Assessing GPS Constellation Resiliency in an Urban Canyon Environment

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Abstract

Satellite constellation resiliency is an important consideration gaining momentum at the top levels of the Air Force and at Air Force Space Command (AFSPC). The increased availability of threats to satellite systems is challenging the capabilities provided by space assets. More specifically, the global positioning system (GPS) satellite constellation is utilized for a variety of missions, to include providing precise geolocation information for navigation. Any degrade in GPS capabilities as observed in an urban canyon environment or due to the loss of a GPS satellite may hinder the overall mission. We use the System Effectiveness Analysis Simulation (SEAS) to model the GPS constellation in an urban canyon environment which provides information to a special operation force (SOF) in their effort to recover a weapon of mass destruction (WMD). By varying the type of operations and the number of satellites lost in the simulation, insight is gained into the impact of degradation through the selected top level mission metrics. A series of statistical difference tests and a designed experiment reveal a resiliency threshold on the number of satellites removed from the constellation. As a result, we conclude that the GPS constellation is resilient even after the loss of several satellites.

Key words: System Effectiveness Analysis Simulation (SEAS), satellite constellation resiliency, agent-based modeling, global positioning system (GPS), urban canyon environment, weapon of mass destruction (WMD)

I dedicate this thesis to my family, future wife, friends, and dog who stood by me throughout the process. Their advice and continual support was pivotal in my successful completion of the thesis.

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Aaron J. Burns

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ASSESSING GPS CONSTELLATION RESILIENCY IN AN URBAN CANYON ENVIRONMENT

I. INTRODUCTION

1.1 Background

Satellite design is shifting from large monolithic satellites of the cold war to smaller more disaggregated satellite constellations. The change is prompted by increasingly accessible satellite degradation techniques which may inhibit national security by reducing the support of mission critical space systems. Butler [8] states that, "All of the Pentagon's war plans are heavily reliant on satellite service, and the economies of the U.S. [United States] and its allies also depend on spaceborne services such as GPS [Global Positioning System] and communications for smooth operation". Air Force Space Command [3] (AFSPC) also states that, "U.S. reliance on space was a potential Achilles Heel". The vulnerability in our space systems is due to an inherent susceptibility to a variety of threats as noted in the following statement by Dr. Stuart Eves: "[a] spectrum of threats from [ASAT] weapons, RF weapons, cyber attacks, demons conducting disruption or surveillance operations, physical attack on ground infrastructure, laser weapons, charged and neutral particle beams, and camouflage concealment and deception" [7]. U.S. satellite systems must be defended from these threats to ensure national security.

Acting Air Force secretary Eric Fanning also recognizes the vulnerability of our military space systems [20]. Interestingly, he notes that we do not necessarily need an offensive capability to defend our space assets [20]. Overall, he asserts the need for, “new strategies and new architectures for space to try to increase resilience” [20]. General Shelton, former commander of AFSPC, echoes Mr. Fanning’s request for an increase in satellite constellation resiliency [3]. As a result, the Space and Missile Center (SMC) of the United State Air Force (USAF) has conducted a Resilient Enterprise Architecture Pathfinder (REAP) study, a leading project in space system resiliency analysis. The results from the REAP study and other resiliency research will have far reaching implications that will effect the design and acquisition process of future satellite space systems. Ensuring the security and capability of military satellite constellations through increasing efforts toward resiliency is essential for national security.

1.2 Problem Definition

The focus of this thesis is on the comparison of resiliency metrics for the GPS constellation under different levels of degradation. Resiliency is difficult to define due to its applicability in many areas of study. It is even more difficult to find a quantitative measurement to use as a standardized metric for comparing the resilience of different systems. Measures of performance (MOPs), measures of effectiveness (MOEs), and measures of outcome (MOOs) are all common quantitative metrics available for a system. Selecting appropriate and universally accepted metrics is essential for credible analysis.

1.3 Research Objective

The goal of this thesis is to successfully compare the resiliency of the GPS satellite constellation in an urban canyon environment using quantitative metrics for a well defined scenario. The metrics selected reflect overall top level mission priorities, also known as MOOs. The MOOs are primarily drawn from the suggested measures found in the Literature Review along with the capabilities of the System Effectiveness Analysis Simulation (SEAS) package. The thesis captures the simulation of the GPS satellite constellation interacting with a blue force in a blue and red force conflict scenario. MOOs are collected for a nominal scenario as well as for varying levels of degraded performance representing system failures, environmental challenges, or adversarial actions.

1.4 Research Scope

Simulation in this thesis is limited to a SEAS scenario provided by SMC. The simulation models each of the satellites in the constellation as unique agents that can be impacted by threats. Additionally, the thesis only compares the top level mission focused MOOs instead of focusing on the low level technical MOEs and MOPs of the system. The analysis of the simulation MOOs includes statistical Paired T tests and proportion confidence interval comparisons between nominal and degraded scenarios to provide insight into the system. Furthermore, a full factorial designed experiment is performed to determine the most important factors for the selected MOOs. The designed experiment has two factors with multiple levels which include the type of scenario, either nominal or degraded, and the number of satellites removed from the constellation from zero to ten. Both methods of analysis provide insight into the resiliency of the GPS satellite constellation.

1.5 Thesis Overview

This thesis contains five chapters, the Introduction, Literature Review, Methodology, Analysis, and Conclusions. The Literature Review covers the definition of resiliency and its associated metrics, an overview of the threats to satellite systems, a description of the GPS constellation, and information on SEAS. The Methodology provides framework for the simulation and the scenario development. Next, the Analysis chapter focuses on the impact of the input parameters on the GPS constellation and the insights gained on the GPS constellation's resiliency. The Conclusion chapter summarizes the important insights gained from the thesis along with identifying areas for further research.

II. LITERATURE REVIEW

2.1 Overview

The Literature Review focuses on several areas which support resiliency analysis. The first section identifies the applications of resiliency across many different areas of study and selects a definition for space resiliency. Additionally, the section identifies current investigations into satellite resiliency along with potential metrics for the thesis. Second, the Literature Review examines threats to satellite systems and their associated countermeasures, if applicable. Third, the Literature Review provides an overview of the GPS satellite constellation and its capabilities. Fourth, the Literature Review describes agent based modeling and its implementation in SEAS.

2.2 Resiliency

Applications.

There are an array of different definitions and applications for resiliency ranging from ecology to economics [30]. One example is the Environmental Protection Agency (EPA) which recognizes that resiliency analysis is still developing and does not have standardized metrics [16]. Nevertheless, the EPA does see the applicability of resiliency studies to better understand social-ecological systems [16]. The EPA also references an organization titled the Resilience Alliance which specifically focuses on social-ecological systems [31]. Additionally, Ohio State University has a Center for Resilience that examines the resilience of industrial systems and their operation [10]. Furthermore, research extends to the MITRE corporation which provides an extensive list of resiliency metrics for the cyber domain [6]. As shown by the variety of different resiliency applications, Reid & Botterill [30] argue that 'resiliency' is becoming convoluted and losing it meaning due to improper and over use. To add to the convolution Reid & Botterill [30] note that resiliency can often be mistaken as ‘recovery’ or ‘adaptability’ or ‘vulnerability’. The examples provided are a small portion of the numerous applications of resiliency.

A specific example of space resiliency comes from Buckerfield de la Roche [7] who comments on the events of the 2011 RUSI Space and National UK Security conference. The conference was focused on increasing resiliency, which included a discussion on cyber and military actions in the space domain. Space system resilience has also taken hold in the United States where General Shelton, former Air Force Space Command commander, provided the following statement:

> Our satellites provide a strategic advantage for the U.S., and as such, we must consider the vulnerabilities and resilience of our constellations. My staff at headquarters Air Force Space Command, alongside the team at the Space and Missile Systems Center, is leading efforts at balancing resilience with affordability. [3]

Resiliency in space systems is important to overall military success and must be defined for the proper application.

Definition.

Air Force Space Command provides a definition of resiliency: “Resiliency is the ability of a system architecture to continue providing required capabilities in the face of system failures, environmental challenges, or adversary actions” [3]. We use AFSPC’s definition of resiliency for the remainder of the thesis. The definition is unique because it encompasses other common resiliency definitions. For example, the adaptability of a space system to threats may be a method for maintaining required capabilities. Additionally, the definition speaks to the system architecture as a whole instead of just specific portions of the system. The all encompassing definition allows for resiliency to be applied not only to the satellite constellation, but also to the ground station and satellite operators who may be effected by threats to overall resiliency.

Current Research.

Investigation into space system resiliency is a new area of study being explored by a number of researchers including Northrop Grumman Aerospace Systems. Northrop Grumman argues that space system resiliency is best assessed by the ability of the system to meet key performance parameters (KPPs). Northrop Grumman also identifies two different KPP approaches to assessing satellite resiliency under adversarial threats: analytical and deterministic modeling. Analytical modeling aims to create a mathematical function to objectively calculate resiliency. Then by comparing the magnitude of the resiliency function for different systems, the most resilient system can be selected. Northrop Grumman Aerospace Systems indicates that an analytical model is difficult to create due to different opinions on the proper function to select for resiliency measurement. Deterministic modeling instead focuses on the breakpoints of the space system. Furthermore, in a deterministic model it appears as though cost and reliability become metrics for comparison. Essentially, the deterministic model compares the cost of the military space system as a ratio to the cost of the threat. Comparing the ratio to possible alternative space systems helps determine which system is more resilient. Northrop Grumman Aerospace Systems argues that a deterministic model is most effective at identifying large differences in resiliency. Intuitively, Northrop Grumman Aerospace Systems notes from initial results that space systems that can be impacted from ground attacks (whether through a ground station or from ground techniques) are less resilient. [26]

A more specific GPS constellation analysis thesis was produced in 2010 by Captain Bryan Bell at the Air Force Institute of Technology (AFIT) titled, “Assuming

GPS Capabilities Under A Contested Space Environment: An Implementation Plan". Bell's research focuses specifically on how best to augment the current GPS constellation to retained its performance under degradation; thereby fulfilling the requirements of Operationally Responsive Space (ORS). For educational purposes only, Bell's area uses Taipei, Taiwan as his area of interest. His GPS constellation is modeled in the Satellite Toolkit (STK) where augmentation satellites can be added and the mission level technical metrics can be recorded. The principle metric Bell uses is the position dilution of precision (PDOP), which is a common technical metric detailing the geolocation geometry provided by the GPS constellation. The goal of his thesis is to identify degraded scenarios where the average and maximum PDOP exceed a value of six often enough to impact military operations and then improve those situations with satellites to augment the constellation. He uses a variety of different satellite augmentations to include the low Earth orbit (LEO) iridium-66 constellation, a highly eccentric orbit (HEO) constellation, and a geosynchronous Earth orbit (GEO) constellation. Bell concludes that the GPS constellation is a robust system that can be best augmented by adding several satellites in GEO. One important insight gained from the study is the importance of the geometry of the satellites over the area of interest. He notes that scenarios with more satellites overhead does not necessarily mean that the PDOP value will be lower than a constellation where fewer satellites provide better geometry. While Bell's research is important to consider moving forward in the methodology of our study, the research presented in our study selects different metrics and methods for analyzing satellite constellation resiliency. [5]

Available Metrics.

Selecting the correct metrics is crucially important to the validity of the final anaylsis. The selected metrics are also important because they define what is relevant to the decision maker. Misinterpretation of the metrics could also occur without a universal acceptance of the metrics. Furthermore, the selected metrics should be parsimonious, allowing for flexibility and application to multiple scenarios. More specifically, Connable references David Kilcullen's opinion on the metrics used during the war in Afghanistan. Kilcullen believes that using a single number as a metric, such as the number of enemy casualties, can be dangerous when taken out of context. Instead, Kilcullen recommends using ratios or percentages which can be more informative metrics. For example, the fire-to-fire ratio allows an analyst to observe which side has the initiative and is more likely in control of the casualty rate. [12]

There are several quantitative metrics available for analyzing satellite system resiliency. For example, Cornara *et al.* [13] states that all satellite constellations aim to provide a minimum level of service. Bell believes that a PDOP value of six defines minimum GPS service [5]. Cornara *et al.* [13] also suggests using mean revisit time and mean percentage of coverage during the simulation as measures of quality of the constellation. The REAP study focuses on MOEs and uses availability, user range error, vertical error, horizontal error, and integrity as metrics [22]. The REAP study also references several MOOs to include target production rate, target strike accuracy, total targets destroyed, and days to end of conflict [22]. Other potential MOOs include the accuracy of weapons, the amount of required ordinance, the number of civilian casualties, and the amount of fuel expended by the satellite. It is also important to remember that the selected metrics must also only be calculated over the area of interest. The selected area might be a specific geographic region or a more general bound of latitude and longitude.

Improvements to Constellations.

There are several considerations for enhancing satellite constellation resiliency. The first is that a constellation with a smaller number of orbital planes reduces the impact of satellite degradation and also achieves levels of service earlier in the deployment phases. The second consideration is the possibility of having reserve satellites ready for operation in a degraded environment. Cornara *et al.* [13] references three general options for replacement satellites. The best option is to have additional satellites in the orbital planes ready for operation. This option is generally implemented for position, naviagation, and timing (PNT) constellations or any other constellations which demand continuous functionality. The second most reactive method is to have spare satellites in parking orbits which can be transferred into operation when required. The final option, generally used by less essential systems such as Earth observation platforms, is to have back up satellites on the ground waiting for launch. Depending upon the objective of the satellite system and its overall mission importance, the correct resiliency method can be implemented. [13]

2.3 Threats

Military satellite systems are crucial to the U.S. however, they are also highly vulnerable. Northrop Grumman Aerospace Systems [26] states that, “especially troubling are the low cost and short cycle times of very effective threats when compared with the investments that are made in [Department of Defense] space systems”. Airst [4] also states that, “[t]hreat[s] [have] expanded from nation-state to informed hobbiest”. The escalation of the availability of threats only increases the need for research into space system resiliency.

Foreign Countries.

China has recently demonstrated the ability to destroy a satellite in LEO and potentially degrade optical payloads with lazer dazzling [3]. Pawlikowski *et al.* [28] recognizes that China is attempting to weaken the United States, who is increasingly reliant on their space capabilities. The Chinese launch of an anti-satellite (ASAT) missile was an attack the United States could only observe and not take action against [28]. Additionally, Pawlikowski *et al.* [28] states that China is not the only concern, other states and even non-state actors could also impact space systems. As foreign countries develop their technology and become more capable, the United States will have to protect the GPS constellation from jamming, spoofing, cyber, and kinetic threats. [28]

Jamming.

Jamming is a common and easily implementable threat available to most foreign actors. Pawlikowski *et al.* [28] states,

> The [t]echnological capability to jam satellites is fairly simple and can be easily assembled by either individuals or nations for a fairly modest investment. Multiple reports of both state and nonstate groups jamming satellites have been seen over the last decade. GPS jammers are well known and offered openly for sale on the Internet. Satellite transit times are available from several websites and can be downloaded onto smart phones.

Additionally, jamming a GPS antennae does not require more than a few picowatts of energy [4]. As a result, foreign militaries have jammers that can output megawatts of power which are highly effective [4]. Furthermore, jamming can occur through attacks on the narrow band, broadband, and spread spectrum [4].

More specifically, North Korea's usage of jammers since 2003 during the Iraq war has been confirmed, along with reports of China also having jammers [4]. Iran also claims to have taken control of a lost U.S. stealth drone in 2011 by jamming its GPS connection [9]. An Iranian engineer claims that, "The GPS navigation is the weakest point...By putting noise [jamming] on the communications, you force the bird into autopilot. This is where the bird loses its brain" [9]. General Moharam Gholizadeh of the Iranian Islamic Revolutionary Guard Corps believes that Iran can even control GPS-guided missiles [9]. Furthermore, even civilians have access to jammers in order to ward off vehicle tracking devices [4].

The DoD is aware of the jamming threat and, as a result, the new GPS satellites will have increased capability to prevent jamming [11]. There are also several defensive techniques to combat jamming. Inherent in a GPS satellite is, "[t]he ability to reject noise [which] also implie[s] a powerful ability to reject most forms of jamming or deliberate interference" [27]. The military also uses the p-code from the GPS satellite which is more resistant to jamming [27]. Nevertheless, jamming is still a potential threat to GPS satellites, which can degrade overall mission effectiveness.

Spoofing.

Spoofing is another type of attack which is applied to GPS receivers [21]. By simply adding a time delay to a GPS signal, adversaries can "spoof" or confuse a GPS receiver adding errors to position estimations and providing incorrect time stamps [4]. Errors in position estimates can be devastating for the military technology which aims to hit targets with precision in order to use a minimal amount of ordinance. Furthermore, the probability of civilian casualties also increases if an ordinance receives even the slightest error measurement from its guidance system. Another example from Airst [4] centers aounrd the stock market which is heavily dependent upon the time information provided by GPS satellites. If a company can control the time stamp for trades in the market, they can easily manipulate stock trading in order to sell high and buy low [4].

Airst [4] argues that spoofing is a significant threat to GPS, primarily due to its inexpensive cost, quick availability, and hidden implementation. There are several devices which are readily available that can spoof GPS receivers. A GPS simulator is the most simplistic option, however, its large size and expense makes it difficult to implement [21]. The next step in complexity is the use of a single software defined GPS receiver to provide a false GPS signal [21]. The final step in complexity is an orchestrated group of software defined GPS receivers [21]. Fortunately, there is still additional software and hardware development required before a software defined GPS receiver can become an effective spoofing device [21]. Additionally, Airst [4] states that there are not any readily available solutions to eliminate spoofing.

There are, however, several potential options to minimize the impact of spoofing attacks. Humphreys *et al.* [21] states that, “Cryptographic authentication is arguably the most secure solution [to spoofing], but would require modification of the civil GPS signal structure, making it an unlikely short-term solution”. One of the next best options for spoofing detection is to use multiple clocks in the satellite system and ensure they all are in synch [4]. If the clocks are disperate, then the GPS satellite can use an “advanced disciplining algorithm” to place the clocks at the correct time [4]. Nevertheless, more research and development must be performed to find a simple yet effective countermeasure to spoofing attacks.

Cyber.

Persistent cyber threats also permeate into the space domain due to a satellite’s inherent dependence upon computer technology. Air Force Space Command [3] states that, “[s]pace systems that rely on complex software and radio-frequency links could be susceptible to [cyber] attacks, despite robust cryptographic protection”. To make matters worse, Air Force Space Command [3] states that, “[c]yberspace threats, in particular, have exceptionally low barriers to entry and are growing rapidly.” Cyber threats are so inexpensive and readily available that an adversary would be ill-advised not to attempt such an attack on the U.S. [9].

Caplan [9] more specifically states that, “satellite vulnerability to cyber attacks has emerged as a threat to U.S. national security, as the U.S. military is increasingly dependent on satellite communications”. It is also important to understand that the military is heavily dependent upon civilian satellites for telecommunication. Increased DoD dependence will result in more cyber attacks toward the poorly protected commercial communication satellites. Caplan [9] also states that Chinese military doctrine suggests attacking space-to-ground communication along with the associated satellite ground stations during a conflict. China is also actively involving several of their electronic companies in intelligence gathering and cyber communications. [9]

A specific example of a satellite cyber attack occurred in 2011 when two environmental imaging satellites were hacked. The hacker was able to access the satellite control system which could have destroyed the satellite. Fortunately the hacker did not issue any commands leaving the satellite unharmed. A statement from the president of Intelsat General Corps states, “In 2011 alone, IntelsatONE, the terrestrial network that links customers to Intelsat’s geosynchronous communications satellite, identified about 300,000 denial-of-service attacks” [9]. Furthermore, the loss of the stealth drone in 2011 also reveals the vulnerability of GPS to cyber attacks. Cyber threats pose a serious threat to space systems and are increasingly prevalent. [9]

Kinetic.

Satellites are also highly vulnerable to kinetic attacks. In 2007, China destroyed a weather satellite with an anti-satellite missile in an effort to shake U.S. dominance in space [1]. The weather satellite was in LEO, however, a Japanese intelligence official reports that China is hoping to target GPS satellites in future conflicts [1]. Lieutenant General Michael Hamel, former director of SMC, states that, "[a] 'nightmare' scenario is for multiple satellites used by the Pentagon to 'blink off', indicating a hostile–possibly kinetic anti-satellite–campaign against the U.S. space assets" [8].

In response to the Chinese ASAT mission, Senator Jon Kyl recommends several actions which should be taken to minimize the threat [2]. Specifically, Senator Kyl states that efforts should be focused on replacing lost satellites quickly [2]. Another option is to quickly identify the ASAT threat and maneuver the targeted satellite to avoid the ASAT [8]. However, Colonel Shawn Barnes, chief of AFSPC Space Superiority Division, states, "[t]oday, we could ascertain that we were under attack–especially from a direct-ascent [ASAT], but we do not have the tools to rapidly assemble all the evidence, and disseminate it in a way that enables collaborative decision making" [8]. Although there are theoretical options available to counter ASATs, further research is needed before there is a concrete solution.

2.4 PNT Satellite Systems

Definition.

Position, navigation, and timing satellites are used in both military and civilian applications. The most familiar PNT satellite constellation is the Global Positioning System which is owned and operated by the United States Air Force [11]. GPS is not the only PNT satellite constellation orbiting Earth. Several other countries and conglomerates also have their own constellations. The European Union is constructing a 30 satellite constellation called Galileo for enhanced civilian GPS coverage in conjunction with GPS [33]. The Russians are using a system called Glonass and the Chinese are using their system called Beidou. Each PNT constellation is similar in theory, but varied in application.

The concept of GPS originated with NAVSTAR developed by U.S. government in the 1970's [27]. GPS has continually developed and today we are launching the GPS Block IIF. There is also currently a contract with Lockheed Martin to produce GPS III as the next revolution in GPS satellites [24]. Impressively, GPS has continued to provide uninterrupted service since its release to the public in 1995 [33]. The military uses GPS for navigation and guiding precision weapons, "which are key strategic weapons for the United States" [1] [27]. Civilians also use GPS for a multitude of tasks to include search and rescue, land surveying, and aircraft collision avoidance systems just to name a few [27].

