source documents. If a news story, report, or specification sheet did not specifically list a mission requirement, it was not included, thus some programs offered more information than others. An example of this is comparing SNaP-3 and the ORS Enabler Satellite (ORSES), for which data offered 14 mission requirements compared to one, respectively. Also, as previously mentioned, grouping of specific mission requirements into summarized mission requirements was completed with subjective interpretation. A different researcher may not group mission requirements the same way or may choose to not group mission requirements at all. That subjectivity opens the data and the interpretation of the data to bias, but was necessary for the purposes of this thesis.

SUPPLEMENTAL

This thesis includes two supplemental files, which can be obtained by contacting the Naval Postgraduate School Dudley Knox Library. One of the files is a Microsoft Excel spreadsheet, which includes the final version of the trade space analysis worksheet. It is one of the decision support tools developed by this thesis based on meta-models produced by JMP. Also included in the spreadsheet are the initial user interface worksheets that were used to collect user-submitted values for input factors and calculate output responses. These initial user interface worksheets provided a foundation for the DOE and macro used by the NPS SEEDS Center. T

JMP data file of the trade space exploration tool also is available as supplemental material. The JMP data file includes the 465-point DOE data table created by the NPS SEEDS Center, which was used in JMP to perform statistical analysis. JMP provided statistical analysis products including the meta-models that were used in the trade space analysis worksheet also provided is the JMP contour profiler that is based on the DOE data table, which allows graphical exploration of the small satellite trade space.

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