GPS satellites nominally operate by transmitting a ranging signal which is collected at a GPS receiver [27]. Since the speed of the GPS signal is a known constant, the GPS receiver can take the difference between the signal transmit time and received time to calculate the distance from the satellite to the receiver [24]. Through the use of atomic clocks, GPS satellites are able to coordinate their time stamps associated with their ranging signal, which is essential in reducing position error [27]. Collecting distances from multiple satellites allows the GPS receiver to locate itself based upon the only possible intersection of the ranging signal from the satellites [24].

Capabilities.

In order to ensure the highest global precision for military efforts, the GPS constellation must provide a minimum of 24 operational satellites [11]. The constellation has six nominally circular planes inclined at 55 degrees each with four operational GPS satellites per plane. Each GPS satellite has a period of 12 hours. Additionally, a GPS receiver must be able to receive GPS data from a minimum of four of the 24 available satellites in order to provide three-dimensional location information. The more satellites a receiver can process and the larger the angle between received satellites, the better the position estimation. [27]

There are several options for GPS constellation improvement that may increase overall performance. One option is to add six satellites, one more in each orbital plane, in order to increase coverage. The new 30 GPS constellation will show improvements in the number of GPS satellites available to the receiver. Another option is to add an equatorial orbital plane that will aid in providing coverage to the mid-latitude regions which are most susceptible to having a fewer number of visible GPS satellites. An increase in coverage also creates another plane which adds to the complexity of the constellation. A final consideration is changing the orbital period of additional GPS satellites to either a six hour orbit in a lower altitude or a 24 hour geosynchronous orbit in a higher altitude [5]. All of the considerations could improve the GPS constellation, however, the gained performance must be weighted against the increased complexity and cost. [27]

Despite the benefits of the GPS constellation, it is not without programmatic delays and error. The Government Accountability Office (GAO) provides a study from 2009 on the setbacks experienced with the GPS constellation upgrade. The study identifies the effects of operating under a diminished GPS constellation. For example, the precision guided munitions used by the military would be less accurate leading to larger or multiple ordinances necessary to ensure the same mission success [1] [11]. Additionally, in the civilian sector, commercial aircraft and 911 emergency responders would also be effected due to decreased accuracy from GPS location estimates [11].

Urban Canyon Environment.

The urban canyon environment is one type of challenging environment which is characterized by tall buildings, long narrow streets with a minimum number of intersections, tunnels, and elevated railways, all of which can negatively impact GPS effectiveness [34]. Vicek *et al.* [34] states that, "[r]eflected signals and relatively poor geometries make GPS derived position fixes less accurate than those made in a more benign environment". Japan experiences habitually unstable GPS service due to the effects of their urban canyon environment [29]. As a result, they are launching four new satellites to augment the GPS constellation over Japan in order to reduce multi path errors and increase satellite availability [29]. The first quasi-zenith satellite is currently supporting Japan and has shown an improvement from 39.5% to 60.9% availability over one of the test cities [15]. Continuing plans indicate the launch of two more quasi-zenith satellites along with a geosynchronous satellite by 2018 [29]. The challenges posed by an urban canyon environment are a reality that cannot be ignored in a combat scenario.

2.5 Agent-Based Modeling

Definition.

Agent-based modeling and simulation (ABMS) is used to model complex adaptive systems (CAS) potentially made up of many different types of agents. North & Macal [25] state that, "Agent-based modeling and simulation (ABMS) is founded on the notion that the whole of many systems or organizations is greater than the simple sum of its constituent parts". The smaller constituent parts can in turn generate larger emergent behaviors. One of the principal strengths of ABMS is to identify the connections between low and high level behavior. A simple analogy for low level actions causing emergent behavior is the "wave" commonly produced at sporting events. North & Macal [25] state that, "Each person or agent makes small, simple movements, but the group as a whole produces complex large-scale results". By accurately modeling the agents and CAS of an ABMS, emergent behaviors can be identified and assessed. [25]

ABMS is used in this thesis to analyze a highly complex weapon of mass destruction (WMD) removal scenario. The model is complex due to the multitude of support assets to the blue and red forces which have a unique impact on the ability of the special operations force (SOF) to complete the mission. It is important to remember that the agent based model for this thesis is heavily dependent upon the blue and red force agents. However, the focus of the study is on the satellites supporting the agents during the simulation. As a result, the efforts of this thesis is not on re-coding the agent behavior, but instead changing the CAS supporting the agents.

SEAS.

The System Effectiveness Analysis Simulation (SEAS) is a computer simulation developed for military utility analysis which supports acquisition programs and system development. SEAS is most often used for scenario focused simulations between opposing forces. The simulation software revolves around ABMS which allows entities to react based upon their perception of the environment and their pre-programmed rule structure. Agent-based modeling allows entities to exhibit complex-adaptive behavior which emerges from the guiding rules structure and entity interaction. SEAS also provides a visual display of the simulation which is useful for verification and debugging portions of the analysis. Furthermore, SEAS is a part of the Air Force Standard Analysis Toolkit and continues to be used for studies in military analysis by a variety of users. [32]

The scenario of interest has been previously developed in SEAS for the analysis of the GPS in an urban combat environment. The code contains a large array of both blue and red forces governed by their unique rule structure. Each of the coded rule structures contributes to the emergent behavior of the entire system. Interpreting the model is aided by the visual display of the agents moving in the region of interest. Furthermore, SEAS collects simulation statistics which can be transformed into resiliency metrics. As a result, SEAS is an adequate simulation software to assess satellite resiliency in our scenario.

2.6 Summary

Accurately modeling satellite resiliency is a difficult task which begins by establishing a definition for resiliency. The definition selected for the study comes from Air Force Space Command which focuses on a system's ability to continue providing required capabilities during periods of degradation. There have been several studies on satellite resiliency along with a variety of proposed metrics. Ultimately, the metrics selected in this study depend upon the definition of resiliency and the capabilities of the modeling software. Resiliency has become an important topic in constellation design because the increasing number of threats to satellite systems. Today more than ever, satellites are susceptible to kinetic, cyber, and electromagnetic threats from a variety of enemies. PNT constellations in particular provide a crucial capability that must be maintained if at all possible. In order to assess the resiliency of a satellite constellation, the agent-based SEAS program is used to model a scenario impacted by GPS performance. The next chapter on Methodology will further develop the process for assessing the resiliency of the GPS constellation under degradation.

III. METHODOLOGY

3.1 Overview

The Methodology focuses on several areas connected to the selected scenario, resiliency metrics, model developments, and the proposed analysis techniques. The first section provides an overview of the selected scenario along with a presentation of the logical process flow and a description of the blue and red force structures. The original model description concludes with the model assumptions and input parameters. Next, we present the chosen resiliency metrics along with a description of the model developments. After the model developments we discuss the proposed analysis techniques, which includes the traditional nominal and degraded model statistical test comparison. The final analysis technique describes a designed experiment which is intended to assess the key components of each resiliency metric. Each of the sections in the Methodology builds a framework for the analysis of the selected scenario.

3.2 Scenario

Description.

The selected scenario focuses on the performance of the GPS constellation in an urban canyon environment [14]. Air Force SMC/XR Military Utility Analysis (MUA) squadron first used the scenario to study the capabilities of GPS satellites in stressed environments [14]. Furthermore, SMC/XR selected SEAS to develop an urban canyon environment due to its short build up time, internal resource availability, and the ability to use previous studies [14].

The model simulates an agent based SOF team moving through a Middle Eastern city searching for a WMD. The scenario begins with the SOF team landing in the city and heading directly to the WMD. After the WMD has been secured, the SOF team navigates through the city to an evacuation location. Successful navigation is aided by the GPS receiver embedded with the SOF team. Major degradations to the GPS constellation can cause the SOF team to lose its position knowledge which can lead to enemy engagements and an extend mission duration. When the SOF team successfully makes it to the evacuation location the mission is considered a success. [14]

The simulation is governed by a complex logic process which is focused around the SOF team as they transit to the evacuation location. The SOF team selects which evacuation location is the best option and navigates to the location. In the process, it is highly likely that the SOF team encounters red forces which can deter the evacuation of the WMD. Once the SOF team reaches the evacuation location, they will secure their position and fend off enemy advances until they can be airlifted to safety. The logical process flow is summarized in Figure 1.

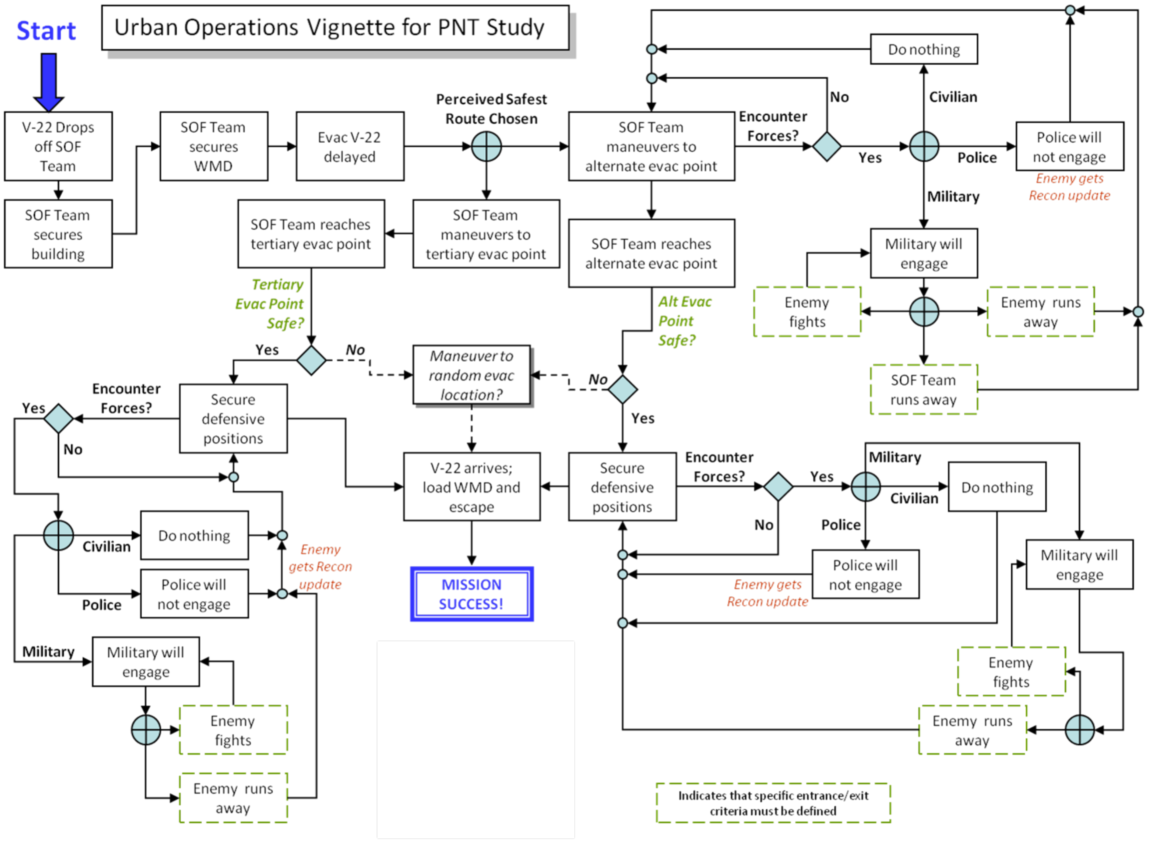


Figure 1. Logical Process Flow [14]

Model Parameters.

The urban canyon scenario has several input parameters that can be changed to reflect desired design points. The first four parameters are GPS constellation specific which represent the accuracy, availability, and timeliness of the GPS constellation along with number of satellites removed due to degradation. GPS accuracy is defined in meters and represents the position accuracy given to the GPS receiver utilized by the SOF team. The smaller the value of GPS accuracy represents a higher effectiveness of the GPS constellation. GPS availability is scaled from 0 to 1 and represents the probability that the GPS constellation is able to provide geolocation information. A lower probability of availability is used to simulate the impact of the urban environment which may reduce the chances of contacting the GPS satellite. Another

GPS parameter is timeliness which reflects the amount of time required for the GPS receiver to provide geolocation information to the SOF team. Additionally, the number of GPS satellites removed is another parameter used to impact the constellation. For example, one of the design points might require five of the original ten satellites in view to be removed from the simulation to reflect a period of degradation. The combination of the four GPS parameters allows for top level mission control of the GPS constellation. It is important to note that the simulation does not use a detailed GPS geolocation algorithm or provide a highly detailed perspective on the satellite constellation. Instead, the program focuses on using the higher level input parameters to reflect the capabilities of the GPS constellation. Each of the GPS parameters and their range of possible values are summarized in Table 1. [14]

Table 1. GPS Parameters

	Input Parameters			
Range	Accuracy	Availability	Timeliness	Number of Satellites Removed
Best	5 m	0.95	5 min	0
Worst	40 m	0.34	5 min	10

Several other input parameters for the scenario include the number of Predator surveillance aircraft, the involvement of the police, and the ability to use visual cues. The number of Predator surveillance aircraft help identify red force threats in the simulation as they circle the area of interest. The involvement of police pertains to the ability of red police to engage the SOF team in combat instead of just identifying their presence. The ability to use visual cues corresponds to the SOF team and their ability to navigate aided by landmarks instead of only using the GPS receiver. For this study these parameters remain constant and are not adjusted between scenarios. As a result, the number of Predators surveillance aircraft will be kept at two, the police do not directly contribute to military engagements, and the SOF team is able to use visual cues.

Force Composition.

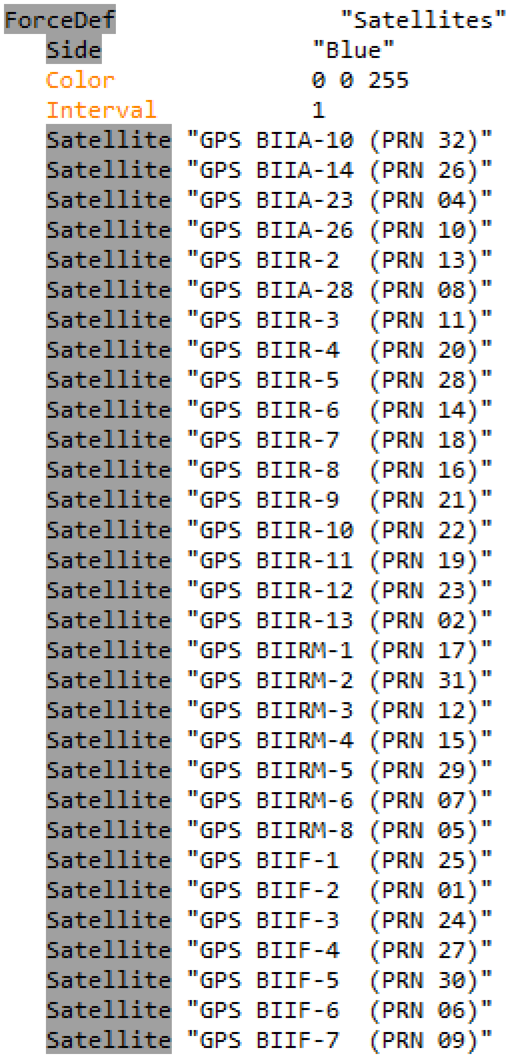
SOF Team.

The principal component of the blue forces is the 50 soldier SOF team. Several rules of engagement govern the actions of the agent based SOF team. The first rule states that the SOF team does not engage in combat unless they are fired upon from the red military forces. If, however, the SOF team is engaged by red military forces, then they are drawn into the fight. The SOF retreats from the battle if they are outnumbered by a 3:1 margin. Furthermore, the SOF team does not interact with the red civilians and attempts to evade the red police forces. Each of the rules of engagement is processed at every time step in the simulation in order to determine the SOF team actions. [17]

Additionally, the SOF team movements are heavily reliant upon their confidence in the GPS geolocation estimation which is dependent upon the number of GPS satellites available. For example, once fewer than six GPS satellites are available, then the SOF team decreases their movement speed. The most extreme impact occurs when there are fewer than four GPS satellites. More accurate movements of the SOF team leads to a shorter mission duration with a minimal loss of life. [17]

Blue Forces.

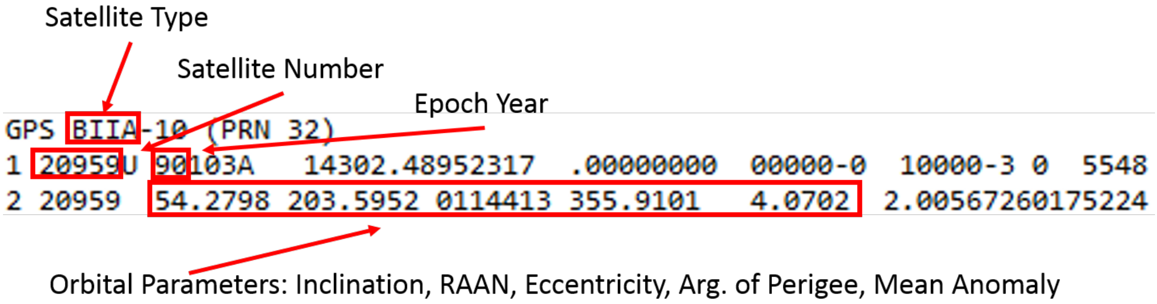
The SOF team is primarily aided by the GPS constellation. The modeled constellation is composed of the 32 current GPS satellites which are listed based upon their different design blocks. The Tactical Programming Language (TPL) code for the GPS satellites is shown in Figure 2.



```
ForceDef                "Satellites"
   Side               "Blue"
   Color              0 0 255
   Interval           1
   Satellite "GPS BIIA-10 (PRN 32)"
   Satellite "GPS BIIA-14 (PRN 26)"
   Satellite "GPS BIIA-23 (PRN 04)"
   Satellite "GPS BIIA-26 (PRN 10)"
   Satellite "GPS BIIR-2  (PRN 13)"
   Satellite "GPS BIIA-28 (PRN 08)"
   Satellite "GPS BIIR-3  (PRN 11)"
   Satellite "GPS BIIR-4  (PRN 20)"
   Satellite "GPS BIIR-5  (PRN 28)"
   Satellite "GPS BIIR-6  (PRN 14)"
   Satellite "GPS BIIR-7  (PRN 18)"
   Satellite "GPS BIIR-8  (PRN 16)"
   Satellite "GPS BIIR-9  (PRN 21)"
   Satellite "GPS BIIR-10 (PRN 22)"
   Satellite "GPS BIIR-11 (PRN 19)"
   Satellite "GPS BIIR-12 (PRN 23)"
   Satellite "GPS BIIR-13 (PRN 02)"
   Satellite "GPS BIIRM-1 (PRN 17)"
   Satellite "GPS BIIRM-2 (PRN 31)"
   Satellite "GPS BIIRM-3 (PRN 12)"
   Satellite "GPS BIIRM-4 (PRN 15)"
   Satellite "GPS BIIRM-5 (PRN 29)"
   Satellite "GPS BIIRM-6 (PRN 07)"
   Satellite "GPS BIIRM-8 (PRN 05)"
   Satellite "GPS BIIF-1  (PRN 25)"
   Satellite "GPS BIIF-2  (PRN 01)"
   Satellite "GPS BIIF-3  (PRN 24)"
   Satellite "GPS BIIF-4  (PRN 27)"
   Satellite "GPS BIIF-5  (PRN 30)"
   Satellite "GPS BIIF-6  (PRN 06)"
   Satellite "GPS BIIF-7  (PRN 09)"
```

Figure 2. GPS Satellites in TPL Code

Each of the satellites is governed by two line element (TLE) data in the gps-ops.txt file attached to the overall SEAS scenario warfile. The TLE files have all been updated as of November 2014. An example of the TLE code is annotated and shown in Figure 3.



```
GPS BIIA-10 (PRN 32)
1 20959U 90103A   14302.48952317  .00000000  00000-0  10000-3 0  5548
2 20959  54.2798 203.5952 0114413 355.9101   4.0702  2.00567260175224
```

Figure 3. GPS TLE Example

Each of the GPS satellites orbit the Earth as dictated in the TLE data and are included in the target list for the GPS Unit. The GPS Unit provides input to the GPS receiver which is used by the SOF team. The SOF team is most aided by a GPS constellation that has a low value for accuracy, high probability of availability, low timeliness, and a high number of visible GPS satellites.

The blue forces are also composed of several additional support assets which provide airlift and surveillance. Airlift is accomplished through the CV-22 which delivers the SOF team in the city and recovers the SOF team from the evacuation point. Surveillance is made possible through the interactions of several different platforms in continual communication. The Predator and Global Hawk units help identify enemy red targets throughout the city as they circle over the area of interest. Additionally, a carrier support group is included in the simulation to help relay the information between the blue forces. The combination of the support elements are not specifically studied in this analysis, however, it is important to understand that they provide the transportation and communication structure for the blue forces.

Red Forces.

The red force structure is composed of several generic unit categories to include military forces, police, and civilians. Red military units are the main threat to the

SOF team and engage in combat whenever possible. The red military is composed of six trucks with 11 soldiers per truck. If the red military engages the SOF team but the number of red military forces do not exceed three times the number of blue forces, then the red forces retreat. The red forces follow the blue forces until red reinforcements arrive. The red military is also programmed to act autonomously from the red police, however, the red military reacts to SOF team locations transmitted over the red police radio. The red police are less numerous and less threatening to the SOF team. They do not engage the SOF team, but proceed about their normal patrols. The police act regionally around their five different police stations and use motorcycles and station wagons as fast transportation. If the red police encounter the SOF team, they broadcast the SOF team location which can be intercepted by the red military. Additionally, the police can be informed about the SOF team location from red civilians. The red civilians continue to grow in number throughout the simulation and move randomly throughout the city. If a civilian encounters the SOF team, then there is a 50 percent chance that they inform the police. The complex red force structure is heavily dependent upon the communication of SOF team's current location. If the civilians and police can communicate effectively, then the red military will be more successful at engaging the SOF team. [17]

Model Assumptions.

The urban canyon scenario has several assumptions built into the model. A list of the model assumptions are summarized below [17]:

1. GPS accuracy is degraded when the SOF team is near a building.
2. An agent's position knowledge is impacted by input parameters.
3. A specific geolocation algorithm is not necessary.

4. The SOF team must maneuver through the streets to reach the evacuation location.

5. The CV-22 is not impacted by GPS degradation.

The first critical assumption is the degradation of GPS accuracy as the SOF team moves closer to buildings. One example provided from the model designers is that the accuracy of GPS can decrease from 2-m to 30-m when the SOF team moves to within a certain distance to the buildings [17]. Another important assumption in the model is that the SOF team's position knowledge is adjusted by three model input parameters, GPS accuracy, availability, and timeliness [17]. Furthermore, the simulation does not use a specific geolocation algorithm, but instead relies on top-level characteristics of GPS to determine position. Each of the assumptions help construct a top-level mission model as opposed to a more detailed tactical engagement level model.

3.3 Model Development

Tactical Programming Language.

Agents within SEAS are governed by logic found in the TPL code. In the scenario simulation code there is a section for "orders" for each agent where the TPL statements are located. The TPL associate logic statements with each agent which enable specific behavior. Conventional logical statements are available in the TPL to include, arrays, variable manipulation, condition statements, logic loops, and a multitude of both user defined and pre-defined functions. Minimal changes to the TPL code are implemented in the scenario of interest to maintain the validity of the current model. Nevertheless, understanding the syntax and proper implementation of different TPL statements is essential to ensuring accurate analysis. [18]

Modifications.

To maintain the current model validity, only minor changes are made to the urban canyon scenario. Additionally, the analysis does not require any additional output variables from the model which greatly simplifies the model development. Instead, model development focuses on logic structure changes along with the changes in the number of available GPS satellites. Each of the model developments are used in combination with input parameter changes to create the degraded scenarios described in the Analysis Approach section.

One modification aims to remove available satellites from the model. Removing satellites is key to assessing overall constellation resiliency and can be accomplished by selectively commenting out satellites. Any number of satellites can be randomly or purposely selected within the model for omission. One example is the removal of the most recently deployed GPS Block IIF series satellites of which there are seven included in the original simulation. To remove satellites from consideration, they must be commented out from both the group definition of the GPS Sats.inc file along with the satellite force definition in the pnt.war file. Removing satellites can be representative of many real world threats to include, kinetic strikes, cyber attacks, environmental weather variations, and system failure.

The second modification is an addition to the GPS Unit logic structure. In the original model, the SOF team would receive a decrease in overall travel speed if less than six GPS satellites were available on the target list. To expand the original model and connect the GPS Unit more directly to the scenario, the logic statements also include changes to the input parameters of GPS accuracy and availability. Additionally, the logic statements are expanded to provide changes to the input parameters for every number of available GPS satellites under ten. The input parameters are changed through a increasing linear scale for GPS availability and a decreasing exponential scale for GPS accuracy as the number of satellites on the target list increases. A view of the proposed factors in the logic development is shown in Table 2.

Table 2. GPS Unit Parameter Factors per Number of GPS Satellites

	Multiplication Factor		
Number of Visible GPS Satellites	Accuracy	Availability	Speed
≤ 4	4	0.4	0.5
5	3.17	0.5	0.75
6	2.52	0.6	0.9
7	2	0.7	0.9
8	1.59	0.8	0.9
9	1.26	.9	0.9
10	1	1	1

The logic factors are translated into specific values for accuracy and availability based on either nominal or degraded operations. The realized values are summarized in Figures 4 and 5.

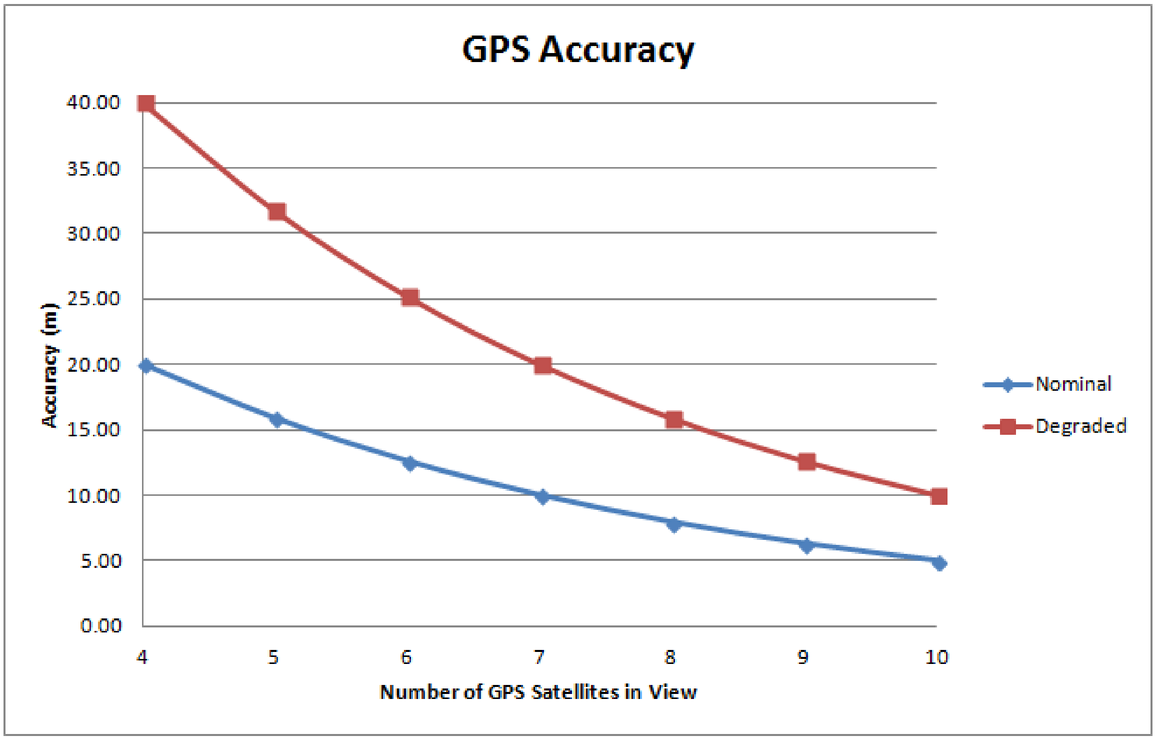


Figure 4. Translated GPS Accuracy

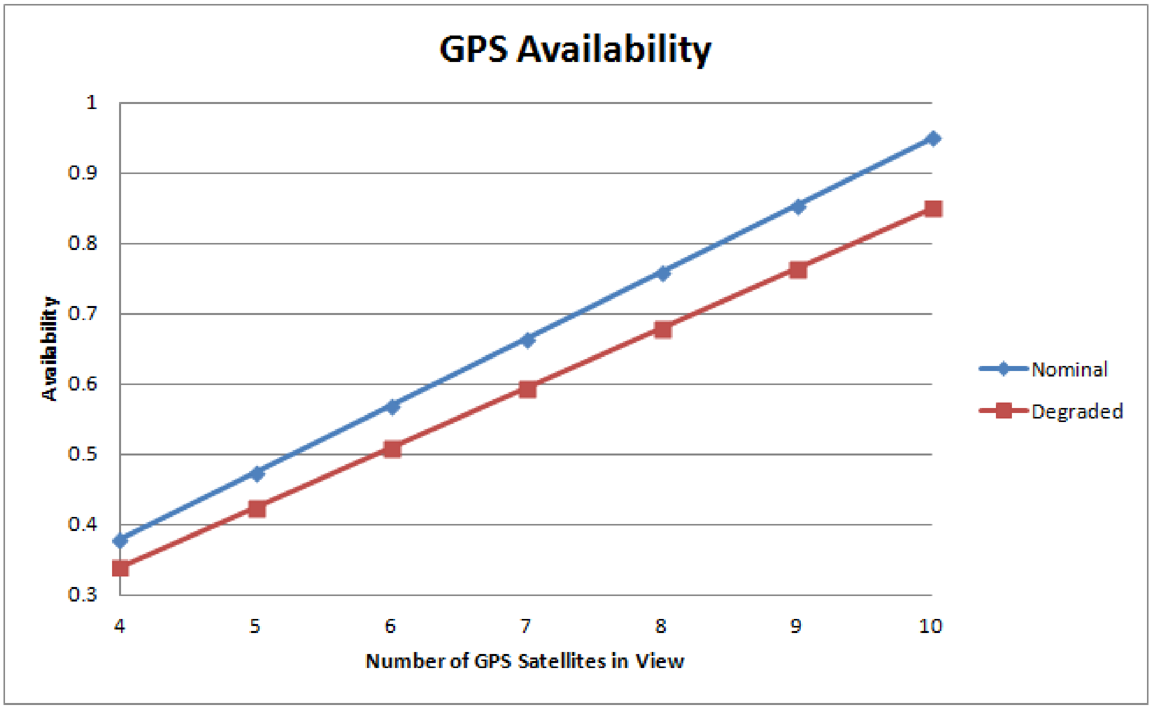


Figure 5. Translated GPS Availability

3.4 Selected Metrics

The analysis in this study focuses on answering the fundamental question of GPS constellation resiliency. As a result of the challenges noted in the Literature Review, the metrics needed to capture GPS resiliency must be insightful and cleverly developed. Furthermore, the metrics must be accessible within the current scenario and cannot require drastic changes in the SEAS TPL code. Limiting the changes in the code and utilizing already available model outputs allow the model to maintain its validity. In order to derive the appropriate metrics, a series of top level mission priorities are established. Each of the selected metrics connect back to one of the four campaign priorities. The list of campaign priorities are shown below:

1. WMD recovery at all costs;
2. Minimize blue force casualties;
3. Minimize mission duration; and
4. GPS is functioning as intended.

Probability that more than 50% of SOF Team Survives (P_{50}).

P_{50} is derived from the number of replications where fewer than 50% casualties are sustained by the SOF team. The metric connects back to the first and second campaign level priorities which reflect the proportion of time that the WMD has been successfully removed with fewer than 25 SOF team casualties. Instead of stopping the simulation once the SOF team casualties exceed 25, we chose to allow the simulation to continue running which represents a need to remove the WMD at all costs. As a result, the mission is classified through the output data by observing if there are more than 25 casualties in the replication. If the metric varies greatly across scenarios then, it is possible to argue that degraded GPS is hindering the mission and the constellation is not exhibiting resiliency.

Mission Duration.

Mission duration assesses the impact of being lost as a result of GPS degradation. The metrics connects directly to the third campaign level priority which aims to reduce the total duration of the mission. An extend mission duration can occur if the GPS constellation is degraded by having a fewer number of satellites which decreases accuracy and availability and increases the probability of being lost. Any additional time lost is a sign of failure of the GPS constellation to provide the required capabilities indicating a lack of resiliency.

Number of Blue Casualties.

The number of blue casualties connects to the second campaign level priority and provides insight into the SOF team losses. The metric is designed to assess the number of casualties as a result of degraded GPS as opposed to poor battle tactics. Intuitively, the number of casualties should increase with an increase in the number of engagements. Reducing the number of engagements is heavily dependent upon correct position data from the GPS constellation. As a result, significant differences in the amount of blue casualties across scenarios reflects a weakness and lack of resiliency of the GPS constellation.

Number of Engagements.

The number of engagements is intertwined with the number of blue casualties and is therefore also connected to the second campaign level priority. Reducing the number of engagements leads to a decreased loss of life along with a decreased mission duration. The best way to avoid engagements is to move precisely through the city to the evacuation point. The number of engagements is included along with the number of casualties to help decipher if GPS is having an impact which may be disguised by a resilient SOF team which does not suffer a large amount of casualties per engagement. As a result, if the number of engagements significantly increases with GPS degradation, then it is possible to conclude that the GPS constellation is not providing the required capability and is therefore not exhibiting resiliency.

Blue Casualties per Number of Engagements.

As noted earlier in the Literature Review, a ratio metric can provide more information beyond just the output from a single variable [12]. Nevertheless, the ratio between the number of casualties and the engagements did not yield any interesting results or insight throughout the analysis. As a result, the specific ratio metric is not considered for the study.

Proportion of Time Lost to Mission Duration.

The proportion between the amount of time the SOF team is lost and the total mission duration connects directly to the third campaign level priority which aims to reduce the total mission duration. When the SOF team losses its position knowledge due to a degraded GPS constellation and is lost, the intuitive result is an increased mission duration. It can be difficult to interpret the specific values of the metric, however, any increase in the metric indicates an increased amount of time being wasted. A statistical difference comparison between the scenarios provides insight into GPS constellation resiliency.

Percentage of Time that the Number of GPS Satellites is less than 4.

The average percentage of time that less than four GPS satellites are in view reflects the functionality of the constellation. GPS is specifically designed to provide accurate geolocation data to a receiver with a minimum of four GPS satellites [27]. If the number of GPS satellites in view drops below four, then it is reasonable to argue that the SOF team movements are significantly impacted and the successful removal of the WMD is diminished. The metric specifically relates back to the fourth priority which is concerned with the functionality of GPS. If the GPS constellation is not functioning as intended, then from a top level mission perspective, the substantial monetary investment in GPS is not providing the expected return in capability.

Percentage of Time that the Number of GPS Satellites is greater than 6.

A similar metric is connected to the functionality and intended operation of the GPS constellation. While the previous metric aims to collect data on the minimal number of satellites required for geolocation, the GPS constellation is ideally created to provide highly accurate geolocation achievable from a large number of satellites. Collecting statistics on having more than six GPS satellites provides information on the portion of the mission which is receiving high quality GPS information. As the model is degraded, it may not be possible for the GPS constellation to retain more than six satellites in view which indicates a loss of resiliency to provide the high resolution data to the SOF team.

3.5 Analysis Approach

Scenario Comparison.

The first method of analysis compares the set of selected metrics across modified scenarios using statistical difference tests. Each scenario is defined by either a nominal or degraded starting operational condition which can be further degraded by removing a number of the satellites attained from the initial target list. The objective is to determine if there is a significant difference between the metrics from one scenario to another. We use the Paired T test for any continuous or integer metrics. For any percentage or proportion metric we perform a classical difference of proportions test in place of a Paired T.

Nominal Operations.

In an effort to represent current scenario performance, the nominal operations are defined by expected GPS constellation input parameters. The two most important parameters are the GPS accuracy and availability which are set at 5 meters and 95% respectfully. It is reasonable to assume that the GPS constellation is not perfect, but it is however highly accurate and readily available. GPS timeliness is kept at five seconds which was the fastest value used by the previous model developers. Additionally, the model includes two Predators, the police do not engage in combat, and the SOF team is able to use landmarks as mentioned previously.

Degraded Operations.

The degraded operations reflect a minor loss of GPS capability. The only changes made to the nominal operations are the reduction of GPS accuracy and availability. GPS accuracy is increased to 10 meters and the availability is reduced to 85%. The degraded scenario represents the impact of the urban canyon environment where the geolocation estimates can be impacted along with the connection to the GPS satellites. The remaining input variables remain the same as those in the nominal operations.

Satellite Removal.

In order to simulate the loss of satellites due to the array of threats mentioned in the Literature Review, satellites are purposefully eliminated from the program code. The satellites selected for removal are attained from the initial target list of the GPS Unit and remain omitted for the duration of the simulation. Using the target list enables the removal of the satellites specifically in view of the area of operations, instead of removing a satellite at random which may not be important. This also implies a red force capability to identify and rapidly target specific satellites. The number of satellites removed ranges from zero to ten of the initial satellites and is used in combination with either the nominal or degraded operations scenarios.

Designed Experiment.

A full factorial designed experiment is performed which provides insight into the most important variables impacting the selected responses. The responses of interest are the selected metrics to assess resiliency. Additionally, the designed experiment is composed of two factors. The first factor is the use of either the nominal or degraded operations, while the second factor is structured on the number of satellites removed. Using the results from the designed experiment, it is possible to determine which factor most impacts the overall resiliency.

3.6 Summary

The WMD removal scenario provided by SMC is highly complex yet adaptable for additional analysis on the GPS constellation resiliency in an urban canyon environment. The simulation is composed of opposing blue and red forces which are assisted by a range of support assets. The simulation revolves around the actions of the SOF team which maneuvers through the city to evacuate the WMD. During the maneuver period, the SOF team is continually confronted by red military forces in their attempt to eliminate the SOF team. A principle support structure for the SOF team is the GPS constellation providing navigation knowledge. The agent based actors in the model are limited by several assumptions to include GPS degradation when the SOF team is near to buildings. To further augment the degradation, several changes are made to the TPL code in SEAS model. The first change is to selectively comment out specific satellites from the model. The second change is to the GPS Unit logic which decreases the GPS accuracy and availability characteristics as the number of satellites in view decrease. To assess the resiliency of the GPS constellation, a series of metrics are selected to support the list of campaign level priorities. The metrics are then assessed across scenarios to determine if there is a statistical difference which provides insight into resiliency. Furthermore, a designed experiment helps provide additional insight into the most important factors behind a specific metric. Chapter 4 presents the analysis derived from the Methodology along with insights gained into GPS constellation resiliency.

IV. ANALYSIS

4.1 Overview

Chapter 4 presents the analysis performed as described in the Methodology and the results attained. First, the appropriate sample size is determined for each scenario along with the required number of model runs. Next, the initial investigation into the data is performed through a series of Paired T or difference of proportions tests and confidence intervals to determine if there is a statistically significant difference in the metrics across scenarios. Those metrics which appear to be important are identified and selected for further analysis. The analysis section also describes the process of attaining all of the production replications required for the designed experiment. Once all of the data is collected, a graphical analysis of the data is presented. Furthermore, a series of linear regression models are generated to determine which factors are most influential for a specific metric. The Analysis chapter concludes with a brief summary of the results which is extended upon in Chapter 5.

4.2 Sample Size and Model Runs

The number of replications for each design point is driven by the need to provide accurate analysis balanced with the resources required to complete one replication. Fortunately, each replication of the simulation only requires several minutes on a personal laptop. However, it is not advantageous to perform as many replications as possible as the information gained from the additional replications experiences a diminishing margin of return. Instead, the sample size is determined to provide a reasonable standard deviation relative to the mean value for all metrics. We looked closely at results for 20, 25, and 30 replications and selected 25 replications as a good balance across all metrics. For the remainder of the study each design point contains

25 replications.

Model parameters for the normal and degraded operations can be varied within a single SEAS warfile with the use of the run matrix logic included in the original model. By choosing to remove satellites by commenting out appropriate portions of the TPL code within a SEAS warfile, each change in number of satellites removed requires a modified warfile. Therefore, the study runs are broken into 50 replications as further discussed in this chapter.

4.3 Initial Analysis

To gain an initial perspective on the data, an initial analysis is composed of a variety of scenarios at the extreme and moderate levels of each factor. The metrics for each scenario are compared to determine if there is a statistically significant difference. The presence of a statistical difference indicates a metric which is impacted by the factor level changes to the simulation. While initial insight is possible through all metrics, the metrics which do exhibit a statistical difference are considered for further analysis. Additionally, the sensitivity of a metric to the initial design points provides information on the range of the factor levels used in the designed experiment. Another benefit of the initial analysis is the generation of the confidence intervals which display the expected range of difference for each metric. The magnitude and range of the confidence interval provides information into the extent of the difference. Furthermore, observing patterns and anomalies in the results leads directly to inferences on the resiliency of the GPS constellation.

Selected Scenarios.

The six selected initial scenarios represent the center and end design points between of the number of satellites removed and the type of operations. By examining the extreme scenarios in conjunction with moderate scenarios allows for greater initial insight over the range of the study. The scenarios are performed in pairs between nominal and degraded operations where the number of satellites removed is held constant. As a result, each run matrix for this initial simulation contains 50 replications of which the first 25 are allocated to the nominal operations and the remaining 25 replications to the degraded operations. Table 3 displays the initial scenarios.

Table 3. Initial Analysis Scenarios

Scenario	Availability	Accuracy (m)	Number of Satellites Removed	Reps
1	0.95	5	0	25
2	0.85	10	0	25
3	0.95	5	5 (9, 1, 31, 17, 23)	25
4	0.85	10	5 (9, 1, 31, 17, 23)	25
5	0.95	5	10 (9, 1, 31, 17, 23, 20, 11, 8, 4, 32)	25
6	0.85	10	10 (9, 1, 31, 17, 23, 20, 11, 8, 4, 32)	25

Metric Averages.

The raw output data from the scenarios shown in Table 3 provide information on the mean values of the metrics in the analysis. A summary of the mean values are presented in Tables 4 and 5 for the nominal and degraded operations respectfully.

Table 4. Metric Averages for Nominal Operations

Metric	Number of Satellites Removed		
	0	5	10
P_{50}	68.00%	44.00%	8.00%
Duration (min)	73.00	80.52	120.31
Casualties	16.76	19.76	33.44
Engagements	4.44	6.64	10.24
% Time Lost	0.37%	1.12%	2.35%
% $<$ 4 GPS	0.25%	1.70%	45.71%
% $>$ 6 GPS	63.61%	54.35%	7.46%

Table 5. Metrics Averages for Degraded Operations

Metric	Number of Satellites Removed		
	0	5	10
P_{50}	40.00%	24.00%	12.00%
Duration (min)	84.13	100.21	139.35
Casualties	23.68	28.44	33.00
Engagements	7.12	10.72	11.20
% Time Lost	1.31%	1.97%	3.12%
% $<$ 4 GPS	0.67%	3.04%	40.68%
% $>$ 6 GPS	66.85%	59.01%	15.76%

Both Tables 4 and 5 support intuitive trends across scenarios. For example, while holding the operations constant as GPS satellites are removed, the scenarios report on average a lower value for P_{50}, longer duration, higher number of casualties, higher number of engagements, an increased percentage of time lost, and fewer satellites available to the GPS unit. Holding the number of satellites removed constant and looking across operations generally shows that the degraded operations perform poorly when compared to the nominal operations. There are a few exceptions where the degraded operations performs better than the nominal operations; however, it is important to remember that these are only mean value comparisons and do not contain an assessment of a statistical difference. Nevertheless, Tables 4 and 5 provide an intuitive first perspective to the metrics.

Paired T and Difference of Proportions Comparisons.

The scenario comparisons gain statistical rigor through the use of the Paired T test on the duration, casualties, and engagement metrics while the difference of proportions confidence interval is used on the remaining metrics which are all percentages. There are several ways to compare point estimators for the mean; however, the Paired T test is the least restrictive in terms of assumptions. One condition for the Paired T test is that the differences between the paired replications should be approximately normally distributed [35]. Fortunately, the Paired T test is rather robust to non-normal data. As a result, with a sample size of 25 replications, we assume that the difference data is approximately normally distributed and passes the first condition. Typically, the Paired T test is required for dependent data which can be achieved by using synchronized random numbers. In this study, we do not attempt to synchronize the random numbers in the simulation and as a result we can conclude that the replications are independent. Therefore, the Paired T test is an acceptable method for comparing the numerical metrics.

The compilation of the Paired T test and confidence interval provide insight into the difference between the metrics in each scenario. The p-value from the Paired T test provides information on the extent of the null hypothesis conclusion to either reject or fail to reject a difference between the metrics in the scenario comparison. In addition, the confidence interval displays the point estimator of the difference along with a range which contains 95% of the observed differences. For cases where we reject the null hypothesis at $\alpha = 0.05$ level of significance, the 95% confidence interval does not contain zero. Both of these results indicate a statistically significant difference between the scenarios.

The proportion metrics are not compared with the Paired T test, but instead through the difference in proportions confidence interval. The data contained in each of the replications for P_{50} are distributed binomially as either a success or failure. As a result, the differences in the Paired T test are not normally distributed or insightful. Additionally, the remaining proportion metrics cannot be assessed through the Paired T test due to inaccuracies in the standard error calculations. Instead, the appropriate comparison method is to determine if the difference in proportions confidence interval contains zero. The proportion confidence interval is shown in Equation 1 [19] where $\hat{p}_1$ and $\hat{p}_2$ represent the proportion correct from the replications of each scenario.

$$p_1 - p_2 = \hat{p}_1 - \hat{p}_2 \pm Z_{0.025}\sqrt{\frac{\hat{p}_1(1-\hat{p}_1)}{n_1} + \frac{\hat{p}_2(1-\hat{p}_2)}{n_2}} \tag{1}$$

Two key differences between the proportion and Paired T test confidence interval are the standard error and distribution statistic. The standard error for a proportion requires a pooled variance estimation from both populations. Each individual variance is also calculated by taking the product of the proportion correct and the proportion of failure and the total number of replications. Furthermore, the difference of proportions interval uses a z statistic in place of the t statistic used for the Paired T.

Initial Comparison.

Several important trends are identified from the initial analysis which provide insight into satellite resiliency and direct the remainder of the analysis. A compiled table of the p-value results for each of the metric comparisons across the different scenarios are shown Tables 6, 8, and 10. Note that p-values are provided for the Paired T test and either a “Reject” (p-value ≤ 0.05) or fail to reject “FTR” for the difference of proportions. Additionally, the confidence interval for each metric comparison is summarized with the mean and half width shown in Tables 7, 9, and 11. Bolded cells indicate that there is a statistically significant difference for the metric in the given scenario comparison.

Table 6. Nominal vs Degraded P-Value Comparison

Metric	Scenario Comparison		
	Nom-0 vs Degrad-0	Nom-5 vs Degrad-5	Nom-10 vs Degrad-10
P_{50}	**Reject**	FTR	FTR
Duration (min)	**0.01**	**0.00**	**0.01**
Casualties	0.13	**0.02**	0.82
Engagements	**0.03**	**0.01**	0.13
% Time Lost	FTR	FTR	FTR
% < 4 GPS	FTR	FTR	FTR
% > 6 GPS	FTR	FTR	FTR

Table 7. Nominal vs Degraded Confidence Interval Comparison

Metric	Scenario Comparison		
	Degrad-0 - Nom-0	Degrad-5 - Nom-5	Degrad-10 - Nom-10
P_{50}	**-0.28% ± 0.27%**	-0.20% ± 0.26%	0.04% ± 0.17%
Duration (min)	**11.13 ± 7.97**	**19.69 ± 7.81**	**19.04 ± 13.97**
Casualties	6.92 ± 9.14	**8.68 ± 7.21**	-0.44 ± 3.88
Engagements	**2.68 ± 2.34**	**4.08 ± 2.83**	0.96 ± 1.28
% Time Lost	0.01% ± 0.05%	0.01% ± 0.07%	0.01% ± 0.09%
% < 4 GPS	-0.00% ± 0.04%	0.01% ± 0.08%	-0.05% ± 0.27%
% > 6 GPS	0.03% ± 0.26%	0.05% ± 0.27%	0.08% ± 0.18%

Table 8. Nominal vs Num Sats Removed P-Value Comparison

Metric	Scenario Comparison		
	Nom-0 vs Nom-5	Nom-0 vs Nom-10	Nom-5 vs Nom-10
P_{50}	FTR	**Reject**	**Reject**
Duration (min)	**0.05**	**0.00**	**0.00**
Casualties	0.57	**0.00**	**0.00**
Engagements	0.14	**0.00**	**0.00**
% Time Lost	FTR	FTR	FTR
% < 4 GPS	FTR	**Reject**	**Reject**
% > 6 GPS	FTR	**Reject**	**Reject**

Table 9. Nominal vs Num Sats Removed Confidence Interval Comparison

Metric	Scenario Comparison		
	Nom-5 - Nom-0	Nom-10 - Nom-0	Nom-10 - Nom-5
P_{50}	-0.24% ± 0.27%	**-0.60% ± 0.21%**	**-0.36% ± 0.22%**
Duration (min)	**7.52 ±7.40**	**47.31 ± 11.18**	**39.79 ± 9.38**
Casualties	3.00 ± 10.86	**16.68 ± 8.21**	**13.68 ± 6.59**
Engagements	2.20 ± 3.00	**5.80 ± 2.28**	**3.60 ± 2.07**
% Time Lost	0.01% ± 0.05%	0.02% ± 0.06%	0.01% ± 0.07%
% < 4 GPS	0.01% ± 0.05%	**0.45% ± 0.20%**	**0.44% ± 0.20%**
% > 6 GPS	-0.09% ± 0.27%	**-0.56% ± 0.21%**	**-0.47% ± 0.22%**

Table 10. Degraded vs Num Sats Removed P-Value Comparison

Metric	Scenario Comparison		
	Degrad-0 vs Degrad-5	Degrad-0 vs Degrad-10	Degrad-5 vs Degrad-10
P_{50}	FTR	**Reject**	FTR
Duration (min)	**0.00**	**0.00**	**0.00**
Casualties	0.11	**0.01**	**0.02**
Engagements	**0.00**	**0.00**	0.53
% Time Lost	FTR	FTR	FTR
% < 4 GPS	FTR	**Reject**	**Reject**
% > 6 GPS	FTR	**Reject**	**Reject**

Table 11. Degraded vs Num Sats Removed Confidence Interval Comparison

Metric	Scenario Comparison		
	Degrad-5 - Degrad-0	Degrad-10 - Degrad-0	Degrad-10 - Degrad-5
P_{50}	-0.16% ± 0.25%	**-0.28% ± 0.23%**	-0.12% ± 0.21%
Duration (min)	**16.08 ± 6.67**	**55.22 ± 12.45**	**39.14 ± 11.63**
Casualties	4.76 ± 5.96	**9.32 ± 6.30**	**4.56 ± 3.64**
Engagements	**3.60 ± 2.38**	**4.08 ± 1.98**	0.48 ± 1.55
% Time Lost	0.01% ± 0.07%	0.02% ± 0.08%	0.01% ± 0.09%
% < 4 GPS	0.02% ± 0.07%	**0.40% ± 0.20%**	**0.38% ± 0.20%**
% > 6 GPS	-0.08% ± 0.27%	**-0.51% ± 0.23%**	**-0.43% ± 0.24%**

Initial Insights.

The first broad trend observed across the p-value comparison tables is the fewer number of significant p-values when comparing the nominal and degraded operations with the same number of satellites removed. The trend shows that the model is more sensitive to the number of satellites lost for a given operation configuration versus strictly the difference between the nominal and degraded operations. This is an intuitive result, as the difference between the nominal and degraded operations is not severe, but the removal of multiple satellites should drastically impact the model and create significant differences in the metrics. The insight gained is useful moving forward and provides verification to the model acting as anticipated under specific configurations.

The second broad trend is that the percentage of time lost is continually insignificant across all scenarios. Additionally, the point estimator and half widths observed in Tables 7, 9, and 11 are small in magnitude. As a result, it is possible to conclude that GPS constellation degradation is not significantly impacting the overall percentage of time in which the SOF team is lost.

Within the specific metrics there are several trends which are nearly significant in every scenario. The first is mission duration which is always significantly different and always increases in value with increased degradation. Tables 7, 9, and 11 also show that there is a large difference between scenarios as indicated by the point estimators in the confidence intervals and half widths. This helps support the conclusion of practically as well as statistically difference in the metrics. A key insight attained from the trend is that the overall mission duration is highly sensitive to GPS performance. If the WMD needs to be removed within a small time window, having the highest performing GPS constellation would be critical.

Two often significant metrics which provide similar information are the percentage of time less than four GPS and greater than six GPS satellites are available. As satellites are removed the percentage of time less than four GPS satellites are available tends to increase while the percentage of time greater than six GPS satellites are available tends to decrease. It is important to note that the significant difference only occurs when the nominal or degraded scenarios are compared with removing ten satellites. This is an intuitive result as removing a large portion of the initial ten satellites in view reduces the overall number of satellites available over the duration of the mission. It is also interesting to note that the point estimator and half width for the comparison between five and ten satellites removed is nearly identical to the statistics from zero to ten satellites removed. As a result, it is possible to conclude that the majority of the impact from removing satellites occurs after five satellites have been removed.

Another key insight gained from both metrics is that the GPS constellation is not able to quickly recover from a large number of lost satellites with the remaining satellites in orbit. Even though the expansive GPS constellation contains many satellites in several different plains, the originally non-impacted satellites will not reach the area of interest in time to restore capability. This is primarily due to the short duration of the selected mission of under a few hours. In reality, a GPS satellite takes 12 hours to complete one orbit around the Earth which is not fast enough to provide near instantaneous resiliency to the constellation. Note in this study we do not consider activating spare satellites or launching additional satellites into the constellation as a responsive tactic referenced in the Literature Review. As a result of the insight gained, the percentage of time less than four GPS satellites are available is retained which represents the more crucial capability of three dimensional geolocation.

A further specific insight is connected to the decrease in P_{50} with an increase in casualties and number of engagements. The evidence is located in Table 8 where there is a difference between metrics with a larger number of satellites removed. Interestingly, there is not a statistically significant difference between zero and five satellite removals which may be an indication of an non linear increase in the metrics with increased satellite removals. Similar evidence is shown in Table 10, but it is not as convincing. Overall, the observed trend supports intuition as an increased number of engagements should lead to more casualties which reduces the chance of losing less than 25 soldiers. Tables 9 and 11 also show that the mean values for the number of casualties and engagements also increase as the number of satellites are removed. The significant changes in the metrics are all indications that a reduced GPS constellation is degrading mission performance. As a result, the number of casualties and engagements are retained for further analysis.

Several important insights are developed from the initial perspective on the data. First, is that mission duration is highly sensitive to GPS degradation while the percentage of time lost is not sensitive. Furthermore, the percentage of time less than four GPS satellites and the percentage of time greater than six GPS satellites are available are intuitively impacted by a reduced number of GPS satellites which presents an initial conclusion on the inherent lack of resiliency of the GPS constellation over short mission durations. Additionally, the connection between P_{50} to number of casualties and engagements is displayed throughout the p-value and confidence interval comparisons. As a result, four metrics provide insight into the model which include mission duration, number of casualties, number of engagements, and percentage of time less than four GPS satellites are available. Each of the four metrics receives further analysis in order to gain additional insight into the GPS constellation resiliency.

4.4 Full Production Runs

The full experiment involves the remaining data from the additional scenarios. The objective is to have data from every level of satellite removal from zero to ten for both the nominal and degraded operations. Table 12 depicts the run configurations required to collect all of the necessary data.

Table 12. Full Production Runs

Factor	Levels	Design Points	Total Reps
Operations	2	22	550
Number of Sats Removed	11		

4.5 Graphical Insight

The JMP statistical package is used for data analysis. Compelling insight and a greater understanding of the model outputs is achieved by observing several plots of the metrics with respect to the number of satellites removed. Additionally, the replications are grouped based upon their type of operations as either nominal or degraded. The distinct patterns are interpretted and retained for further analysis.

Mission Duration vs Number of Satellites Removed.

The first graph of interest plots the individual 95% confidence intervals of the mission duration as the number of satellites removed increases as shown in Figure 6. The confidence intervals show a generally increasing trend in mission duration as the number of satellites removed increase regardless of the type of operations. A key observation from the "Degraded" section of the graph displays a distinct jump between five and six satellites removed where the confidence intervals no longer overlap. This is an indication of a statistically longer mission duration once the GPS constellation loses six satellites.

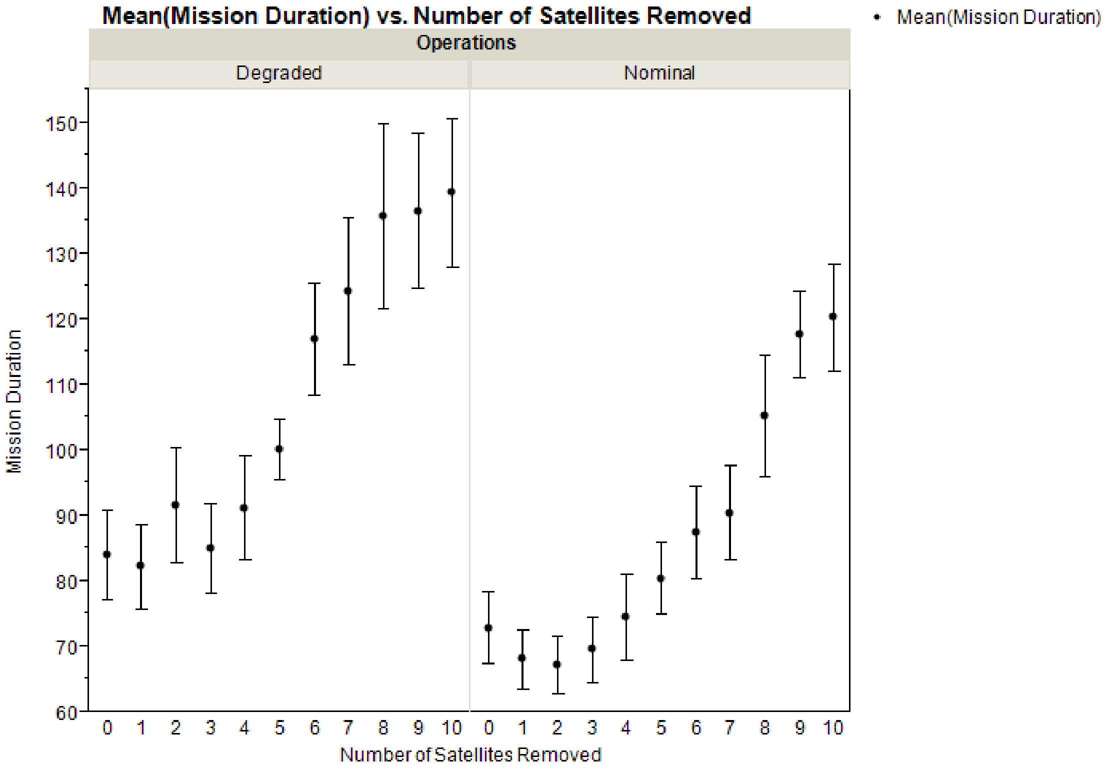


Figure 6. Mission Duration Individual 95% Confidence Interval Graph

Number of Engagements vs Number of Satellites Removed.

A similar and more abrupt pattern is observed in the "Degraded" portion of the individual 95% confidence interval graph for the number of engagements shown in Figure 7. The jump occurs between four and five satellites removed which is similar to the threshold noted from mission duration. An important insight gained is that there is a statistically significant increase in the number of engagements if the GPS constellation loses more than four satellites.

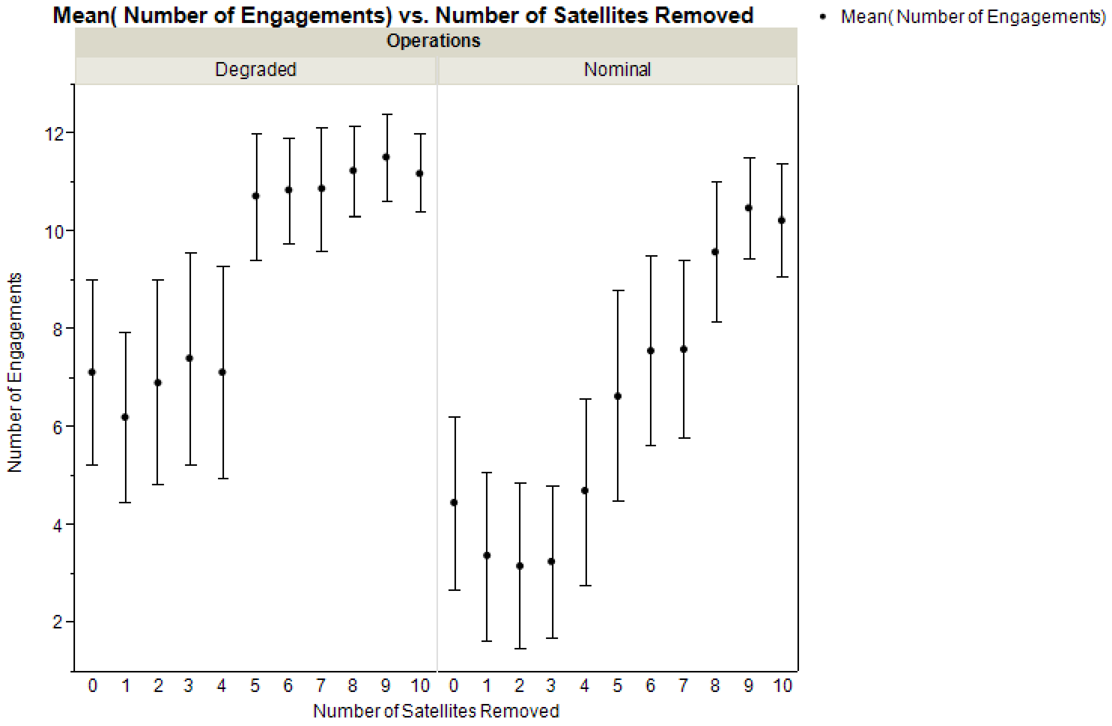


Figure 7. Number of Engagements Individual 95% Confidence Interval Graph

Number of Casualties vs Number of Satellites Removed.

Another response providing insight are the individual 95% confidence intervals associated with the number of casualties as shown in Figure 8. The graphic shows an increasing trend in the number of casualties as the scenario becomes more degraded. The key observation from the "Degraded" portion of Figure 8 is the narrowing of the confidence interval after removing four satellites. A smaller range of the confidence interval is indicative of a reduction in variation from the replications. At the moment it is not obvious what is causing the variance reduction; however, it is important to infer that there is a consistently high number of casualties once a large number of satellites have been removed.

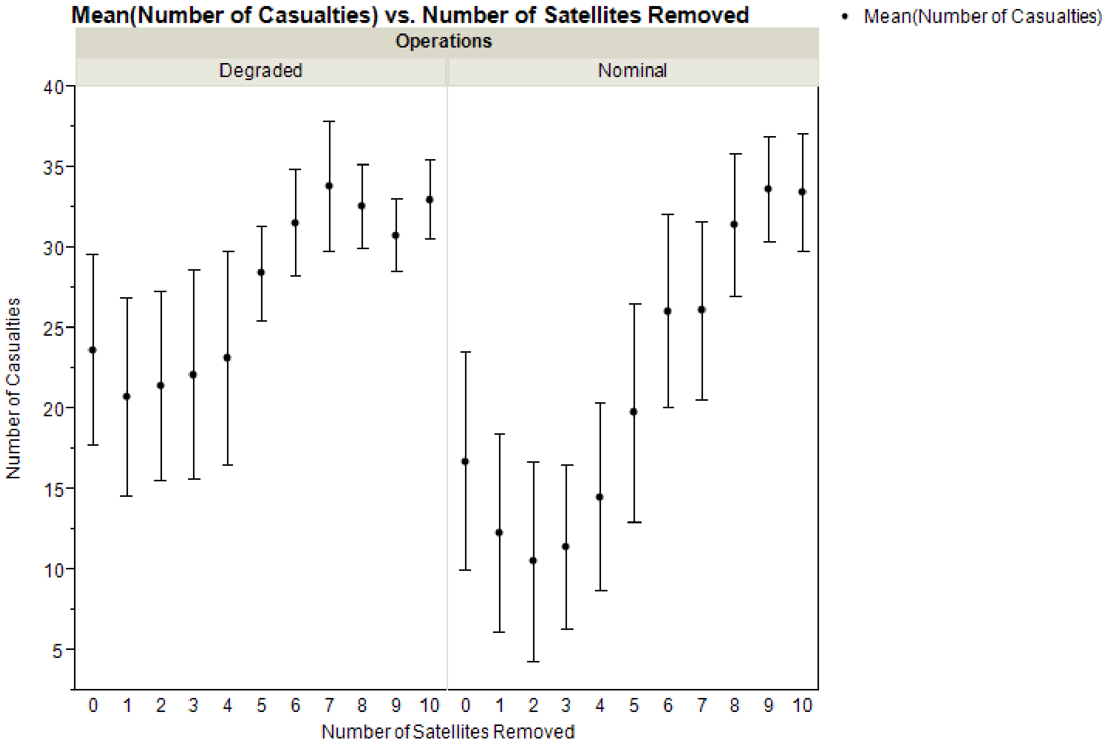


Figure 8. Number of Casualties Individual 95% Confidence Interval Graph

Percentage of GPS Satellites Available vs Number of Satellites Removed.

Observing the data output for the percentage of time less than four GPS satellites are available provides information into the exponential nature of the response variable as shown in Figure 9. The output data is displayed instead of the confidence intervals due to the inability to automatically display the correct proportion confidence intervals required for the metric. Nevertheless, the output data does display results which provide insight into the response. The data remains fairly constant until more than seven satellites are removed at which point the percentage of time in which less than four GPS satellites are in view increases dramatically. A similar graph is displayed from the data output from the percentage of time greater than six GPS satellites are available shown in Figure 10. The threshold now occurs around five to six satellites removed and displays a dramatic decrease in the response variable. Both of the reponses are highly dependent upon the number of number of satellites available. If too many satellite are removed then it is increasingly likely to register high values for the percentage of time there are fewer than four satellites available and low values for the percentage of time that there are greater than six satellites available.

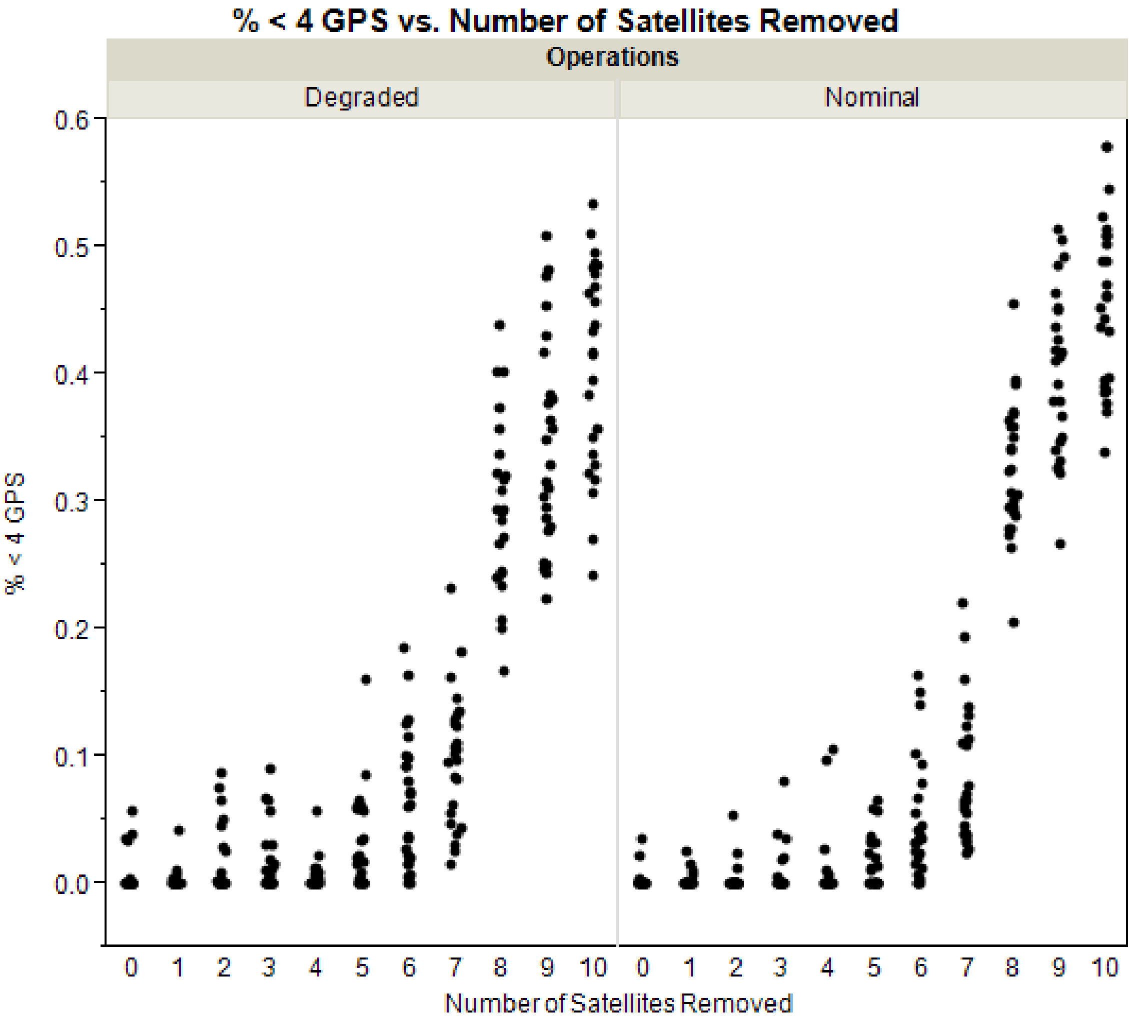


Figure 9. Percent of Time Less Than Four GPS Satellites Available Output Data

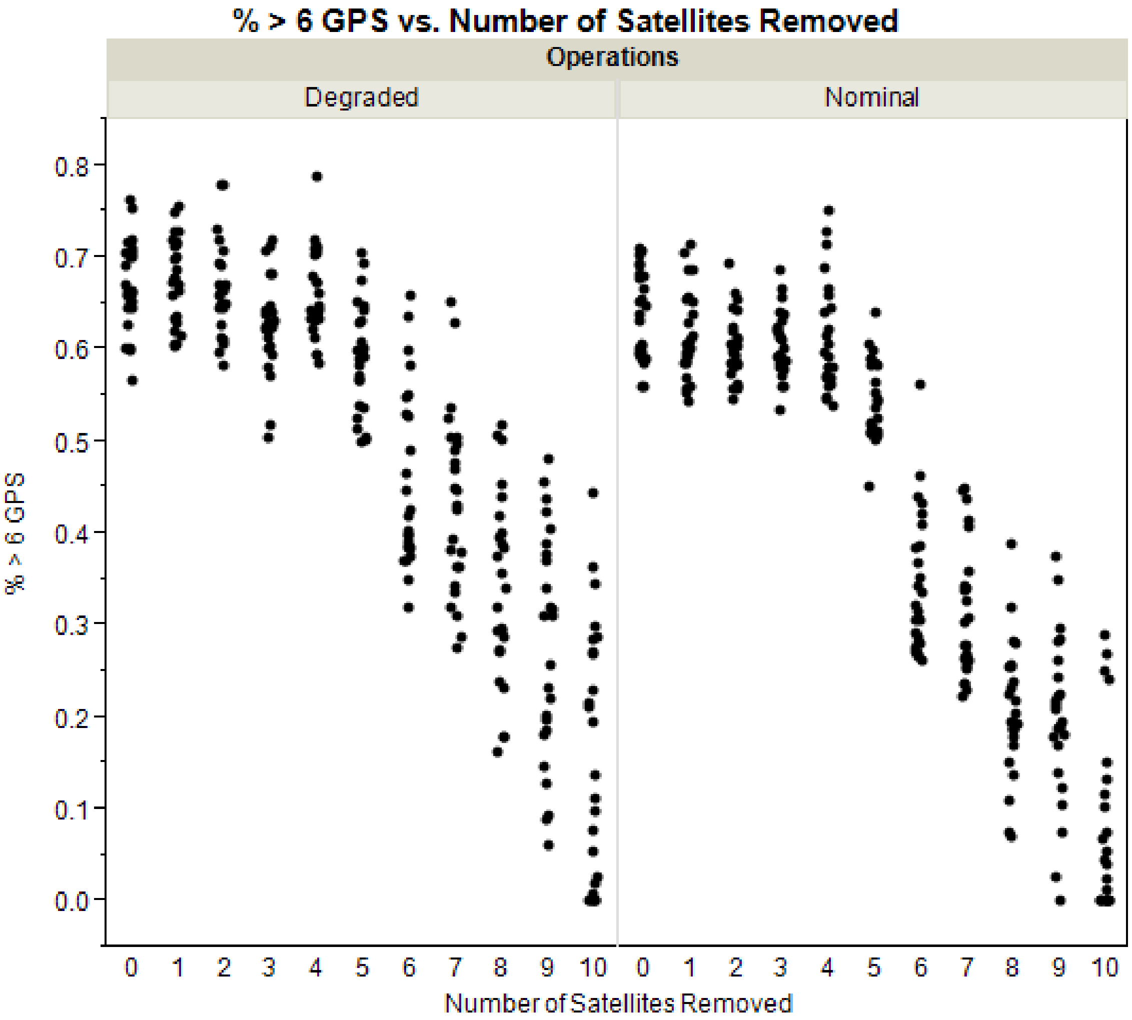


Figure 10. Percent of Time Greater Than Six GPS Satellites Available Output Data

P_{50} **vs Number of Satellies Removed.**

Figure 11 provides the mean value for P_{50} when compared with the number of satellites removed. Similar to the output data shown in Figures 9 and 10, the mean value is the most accessible and yet still insightful perspective on P_{50}. As evident by both type of operations, P_{50} is negatively impacted by an increasing number of satellites removed. When large numbers of satellites are removed, it appears as though there is a small probability of completing the mission with fewer than 25 casualties. Additionally, the low starting point for the "Degraded" operations even when none of the satellites have been removed is an important disparity worth noting.

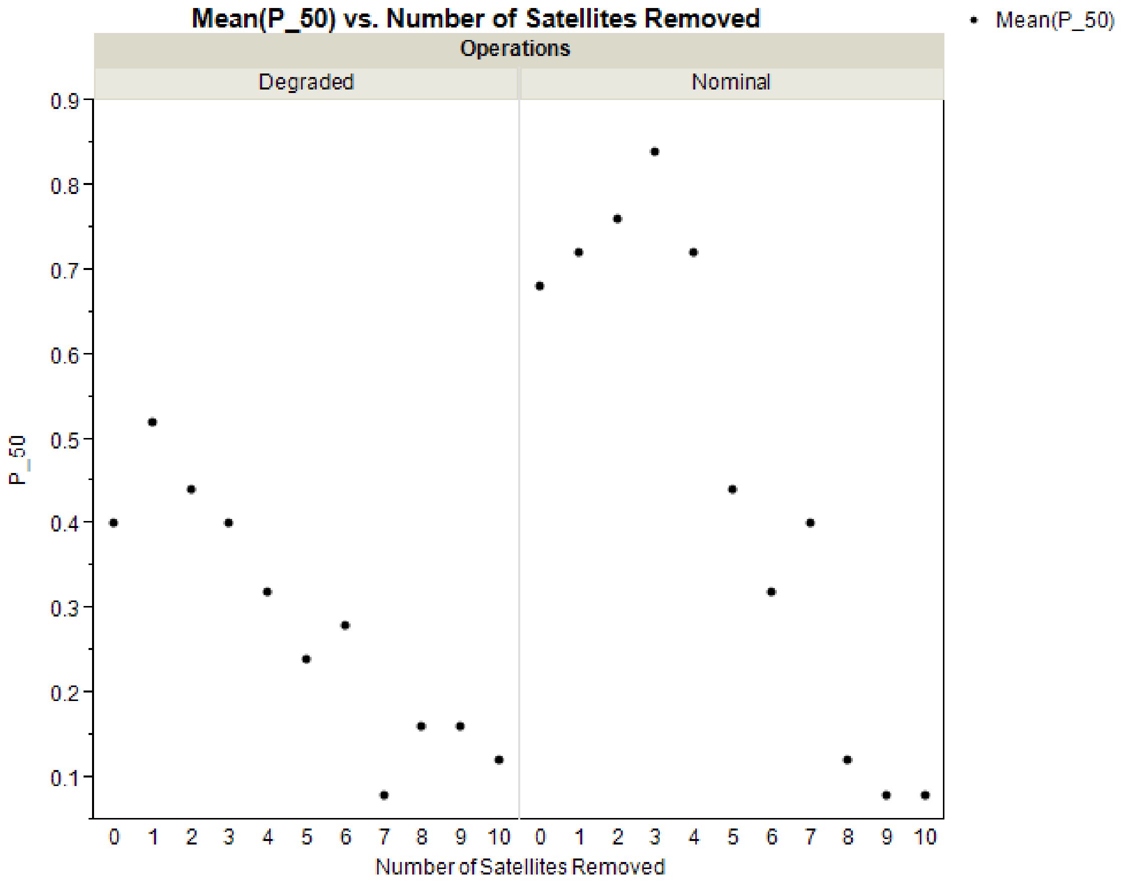


Figure 11. P_{50} Mean Value Graph

4.6 DOE

A designed experiment is performed to determine how the factors effect the response variables. Due to the minimal resources required to complete one replication, a full factorial design is utilized to provide un-aliased analysis between the levels of the factors. Insights are gained from an effects model which focuses on each factor along with the interaction between the factors. The results are analyzed in the two-factor analysis of variance (ANOVA) table to determine the significance of each factor. [23]

Responses.

The responses under consideration are the mission duration, number of casualties, number of engagements, and the percentage of time less than four GPS satellites are available, as identified as being sensitive to the factors in the initial analysis. Mission duration is classified as a continuous response where as casualties and engagements are integer variables. The percentage of time less than four GPS satellites are available is also unique in that it is continuous, but is bounded between 0 and 1. Each of the responses are analyzed through the ANOVA.

Factors.

There are two factors used in the model to include the type of operations and the number of satellites removed. The type of operations is a nominal variable composed of two levels; nominal or degraded operations as described in Chapter 3. The number of removed satellites from the model is the second factor which is also considered nominal and has 11 different levels to reflect the integer value of satellites removed from zero to ten. The full factorial run configuration requires 22 different design points to cover all combinations of the factors.

ANOVA.

The ANOVA is performed on each response variable by using both factors and their interaction. Upon further inspection, the addition of the interaction variable between the factors does not provide any significant benefit to the model. Instead, the marginal gain in model statistics with the interaction term is not worth over fitting the model with a new set of variables. Furthermore, with the exception of the percentage of time less than four GPS satellites are available, the lack of fit test did not reject the null hypothesis indicating that an interaction term is not necessary.

As a result, all of the regression models are restricted to using the single factors as effects.

Key results from the ANOVA include the significance of the overall model along with the individual factors. Furthermore, the numerical impact of each factor and factor level is estimated to provide specific insight into the impact on the response. Additionally, using Tukey's test allows for the statistical pairwise comparison between the levels of each factor providing more insight into any large changes in the responses. ANOVA enables insight into the specific situations which most impact GPS constellation resiliency.

Assumption Verification.

There are four assumptions to check before interpreting the results from the ANOVA. The assumptions assess the residuals of the ANOVA model on their normality, independence, constant variance against predicted values, and constant variance against the variables of the model. The residuals exhibit normality for all of the ANOVA models as shown by a histogram and normal probability plots of the residuals shown in the Appendix A. One minor normality violation may be present in the percentage of time less than four GPS satellites are available model where the majority of the residuals are contained near the center of the distribution. Independence of the residuals is not directly assessed in the study, however, we can confidently conclude that each replication is initiated with its own random number and that the simulation is not dependent upon the results from the previous replication. The residuals versus predicted plots yield some concern as far as non-constance variance for all of the ANOVA models, however, no transformations are performed on the responses. The non-constant variance does not appear to be severe enough to warrant the loss of interpret-ability from a transformation. Furthermore, almost all of the residual versus variable plots exhibit constant variance with the except of the percentage of time less than four GPS satellites are available model where the residuals appear to fan outward with an increasing number of removed satellites. Overall, the model residuals meet all of the required assumptions for the ANOVA models and the respective plots are displayed in the Appendix A.

Summary Statistics.

The ANOVA models are generated in JMP and the parameter estimates are available in the appendix. Summary statistics from each of the models are displayed in Table 13.

Table 13. ANOVA Model Statistics w/o Interaction Term

Summary Statistics	Response			
	Duration	Casualties	Engagement	% < 4 GPS
R^2	0.577	0.255	0.327	0.922
R^2-adj	0.568	0.24	0.314	0.92
MSE	385.4	158.36	15.593	0.002
Overall F	$<$ **.0001**	$<$ **.0001**	$<$ **.0001**	$<$ **.0001**
Lack of Fit	0.0627	0.0771	0.4188	$<$ **.0001**
Operations	$<$ **.0001**	$<$ **.0001**	$<$ **.0001**	0.0988
Sats Removed	$<$ **.0001**	$<$ **.0001**	$<$ **.0001**	$<$ **.0001**

All of the generated models are significant due to the results from the overall model F test, however several models explain a larger proportion of the total variance in the data. The R^2 and R^2-adj statistics assess the proportion of the total variance explained by the specific model. The results show that the mission duration and percentage of time less than four GPS satellites are available models explain a larger proportion of the total variance than the number of casualties and engagements. As a result, it is possible to conclude that mission duration and percentage of time less than four GPS satellites are available are more sensitive to the factors than the number of casualties and engagements. Intuition supports the high R^2 and R^2-adj statistics dependency of the percentage of time less than four GPS satellites are available model due to the inherent relationship between removing satellites from the model and the possibility of having fewer satellites in view. Additionally, as mentioned above all of the models except percentage of time less than four GPS satellites are available fail to reject the lack of fit test demonstrating that interaction terms are not required and that the models are properly specified.

Both operations and the number of satellites removed are significant factors in the models. One exception occurs for the percentage of time less than four GPS satellites are available response where operations is not significant indicating that the type of operations does not significantly impact the metric. Aside from the one exception, there is compelling evidence to suggest that the factors are highly significant variables toward defining the metrics. As a result, it is possible to conclude that adequately controlling the type of operations and the number of satellites removed is essential for improving satellite resiliency.

Pairwise Comparison - Tukey Test.

To gain further insight into the ANOVA models, the Tukey test is used to perform a pair-wise comparison of the levels of the number of satellites removed. The mission duration model demonstrates that there are several important locations in terms of the number of satellites removed. The results from the Tukey test are shown in Figure 12.

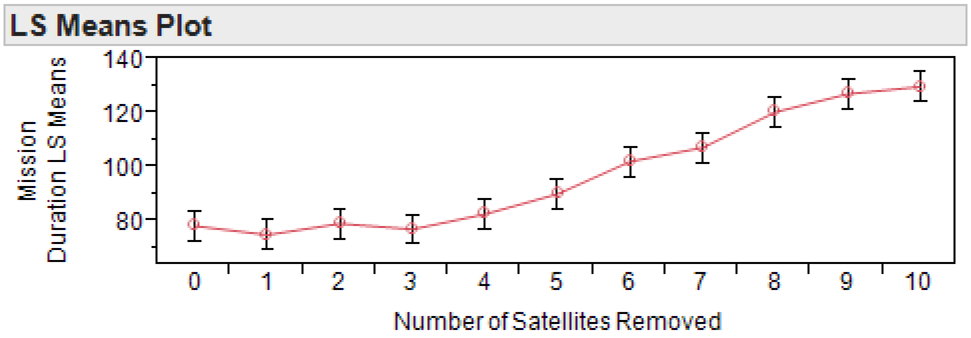


Figure 12. Mission Duration Tukey Test Results

There are several unique groupings displayed in the Tukey test results for the duration model. The first grouping displays that removing eight, nine, or ten satellites produces statistically similar outputs that are statistically different from the remaining levels of satellites removed. Other groupings occur for six and seven satellite removals along with the remaining zero through five satellite removals. Each of the groupings indicate specific threshold values for the levels that will generate the same response. For example, the GPS constellation could lose from zero to five satellites and experience the same impact to mission duration. However, once a sixth satellite is removed, then the GPS constellation experiences degradation leading to an extended missions duration above 100 minutes on average. If more than seven satellites are removed, then mission duration increase to 120 minutes on average. As a result, the different threshold levels provide information into satellite resiliency.

Similar insight is attained from the Tukey plots from each of the ANOVA models. The results from the Tukey test for the number of casualties response are shown in Figure 13.

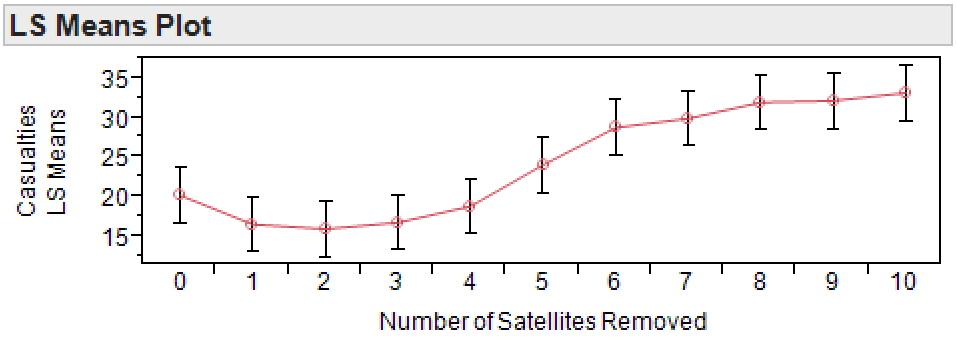


Figure 13. Casualties Tukey Test Results

The most important shift observed in Figure 13 is the jump around five satellites removed. The grouping of satellite removals from zero to four reports below 20 casualties on average whereas the group from six to ten report near 30 casualties. As a result, the threshold level is the removal of five satellites where the GPS constellation is resilient in terms of the number of casualties.

The results from the Tukey test for the number of engagements response are shown in Figure 14.

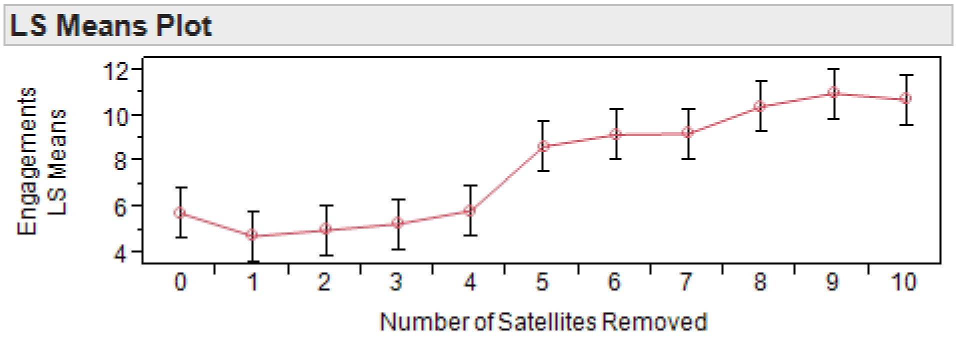


Figure 14. Engagements Tukey Test Results

There are two distinct groups identified in the Tukey test with the threshold located by removing five satellites. The average number of engagements appear to double in mean value once more than four satellites are removed. From the insight gained it is possible to conclude that the GPS constellation exhibits resiliency until more than four satellites are removed. As a result, maintaining the performance of the GPS constellation is achievable by ensuring that the number of satellites removed does not exceed four.

The results from the Tukey test for the percentage of time less than four GPS satellites are available response are shown in Figure 15.

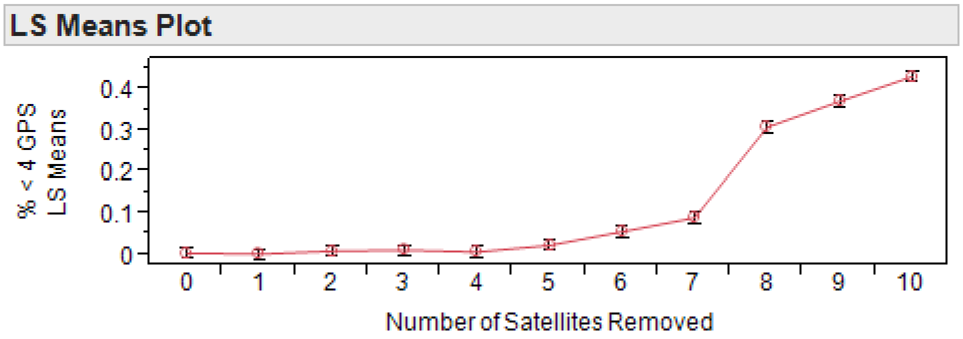


Figure 15. % < 4 GPS Tukey Test Results

As displayed in Figure 15, the width on the confidence interval is small with relation to the other Tukey plots. Additionally, removing zero through five satellites does not generate a significant difference in the percentage of time less than four GPS satellites are available. However, every additional satellite removed creates a different output for the response. As a result, the threshold value for resiliency is located at five satellites removed. Additionally, it is important to note that mitigating the number of satellites removed beyond five is important as each satellite removed creates a significant difference. Also worth consideration is a large jump between seven and eight satellite removals where the percentage of time less than four GPS satellites are available triples in value. Avoiding the loss of an extreme number of GPS satellites improves overall GPS constellation resiliency.

Each of the Tukey plots provide unique insight into the levels of the number of satellites removed factor and help identify the critical thresholds for assessing satellite resiliency. Across all of the Tukey plots, it appears as though losing more than five

GPS satellites leads to significant differences in the response variable. If the number of satellites lost can be kept below five, then it is possible to maintain response values that are similar to a scenario with zero satellites lost. The ability to operate in a degraded state with a number of satellites removed and still provide the initial metric values indicates that the GPS constellation is resilient. As a result, it is possible to conclude that the GPS constellation is resilient up to the removal of five satellites from the initial configuration.

4.7 Conclusion

Chapter 4 performs the analysis and interprets the results as they pertain to GPS constellation resiliency. The initial analysis is used to gain a first perspective into the output data from a series of design points. The p-values from the Paired T test and confidence intervals reveal that mission duration, number of casualties, number of engagements, and the percentage of time less than four GPS satellites are available are sensitive to the factors. Furthermore, an increased number of satellites removed appears to increase the sensitivity of the metrics and create statistically significant differences. Completing the remaining production runs enables the graphical analysis of the output data. Several of the confidence interval graphs display trends along with threshold values to statistically significant differences in the metric. Additionally, graphs of the data as satellites are removed show exponential trends in the number the satellites available along with a sharp decrease in the P_{50} metric. Finally, a formal ANOVA model for each response variable is generated which provides insight into the significance of the effects. In general, the ANOVA models pass the assumption tests along with providing significance p-values for each of the factors. The most compelling takeaway from Chapter 4 are the results from the pairwise Tukey Test between the levels of the number of satellites removed. It is evident in each of the four selected metrics that there is a threshold value once five satellites have been removed. As soon as a sixth satellite is removed the metrics register a significant difference in value. As a result, it is possible to conclude that the GPS constellation provides the highest level of performance and exhibits resiliency until five satellites have been removed, at which point the GPS constellation experiences a significant decrease in performance, both statistically and practically. Chapter 5 contains a summary of the most important results from the analysis along with areas for further research.

V. CONCLUSIONS

5.1 Overview

Chapter 5 concludes the study on GPS constellation resiliency. The chapter focuses on the contributions provided through the Methodology along with a summary of the important insights from the analysis. Each of the insights provide evidence that supports the conclusion on the GPS constellation resiliency. Chapter 5 also details areas for further research that provide more insight and refinement into the assessment of satellite resiliency. The chapter concludes with a conclusion for the study.

5.2 Contributions and Analysis Conclusions

Assessing satellite resiliency is a recent topic that has gained traction due to the increasing availability of threats and our increasing dependency on space assets. Due to the new emphasis, there are only a few studies which model and assess satellite constellation resiliency. Our research specifically focuses on the resiliency of the GPS constellation in an urban canyon environment. Additionally, the research provides a new perspective for modeling satellite constellation resiliency by using the agent-based SEAS program and collecting metrics from a top level mission viewpoint. Traditional studies on the GPS constellation have a technical perspective where the specific GPS parameters, such as position dilution of precision (PDOP), are compared across degraded scenarios. In reality, however, what might be a statistically significant difference between the PDOP in a scenario comparison, might not actually impact the mission in which the GPS constellation is supporting. Instead, by using an agent-based model and capturing top level mission metrics, the SOF team in our model can stochastically respond to a degraded GPS constellation to determine if there is an impact to the overall mission. While there is not one definitive metric for resiliency as noted during the Literature Review, a compilation of output statistics provide insight into constellation resiliency. Each of the selected metrics connect back to the mission priorities which include minimizing casualties, duration, engagements, and the percentage of time less than four GPS satellites are available. Furthermore, the logic within the SEAS warfile has been adapted to provide degradation to the GPS constellation performance with the removal of satellites. As a result, the research provides a new methodology for future studies into satellite constellation resiliency.

To further strengthen the study, the analysis is given statistical rigor through difference hypothesis tests and confidence intervals. The initial analysis reveals that the model is sensitive to a large increase in the number of satellites removed from the simulation. Furthermore, it appears as though the majority of the impact to the metrics occurs between five and ten satellites removed which indicates that degraded GPS performance may have an non linear impact with an increase in satellites removed. It is also evident from the full production run data that mission duration is highly impacted by removing satellites as shown in Figure 6. Additionally, the mission duration is also increased in the "Degraded" operations. Similar results are shown with the number of engagements and casualties in Figures 7 and 8 respectfully. Another important conclusion is the large disparity between the type of operations and the low values for the P_{50} metric as shown in Figure 11. All of the initial statistical conclusions confirm intuition that the top level mission statistics are highly impacted by a large loss of GPS satellites.

The designed experiment and ANOVA also support the conclusion that reducing the number of GPS satellites significantly impacts the response variables. Each of the ANOVA results are summarized in Table 13 which shows that the mission duration and percentage of time that there are less than four GPS satellites available are the strongest models in terms of R^2-adj. Furthermore, it appears as though the number of satellites removed is a significant factor for all of the responses. The key insight gained from the ANOVA models is found in the series of Tukey tests on the number of satellites removed for each of the models. Tukey's test clearly indicates a threshold value near five satellites removed where the metrics experience a significant shift in response values. The significant difference indicates that the GPS constellation is exhibiting resiliency even though several satellites have been removed from the model. As a result, the designed experiment provides further support for the initial analysis along with the most compelling insights into satellite resiliency.

The analysis suggests that the GPS constellation in our scenario does exhibit resiliency in a degraded urban canyon environment. The ability to provide statistically similar model output metrics indicates that even though the GPS specific parameters are degraded, the overall mission performance is not impacted. This finding connects directly back to the selected definition of resiliency from AFSPC which is, "the ability of a system architecture to continue providing required capabilities in the face of system failures, environmental challenges, or adversary action" [3]. We believe the resiliency of the GPS constellation is inherent in the constellation design which has nearly a dozen satellites initially over the area of interest. The large number of satellites over the area of interest is due to the global coverage pattern of the constellation which provides a large amount of overlap. While the GPS constellation does exhibit resiliency, it is not resilient beyond the loss of five satellites. The Tukey plots, Paired T tests, and confidence intervals support this conclusion by indicating a quickly changing negative impact in the response metrics after more than five satellites are lost. Additionally, as noted in the initial analysis, if nearly all of the satellites initially available are removed from the scenario, then the GPS constellation does not provide instantaneous resiliency for a short mission duration. Instead, a longer mission would be able to recover as soon as the remaining GPS satellites pass over the area of interest. Furthermore, it is important to note that the threshold value near five satellites lost and conclusions developed throughout the analysis are heavily dependent upon the GPS Unit logic in the SEAS warfile. As a result, policy considerations on the resiliency of the GPS constellation require more specific study. Nevertheless, the empirical evidence indicates that the GPS constellation is resilient.

5.3 Future Research

There are several areas for further research found in the GPS Unit logic structure, the factors included in the designed experiment, the geometry of the the GPS satellites, and the satellite constellation under consideration. It is important to remember that this study is purely for education purposes and does not contain any sensitive parameters which limits the model validity. Additionally, due to time constants, the current study did not permit significant changes to the provided SEAS model. As a result, there are several areas in which the research can be expanded and further developed.

One area for further research is the sensitivity of the GPS Unit logic structure in the SEAS warfile. We developed a logic structure without any direct references that at face value appears reasonable. However, it is highly likely that further investigation into the accuracy and availability of the GPS constellation will provide a different logic structure. If the desire is to keep the research unclassified, then sensitivity analysis can be performed by providing a series of different logic structures to the GPS Unit. Then by replicating the analysis performed in this study over each of the new logic structures it is possible to provide insight into the impact of the factors along with determining a resiliency threshold value. Further refinement of the logic structure is essential for adding more credibility to the study.

Another area for further research includes incorporating additional factors to the designed experiment. It was evident that the $R^2 - adj$ values did not perform as desired for the number of casualties and engagement responses. An example of an additional factor is examining the level of degradation as the SOF team is closer to the buildings. While additional factors appear to be a straight forward improvement, selecting factors which are directly connected to the GPS constellation and implementing them into the warfile is a challenge. Nevertheless, investigating further factors is worth the added effort in order to identify the most important pieces for attaining satellite resiliency.

As noted by Bell's thesis in the Literature Review, the geometry of the satellites is important to GPS capability instead of just the number of satellites in view. For example, a fewer number of satellite with a better geometry provides better accuracy for the GPS reciever. Currently there is not a geolocation algorithm provided in the SEAS warfile. Implementation of the geolocation algorithm may be challenging within SEAS, however, successful implementation provides a more accurate model along a new source of metrics for analysis. We highly suggest adding a geolocation algorithm as an area for further research.

A final area for further research is to model different satellites constellations. The GPS constellation is inherently resilient due to its number of satellites in several difference planes. Other constellations, however, are not as diverse and may not be able to provide the same capabilities under degraded scenarios. Furthermore, other constellations provide unique capabilities which requires a different model with different metrics to assess resiliency. Nevertheless, constellation resiliency is crucial for all of our space systems and is worth the added effort.

5.4 Conclusion

Satellite constellation resiliency is an important consideration moving forward. Both current operational decisions and future programmatic purchases should focus on selecting the constellation that will continue to provide the necessary capabilities even in a contested environment. The methods and metrics for assessing satellite resiliency are vital to ensuring that the analysis is directed properly and provides relevant information. We have provide one method and set of metrics for assessing the resiliency of the crucial GPS constellation in a challenging and degraded environment. While our results do indicate that the GPS constellation exhibits resiliency, the required capabilities are negatively impacted after the loss of multiple satellites. Further refinement of the study is required through either sensitivity analysis on the logic structure or a more complex designed experiment in order to provide more definitive guidance to decision makers. Also, adding a geolocation algorithm is also an important aspect of the warfile for strengthening the validity of the model. In addition, the methodology can be applied to other satellite constellations in order to reveal the hidden strengths and weaknesses of our space assets. Ensuring resiliency for all of our satellite constellations is necessary for current and future operations in an effort to maintain national security.

Appendix A. ANOVA ASSUMPTIONS AND MODELS

1.1 Normal Probability Plots

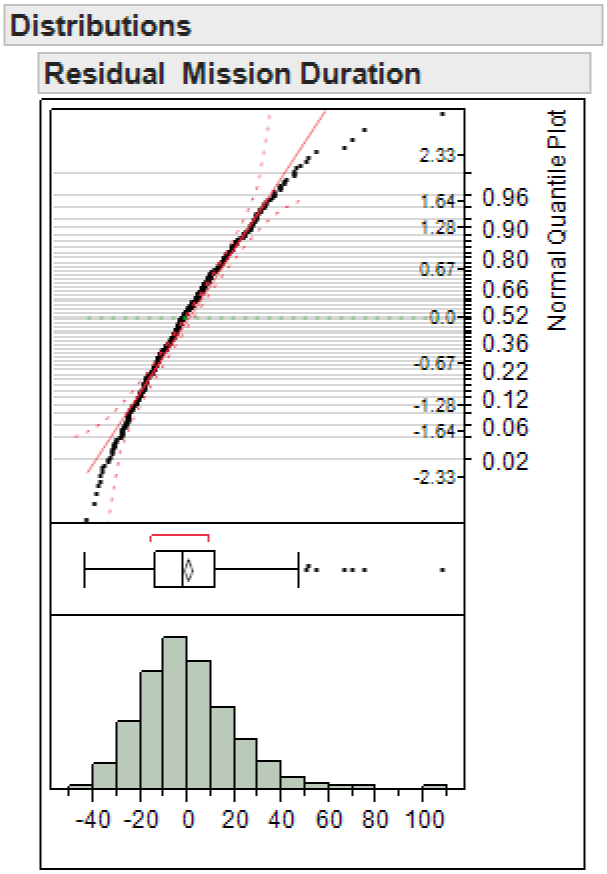


Figure 16. Mission Duration Normal Probability Plot

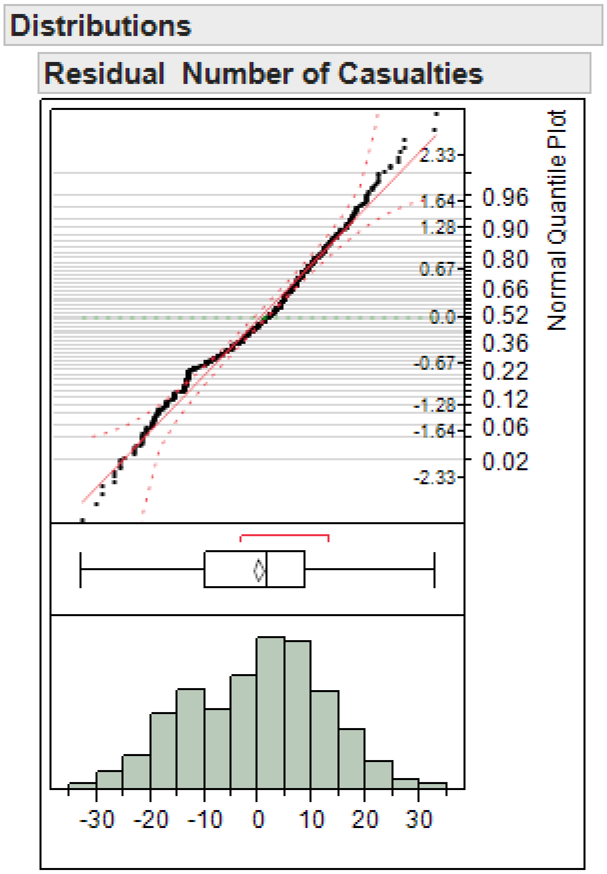


Figure 17. Number of Casualties Normal Probability Plot

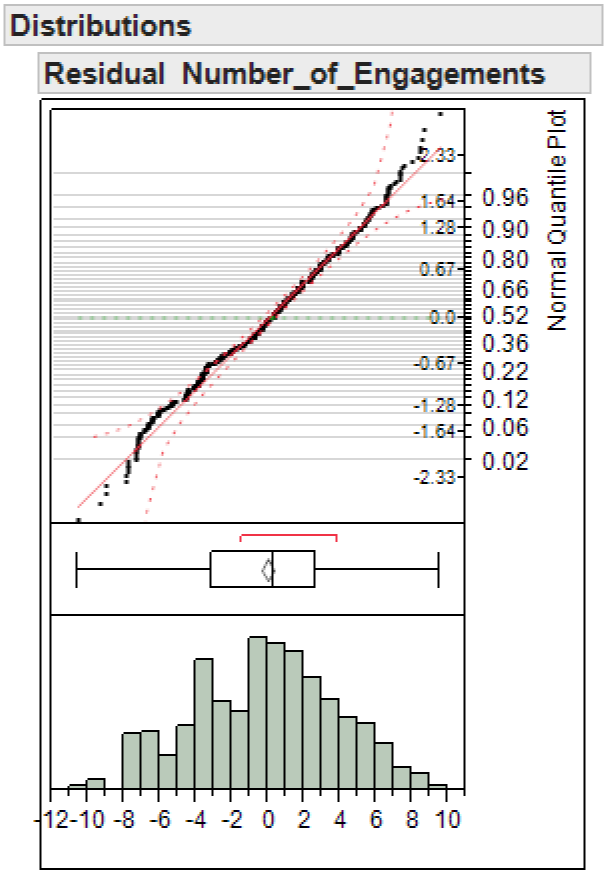


Figure 18. Number of Engagements Normal Probability Plot

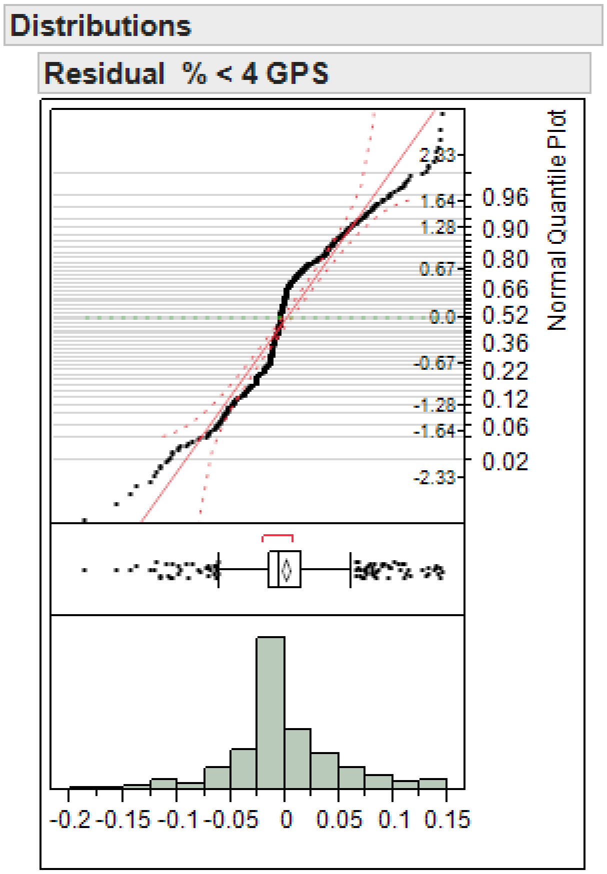


Figure 19. % < 4 GPS Normal Probability Plot

1.2 Residual vs Predicted Plots

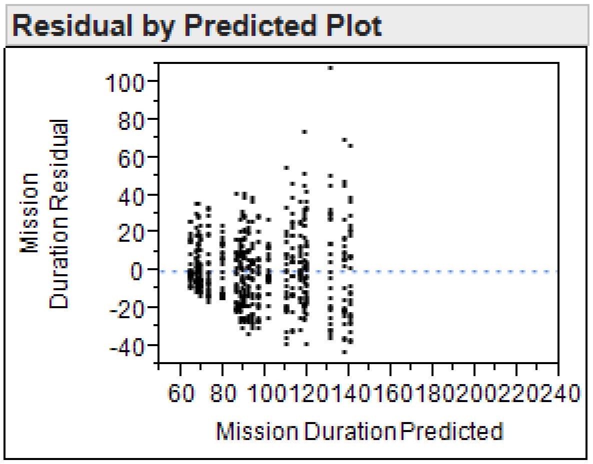


Figure 20. Mission Duration Residual vs Predicted Plot

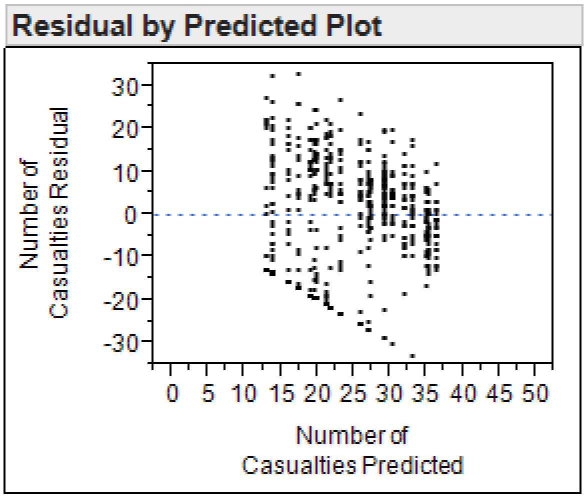


Figure 21. Number of Casualties Residual vs Predicted Plot

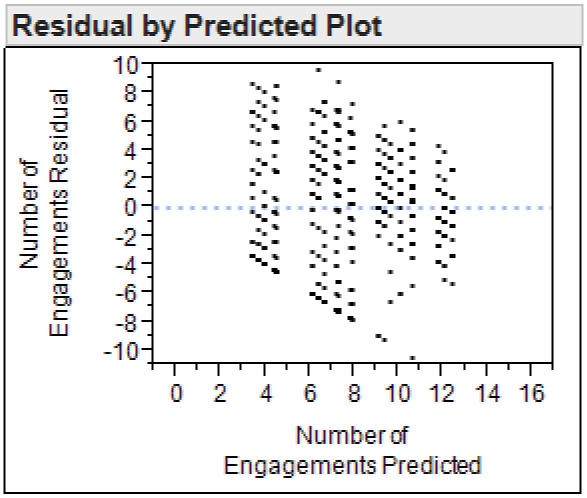


Figure 22. Number of Engagements Residual vs Predicted Plot

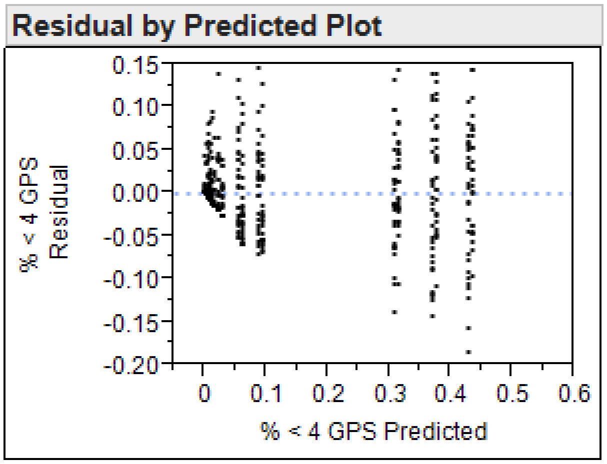


Figure 23. % < 4 GPS Residual vs Predicted Plot

1.3 Residual vs Variable Plots

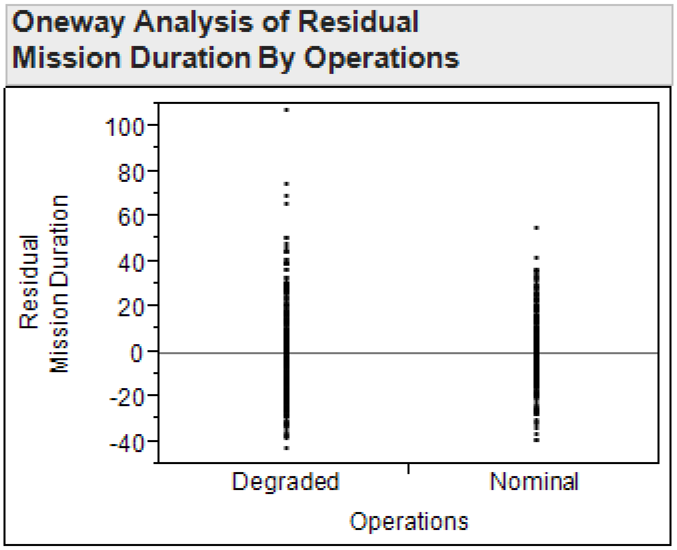


Figure 24. Mission Duration Residual vs Operations Plot

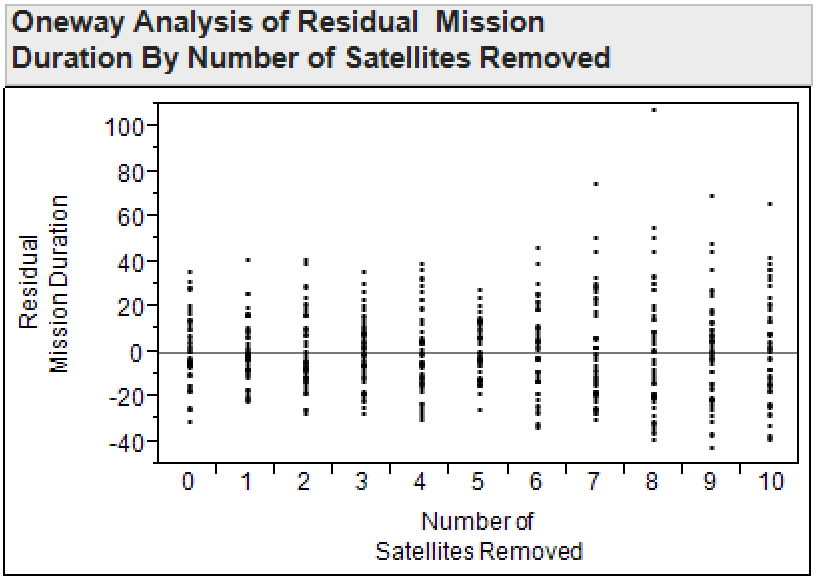


Figure 25. Mission Duration Residual vs Number of Satellites Removed Plot

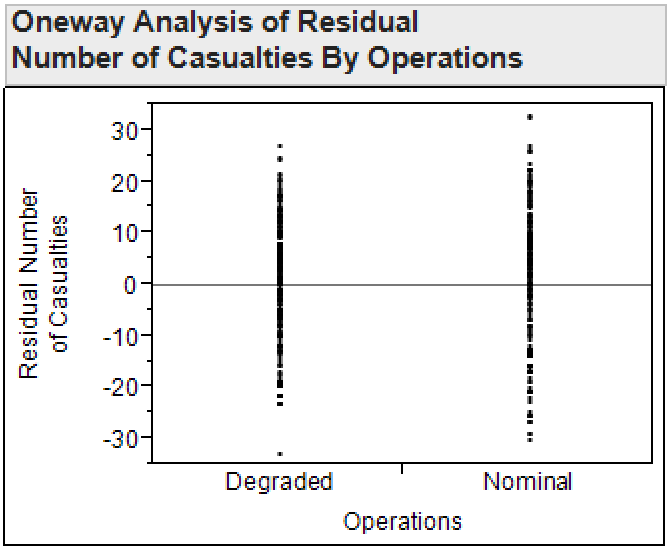


Figure 26. Number of Casualties Residual vs Operations Plot

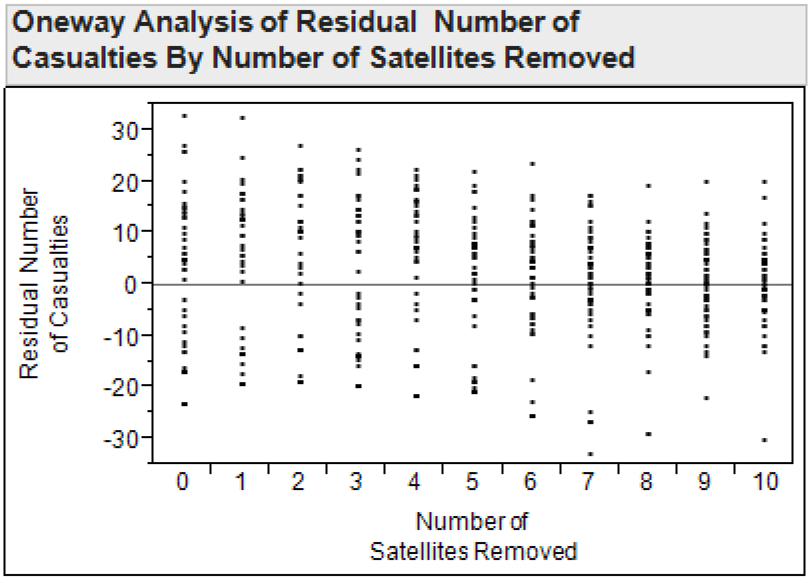


Figure 27. Number of Casualties Residual vs Number of Satellites Removed Plot

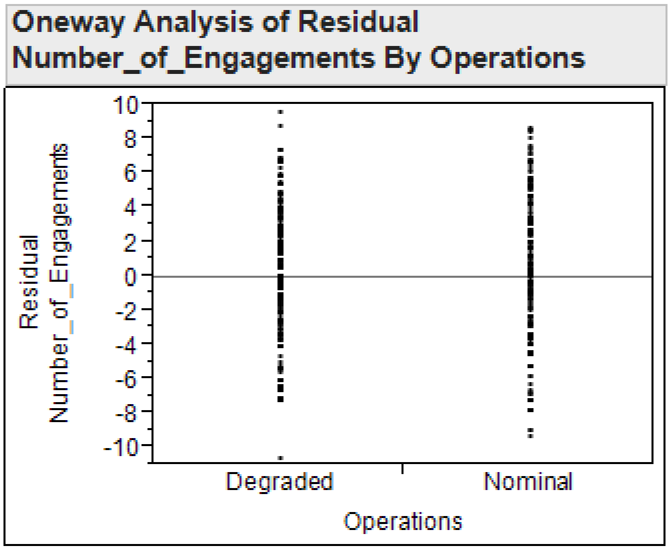


Figure 28. Number of Engagements Residual vs Operations Plot

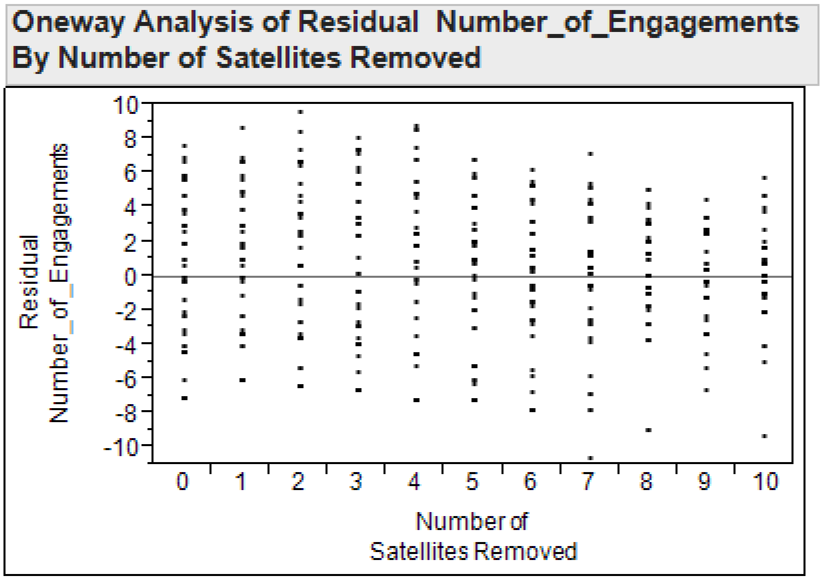


Figure 29. Number of Engagements Residual vs Number of Satellites Removed Plot

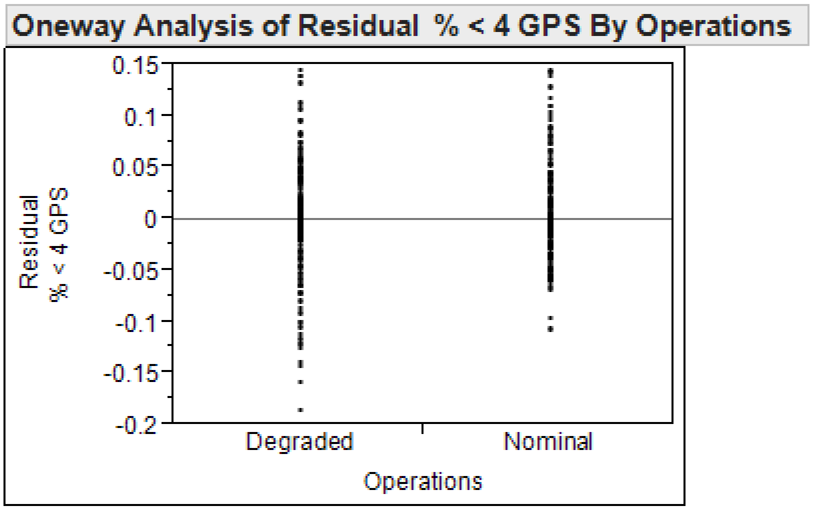


Figure 30. % < 4 GPS Residual vs Operations Plot

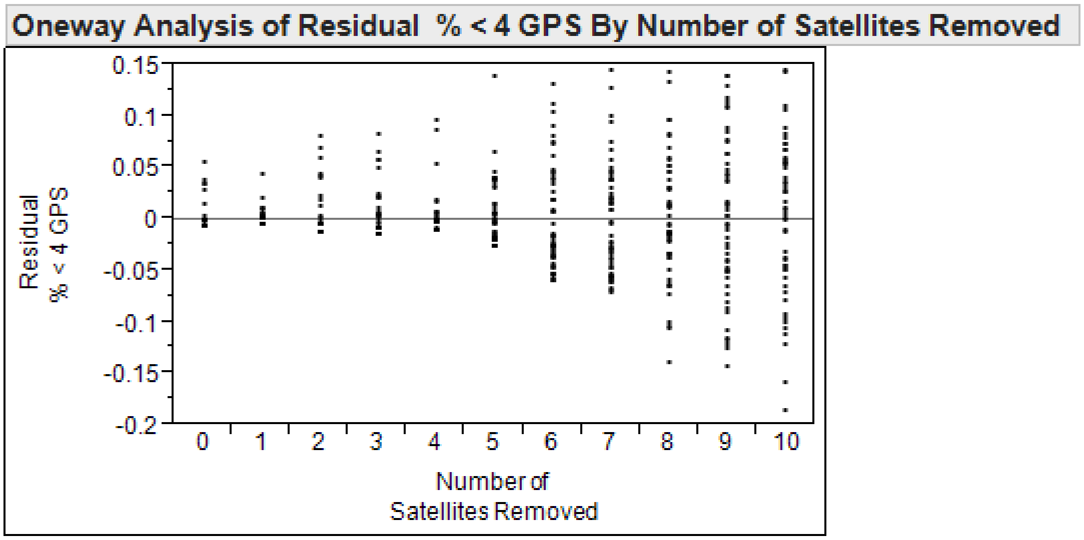
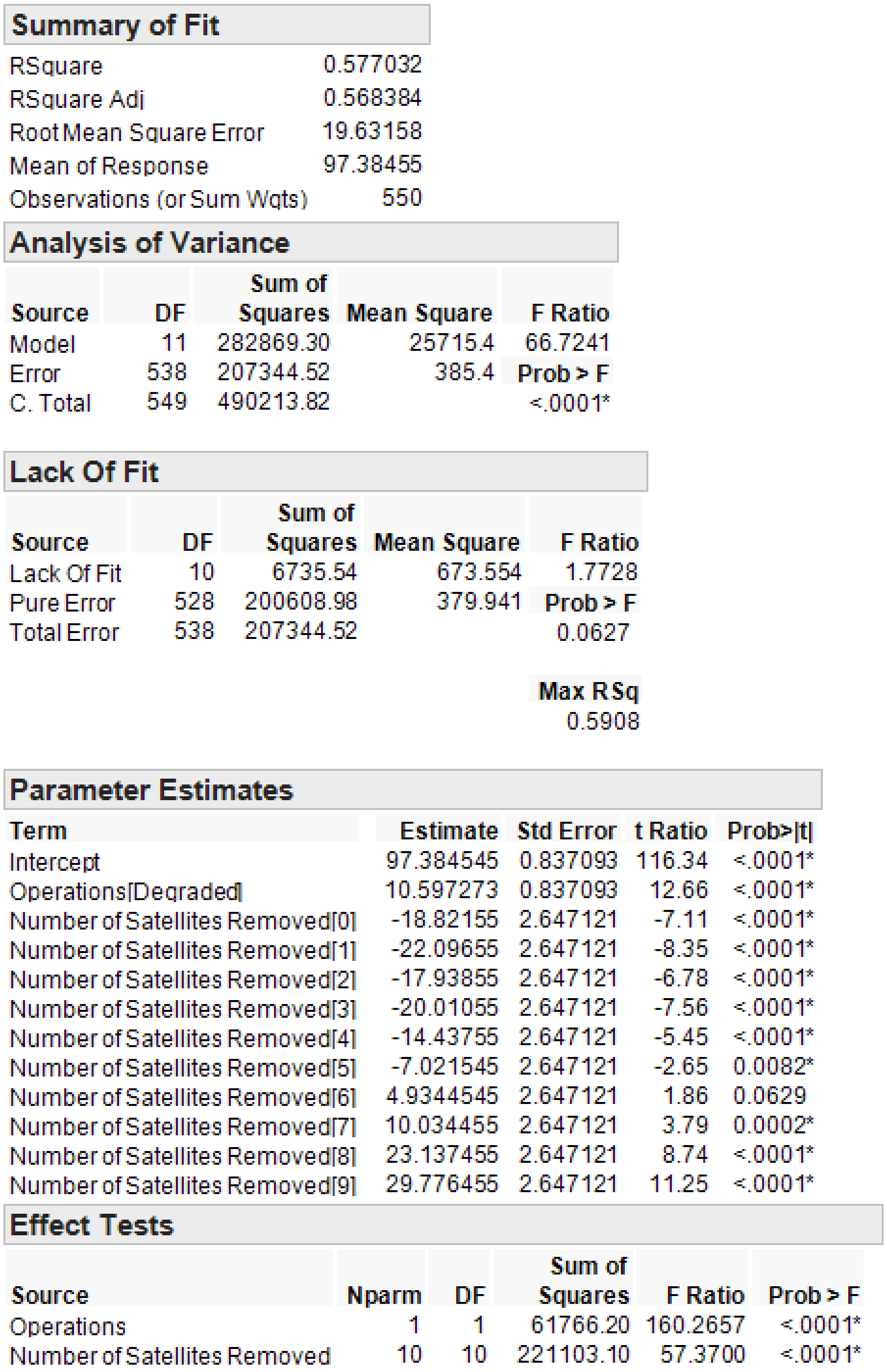


Figure 31. % < 4 GPS Residual vs Number of Satellites Removed Plot

1.4 Model Statistics

Mission Duration Model.



Summary of Fit

RSquare	0.577032
RSquare Adj	0.568384
Root Mean Square Error	19.63158
Mean of Response	97.38455
Observations (or Sum Wgts)	550

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	11	282869.30	25715.4	66.7241
Error	538	207344.52	385.4	**Prob > F**
C. Total	549	490213.82		<.0001*

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	10	6735.54	673.554	1.7728
Pure Error	528	200608.98	379.941	**Prob > F**
Total Error	538	207344.52		0.0627
				Max RSq
				0.5908

Parameter Estimates

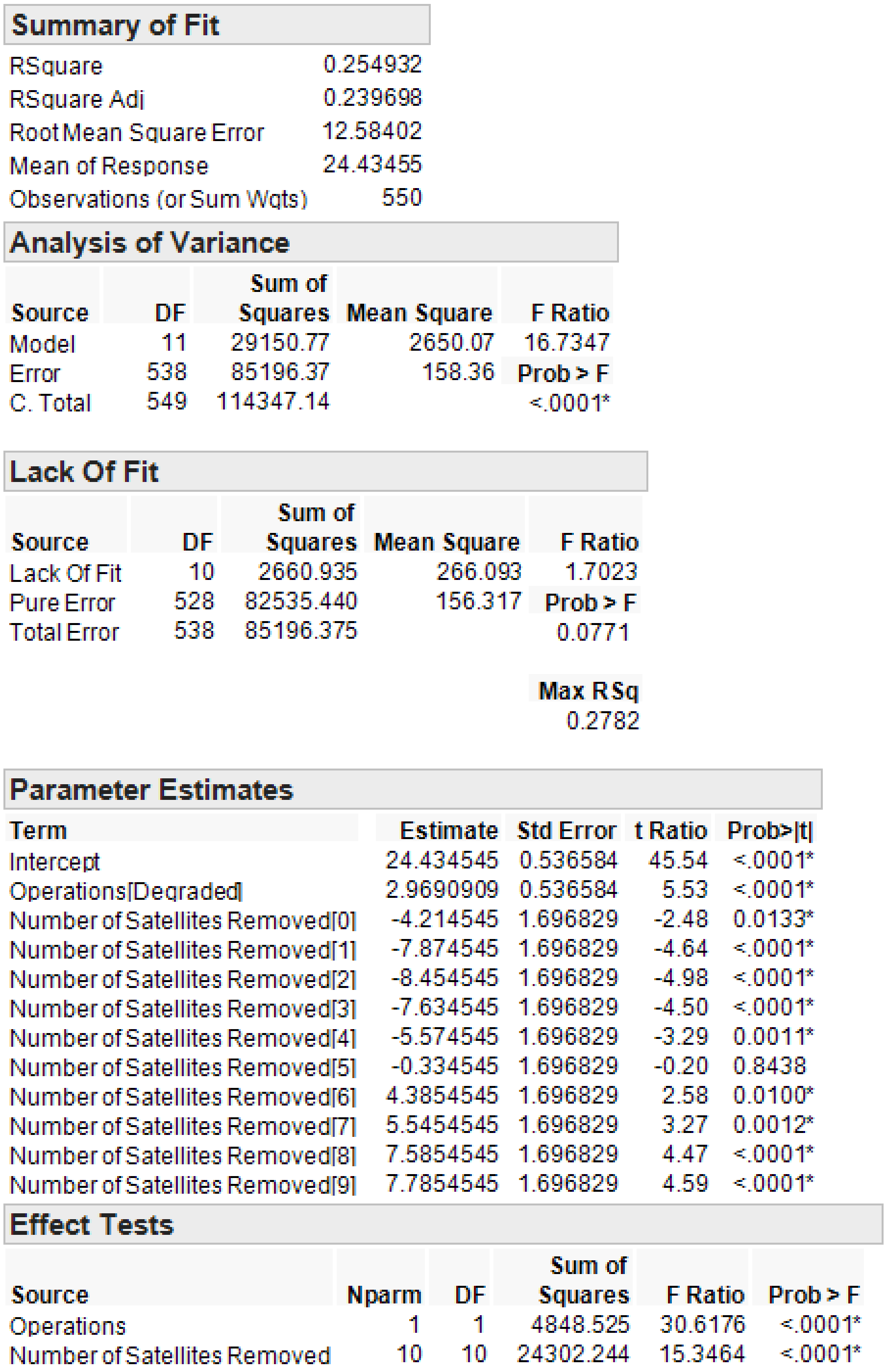
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	97.384545	0.837093	116.34	<.0001*
Operations[Degraded]	10.597273	0.837093	12.66	<.0001*
Number of Satellites Removed[0]	-18.82155	2.647121	-7.11	<.0001*
Number of Satellites Removed[1]	-22.09655	2.647121	-8.35	<.0001*
Number of Satellites Removed[2]	-17.93855	2.647121	-6.78	<.0001*
Number of Satellites Removed[3]	-20.01055	2.647121	-7.56	<.0001*
Number of Satellites Removed[4]	-14.43755	2.647121	-5.45	<.0001*
Number of Satellites Removed[5]	-7.021545	2.647121	-2.65	0.0082*
Number of Satellites Removed[6]	4.9344545	2.647121	1.86	0.0629
Number of Satellites Removed[7]	10.034455	2.647121	3.79	0.0002*
Number of Satellites Removed[8]	23.137455	2.647121	8.74	<.0001*
Number of Satellites Removed[9]	29.776455	2.647121	11.25	<.0001*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Operations	1	1	61766.20	160.2657	<.0001*
Number of Satellites Removed	10	10	221103.10	57.3700	<.0001*

Figure 32. Mission Duration Model Statistics

Number of Casualties Model.



Summary of Fit

RSquare	0.254932
RSquare Adj	0.239698
Root Mean Square Error	12.58402
Mean of Response	24.43455
Observations (or Sum Wgts)	550

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	11	29150.77	2650.07	16.7347
Error	538	85196.37	158.36	**Prob > F**
C. Total	549	114347.14		<.0001*

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	10	2660.935	266.093	1.7023
Pure Error	528	82535.440	156.317	**Prob > F**
Total Error	538	85196.375		0.0771
				Max RSq
				0.2782

Parameter Estimates

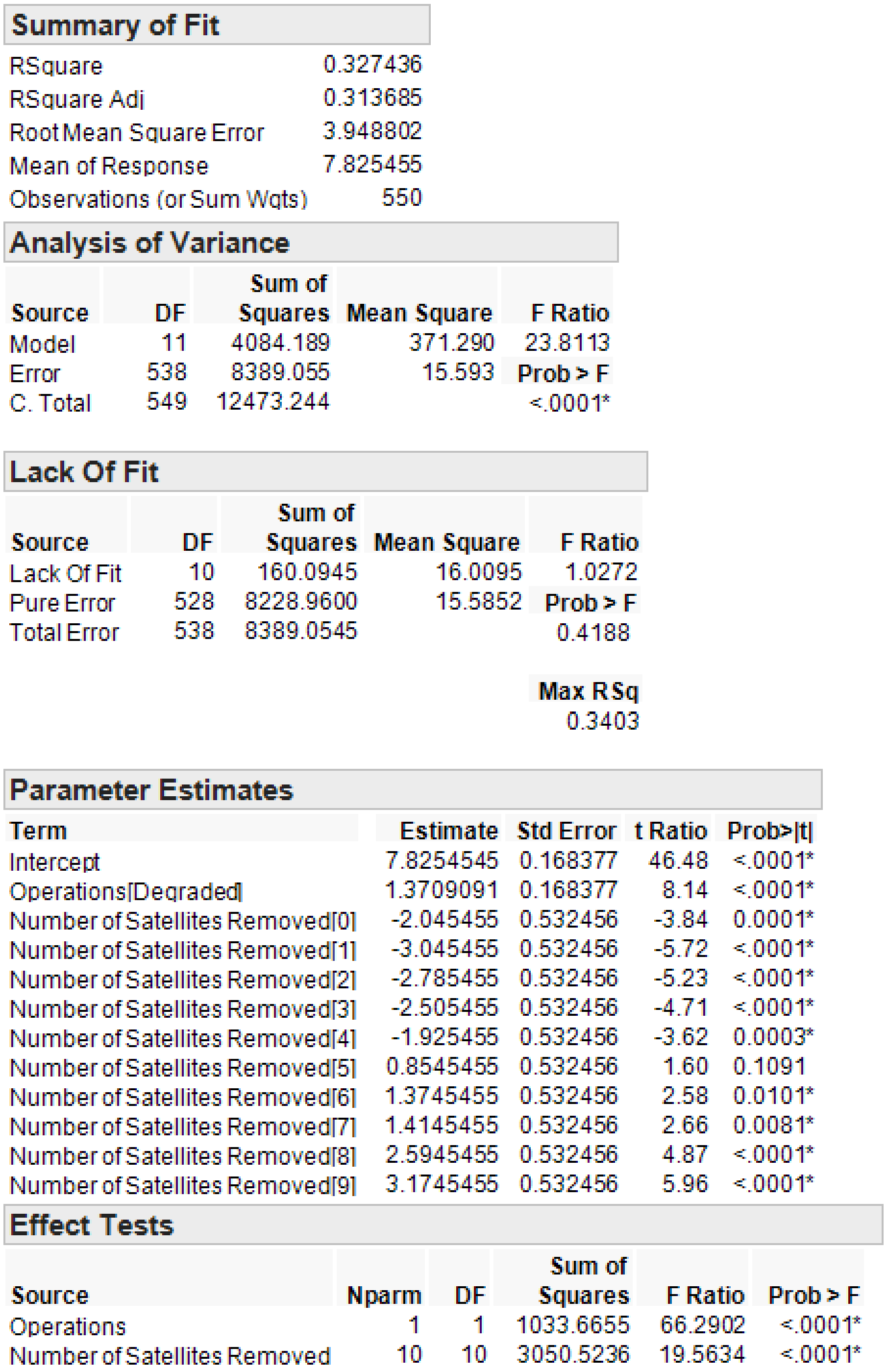
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	24.434545	0.536584	45.54	<.0001*
Operations[Degraded]	2.9690909	0.536584	5.53	<.0001*
Number of Satellites Removed[0]	-4.214545	1.696829	-2.48	0.0133*
Number of Satellites Removed[1]	-7.874545	1.696829	-4.64	<.0001*
Number of Satellites Removed[2]	-8.454545	1.696829	-4.98	<.0001*
Number of Satellites Removed[3]	-7.634545	1.696829	-4.50	<.0001*
Number of Satellites Removed[4]	-5.574545	1.696829	-3.29	0.0011*
Number of Satellites Removed[5]	-0.334545	1.696829	-0.20	0.8438
Number of Satellites Removed[6]	4.3854545	1.696829	2.58	0.0100*
Number of Satellites Removed[7]	5.5454545	1.696829	3.27	0.0012*
Number of Satellites Removed[8]	7.5854545	1.696829	4.47	<.0001*
Number of Satellites Removed[9]	7.7854545	1.696829	4.59	<.0001*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Operations	1	1	4848.525	30.6176	<.0001*
Number of Satellites Removed	10	10	24302.244	15.3464	<.0001*

Figure 33. Number of Casualties Model Statistics

Number of Engagements Model.



Summary of Fit

RSquare	0.327436
RSquare Adj	0.313685
Root Mean Square Error	3.948802
Mean of Response	7.825455
Observations (or Sum Wgts)	550

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	11	4084.189	371.290	23.8113
Error	538	8389.055	15.593	Prob > F
C. Total	549	12473.244		<.0001*

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	10	160.0945	16.0095	1.0272
Pure Error	528	8228.9600	15.5852	Prob > F
Total Error	538	8389.0545		0.4188
				Max RSq
				0.3403

Parameter Estimates

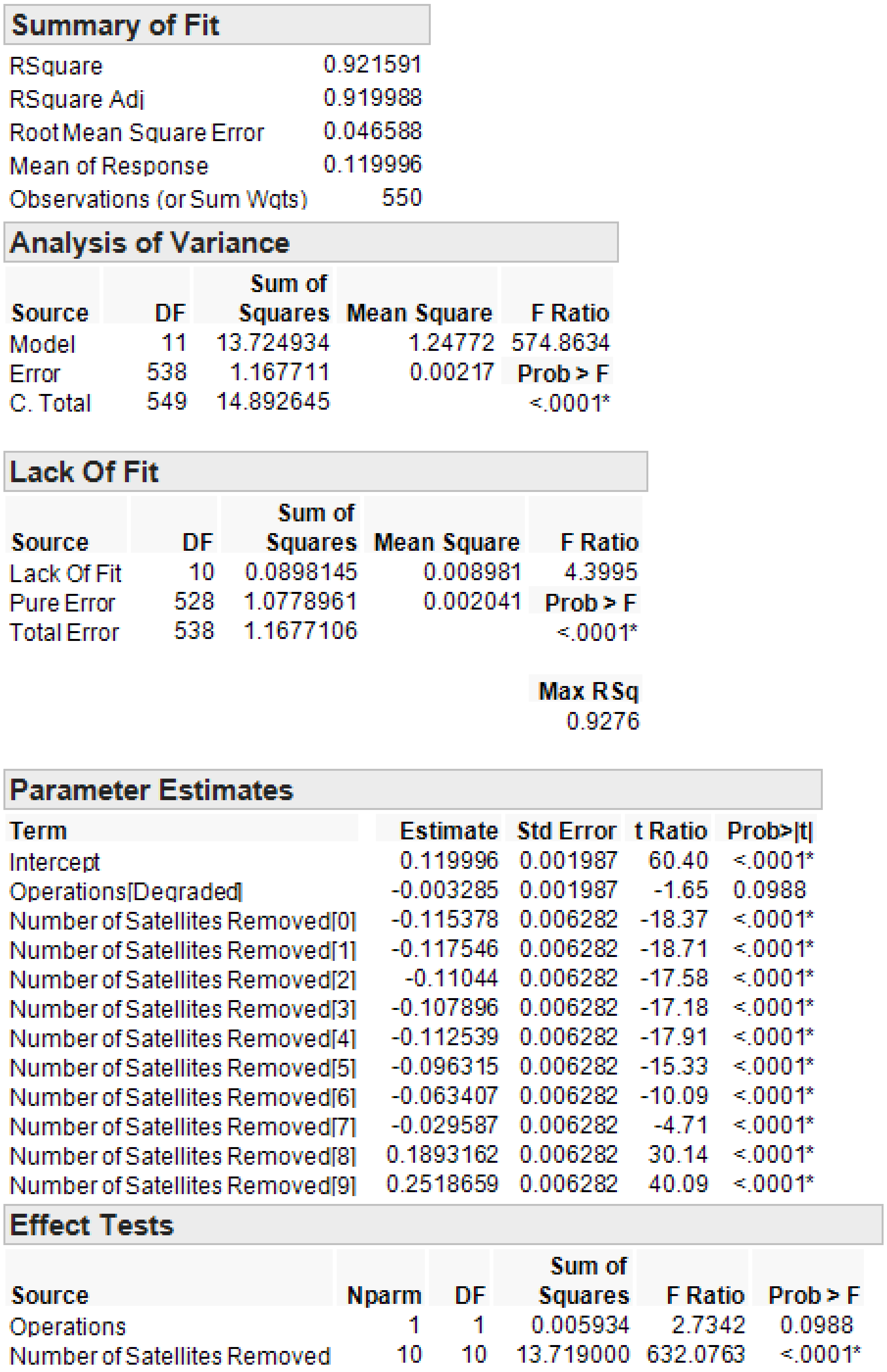
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	7.8254545	0.168377	46.48	<.0001*
Operations[Degraded]	1.3709091	0.168377	8.14	<.0001*
Number of Satellites Removed[0]	-2.045455	0.532456	-3.84	0.0001*
Number of Satellites Removed[1]	-3.045455	0.532456	-5.72	<.0001*
Number of Satellites Removed[2]	-2.785455	0.532456	-5.23	<.0001*
Number of Satellites Removed[3]	-2.505455	0.532456	-4.71	<.0001*
Number of Satellites Removed[4]	-1.925455	0.532456	-3.62	0.0003*
Number of Satellites Removed[5]	0.8545455	0.532456	1.60	0.1091
Number of Satellites Removed[6]	1.3745455	0.532456	2.58	0.0101*
Number of Satellites Removed[7]	1.4145455	0.532456	2.66	0.0081*
Number of Satellites Removed[8]	2.5945455	0.532456	4.87	<.0001*
Number of Satellites Removed[9]	3.1745455	0.532456	5.96	<.0001*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Operations	1	1	1033.6655	66.2902	<.0001*
Number of Satellites Removed	10	10	3050.5236	19.5634	<.0001*

Figure 34. Number of Engagements Model Statistics

Percentage of Time < 4 GPS Available Model.



Summary of Fit

RSquare	0.921591
RSquare Adj	0.919988
Root Mean Square Error	0.046588
Mean of Response	0.119996
Observations (or Sum Wgts)	550

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	11	13.724934	1.24772	574.8634
Error	538	1.167711	0.00217	**Prob > F**
C. Total	549	14.892645		<.0001*

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	10	0.0898145	0.008981	4.3995
Pure Error	528	1.0778961	0.002041	**Prob > F**
Total Error	538	1.1677106		<.0001*
				Max RSq
				0.9276

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.119996	0.001987	60.40	<.0001*
Operations[Degraded]	-0.003285	0.001987	-1.65	0.0988
Number of Satellites Removed[0]	-0.115378	0.006282	-18.37	<.0001*
Number of Satellites Removed[1]	-0.117546	0.006282	-18.71	<.0001*
Number of Satellites Removed[2]	-0.11044	0.006282	-17.58	<.0001*
Number of Satellites Removed[3]	-0.107896	0.006282	-17.18	<.0001*
Number of Satellites Removed[4]	-0.112539	0.006282	-17.91	<.0001*
Number of Satellites Removed[5]	-0.096315	0.006282	-15.33	<.0001*
Number of Satellites Removed[6]	-0.063407	0.006282	-10.09	<.0001*
Number of Satellites Removed[7]	-0.029587	0.006282	-4.71	<.0001*
Number of Satellites Removed[8]	0.1893162	0.006282	30.14	<.0001*
Number of Satellites Removed[9]	0.2518659	0.006282	40.09	<.0001*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Operations	1	1	0.005934	2.7342	0.0988
Number of Satellites Removed	10	10	13.719000	632.0763	<.0001*

Figure 35. Percentage of Time < 4 GPS Model Statistics

Appendix B. ACRONYMS

ABMS = Agent-Based Modeling and Simulation

AFIT = Air Force Institute of Technology

AFSPC = Air Force Space Command

ANOVA = Analysis of Variance

ASAT = Anti-Satellite

CAS = Complex Adaptive System

DoD = Department of Defense

EPA = Environmental Protection Agency

GAO = Government Accountability Office

GEO = Geosynchronous Earth Orbit

GPS = Global Positioning System

HEO = Highly Elliptical Orbit

KPP = Key Performance Parameter

LEO = Low Earth Orbit

MOE = Measure of Effectiveness

MOO = Measure of Outcome

MOP = Measure of Performance

MUA = Military Utility Analysis

ORS = Operationally Responsive Space

PDOP = Position Dilution of Precision

PNT = Position, Navigation, and Timing

REAP = Resilient Enterprise Architecture Pathfinder

SEAS = System Effectiveness Analysis Simulation

SMC = Space and Missile Center

SOF = Special Operations Force

STK = Satellite Toolkit

TLE = Two Line Element

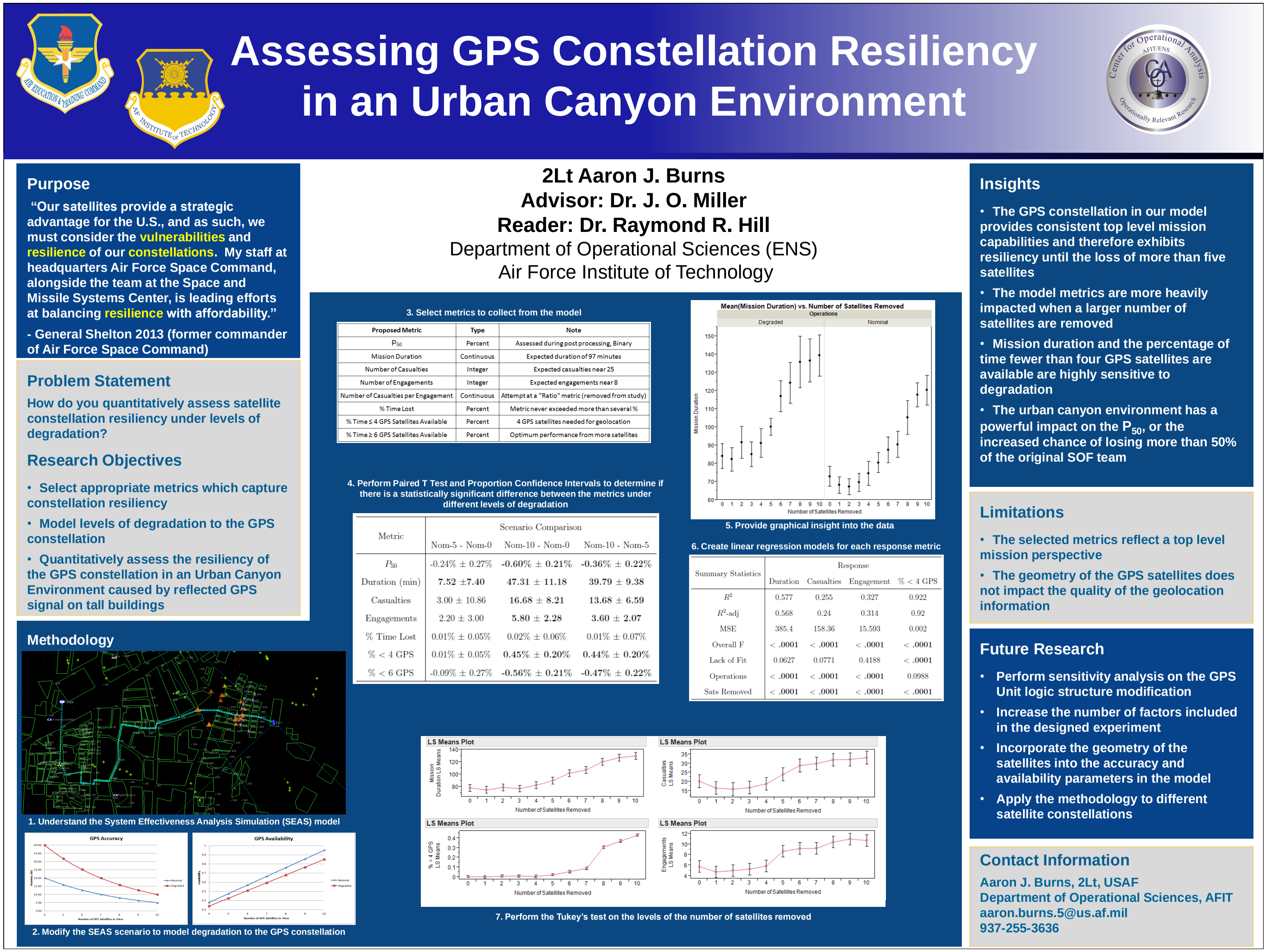
TPL = Tactical Programming Language

U.S. = United States

USAF = United States Air Force

WMD = Weapon of Mass Destruction

Appendix C. QUAD CHART



Assessing GPS Constellation Resiliency in an Urban Canyon Environment

2Lt Aaron J. Burns
Advisor: Dr. J. O. Miller
Reader: Dr. Raymond R. Hill
Department of Operational Sciences (ENS)
Air Force Institute of Technology

Purpose

"Our satellites provide a strategic advantage for the U.S., and as such, we must consider the vulnerabilities and resilience of our constellations. My staff at headquarters Air Force Space Command, alongside the team at the Space and Missile Systems Center, is leading efforts at balancing resilience with affordability."

- General Shelton 2013 (former commander of Air Force Space Command)

Problem Statement

How do you quantitatively assess satellite constellation resiliency under levels of degradation?

Research Objectives

- Select appropriate metrics which capture constellation resiliency
- Model levels of degradation to the GPS constellation
- Quantitatively assess the resiliency of the GPS constellation in an Urban Canyon Environment caused by reflected GPS signal on tall buildings

Methodology

1. Understand the System Effectiveness Analysis Simulation (SEAS) model

2. Modify the SEAS scenario to model degradation to the GPS constellation

3. Select metrics to collect from the model

Proposed Metric	Type	Note
P_{50}	Percent	Assessed during post processing, Binary
Mission Duration	Continuous	Expected duration of 97 minutes
Number of Casualties	Integer	Expected casualties near 25
Number of Engagements	Integer	Expected engagements near 8
Number of Casualties per Engagement	Continuous	Attempt at a "Ratio" metric (removed from study)
% Time Lost	Percent	Metric never exceeded more than several %
% Time ≤ 4 GPS Satellites Available	Percent	4 GPS satellites needed for geolocation
% Time ≥ 6 GPS Satellites Available	Percent	Optimum performance from more satellites

4. Perform Paired T Test and Proportion Confidence Intervals to determine if there is a statistically significant difference between the metrics under different levels of degradation

Metric	Scenario Comparison		
	Nom-5 - Nom-0	Nom-10 - Nom-0	Nom-10 - Nom-5
P_{50}	-0.24% ± 0.27%	**-0.60% ± 0.21%**	**-0.36% ± 0.22%**
Duration (min)	**7.52 ±7.40**	**47.31 ± 11.18**	**39.79 ± 9.38**
Casualties	3.00 ± 10.86	**16.68 ± 8.21**	**13.68 ± 6.59**
Engagements	2.20 ± 3.00	**5.80 ± 2.28**	**3.60 ± 2.07**
% Time Lost	0.01% ± 0.05%	0.02% ± 0.06%	0.01% ± 0.07%
% < 4 GPS	0.01% ± 0.05%	**0.45% ± 0.20%**	**0.44% ± 0.20%**
% < 6 GPS	-0.09% ± 0.27%	**-0.56% ± 0.21%**	**-0.47% ± 0.22%**

5. Provide graphical insight into the data

6. Create linear regression models for each response metric

Summary Statistics	Response			
	Duration	Casualties	Engagement	% < 4 GPS
R^2	0.577	0.255	0.327	0.922
R^2-adj	0.568	0.24	0.314	0.92
MSE	385.4	158.36	15.593	0.002
Overall F	< .0001	< .0001	< .0001	< .0001
Lack of Fit	0.0627	0.0771	0.4188	< .0001
Operations	< .0001	< .0001	< .0001	0.0988
Sats Removed	< .0001	< .0001	< .0001	< .0001

7. Perform the Tukey's test on the levels of the number of satellites removed

Insights

- The GPS constellation in our model provides consistent top level mission capabilities and therefore exhibits resiliency until the loss of more than five satellites
- The model metrics are more heavily impacted when a larger number of satellites are removed
- Mission duration and the percentage of time fewer than four GPS satellites are available are highly sensitive to degradation
- The urban canyon environment has a powerful impact on the P_{50}, or the increased chance of losing more than 50% of the original SOF team

Limitations

- The selected metrics reflect a top level mission perspective
- The geometry of the GPS satellites does not impact the quality of the geolocation information

Future Research

- Perform sensitivity analysis on the GPS Unit logic structure modification
- Increase the number of factors included in the designed experiment
- Incorporate the geometry of the satellites into the accuracy and availability parameters in the model
- Apply the methodology to different satellite constellations

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Figure 36. ENS Quad Chart

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14. ABSTRACT

Satellite constellation resiliency is an important consideration gaining momentum at the top levels of the Air Force and at Air Force Space Command (AFSPC). The increased availability of threats to satellite systems is challenging the capabilities provided by space assets. More specifically, the global positioning system (GPS) satellite constellation is utilized for a variety of missions, to include providing precise geolocation information for navigation. Any degrade in GPS capabilities as observed in an urban canyon environment or due to the loss of a GPS satellite may hinder the overall mission. We use the System Effectiveness Analysis Simulation (SEAS) to model the GPS constellation in an urban canyon environment which provides information to a special operation force (SOF) in their effort to recover a weapon of mass destruction (WMD). By varying the type of operations and the number of satellites lost in the simulation, insight is gained into the impact of degradation through the selected top level mission metrics. A series of statistical difference tests and a designed experiment reveal a resiliency threshold on the number of satellites removed from the constellation. As a result, we conclude that the GPS constellation is resilient even after the loss of several satellites.

15. SUBJECT TERMS

System Effectiveness Analysis Simulation (SEAS), satellite constellation resiliency, agent-based modeling, global positioning system (GPS), urban canyon environment, weapon of mass destruction (WMD)

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