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USING SEAS TO ASSESS 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. We use the System Effectiveness Analysis Simulation (SEAS) to model the Global Positioning System (GPS) constellation in an urban canyon environment. The GPS 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. 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.

1 INTRODUCTION

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. 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 [Anti-Satellite] 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” (Buckerfield de la Roche 2011). U.S. satellite systems must be robust to these threats to ensure national security.

Acting Air Force secretary Eric Fanning also recognizes the vulnerability of our military space systems (Host 2013). He asserts the need for, “new strategies and new architectures for space to try to increase resilience” (Host 2013). General Shelton, former commander of AFSPC, echoes Mr. Fanning's request for an increase in satellite constellation resiliency in 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 (Air Force Space Command 2013).

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As a result, the Space and Missile Center (SMC) of the United States Air Force (USAF) has begun research into space system resiliency analysis. The results from the resiliency research will have far-reaching implications that will affect 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.

The goal of this paper is to demonstrate a methodology for GPS satellite constellation resiliency analysis in an urban canyon environment. Resiliency is assessed by using quantitative metrics captured from a scenario modeled in SEAS. The metrics selected reflect overall top level mission priorities and are primarily drawn from the suggested measures found in the background research along with the capabilities of SEAS. Furthermore, insight from the metrics is gained with statistical confidence intervals and a designed experiment.

The paper beings with some background on resiliency, GPS type satellites constellations, and SEAS. We describe our scenario and modifications made to capture resiliency for our simulation study. Results and analysis are presented along with suggestions for future research.

2 BACKGROUND

2.1 Resiliency

There are an array of different definitions and applications for resiliency ranging from ecology to economics (Reid 2013). As a result, it is important to select the correct definition of resiliency that is specific to space systems. Fortunately, AFSPC 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” (Air Force Space Command 2013). We use AFSPC's definition of resiliency for the remainder of the paper.

Investigation into space system resiliency is a new area of study being explored by a number of researchers including Northrop Grumman Aerospace Systems and the Air Force Institute of Technology (AFIT). 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. A more detailed engineering level GPS constellation analysis by Bell (2010) focuses specifically on how best to augment the current GPS constellation to retain its performance under degradation. The principle metric Bell collected from the Systems Toolkit (STK) is the position dilution of precision (PDOP), which is a common technical metric detailing the geolocation geometry provided by the GPS constellation. 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 better than a constellation where fewer satellites provide better geometry (Bell 2010).

Several other notable studies focus on GPS in an urban canyon environment. The first study is performed in Brazil and assesses GPS performance in a computer simulation using elevation and building databases (Costa 2011). The research focuses on the signal to noise ratio of the path between the satellite and the user to determine if the environment is affecting the transmission of geolocation information (Costa 2011). Validation of the simulation model is accomplished by collecting real world GPS data from four stationary locations and two different routes in Rio de Janeiro (Costa 2011). During the two validation routes, Costa (2011) collects data on the probability of having geolocation information from four or more satellites, which is also reflected in our study. Another article discusses the techniques to overcome GPS degradation in an urban canyon environment (Chang 2009). The article covers several methods to include: a pseudorange predictor when GPS ranging signal is blocked by buildings, an altitude-hold algorithm which can be used when only three GPS satellites are visible, a clock bias predictor used in combination with the altitude-hold algorithm once the number of GPS satellites drops to two, and a constraintfiltering method for zero or one GPS satellites in view (Chang 2009). They also provide static and dynamic experimental results to validate their methods (Chang 2009).

2.2 Threats

Military satellite systems are crucial to the U.S.; however, they are also highly vulnerable. Northrop Grumman 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”. For example, jamming is a common and easily implementable threat available to most foreign actors. Spoofing is another type of attack that can be applied to GPS receivers (Humphreys, Psiaki, and Kintner 2009). 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 (Airst 2010). Persistent cyber threats also permeate into the space domain due to a satellite's inherent dependence upon computer technology. A report from AFSPC states that, “Space systems that rely on complex software and radio-frequency links could be susceptible to [cyber] attacks, despite robust cryptographic protection”. Satellites are also highly vulnerable to kinetic attacks. In 2007, China destroyed a weather satellite with an anti-satellite missile in a supposed effort to shake U.S. dominance in space (East-Asia-Intel Reports 2007). The escalation of the availability of threats only increases the need for research into space system resiliency.

2.3 Position, Navigation, and Timing (PNT) Satellite Systems

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 (Chaplain 2009). GPS satellites nominally operate by transmitting a ranging signal that is collected at a GPS receiver (Parkinson 1996). Since the speed of the GPS signal is a known constant and the position of the GPS satellite is known, 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. Collecting distances from multiple satellites allows the GPS receiver to locate itself based upon the only possible intersection of the ranging signals from the satellites (Space-Based PNT National Executive Committee 2014).

In order to ensure the highest global precision for military efforts, the GPS constellation must provide a minimum of 24 operational satellites (Chaplain 2009). The constellation has six nominally circular planes inclined at 55 degrees each with four operational GPS satellites per plane. Each GPS satellite has an orbital 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. (Parkinson 1996)

The urban canyon environment is one type of challenging environment for GPS that is characterized by tall buildings, long narrow streets with a minimum number of intersections, tunnels, and elevated railways, all of which can negatively affect GPS effectiveness (Vicek, McLain, and Murphy 1993). Vicek, McLain, and Murphy (1993) further state that, “Reflected 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 (QZSS 2013). 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 (QZSS 2013).

2.4 SEAS

SEAS is an Agent-Based Simulation (ABS) developed for military utility analysis supporting acquisition programs and system development. SEAS is most often used for scenario focused simulations between opposing forces. As an ABS, SEAS allows entities to react based upon their perception of the environment and their pre-programmed rule structure, ideal for use in this study.

3 METHODOLOGY

3.1 Scenario Description

The selected scenario was developed by SMC/XR with initial analysis presented at the Military Operations Research Society (MORS) symposium (Dainty 2009). The urban canyon scenario simulates a Special Operations Force team moving through a Middle Eastern city searching for a Weapon of Mass Destruction. 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 extend mission duration. When the SOF team successfully makes it to the evacuation location the mission is considered a success. Figure 1 displays the logic of the scenario.

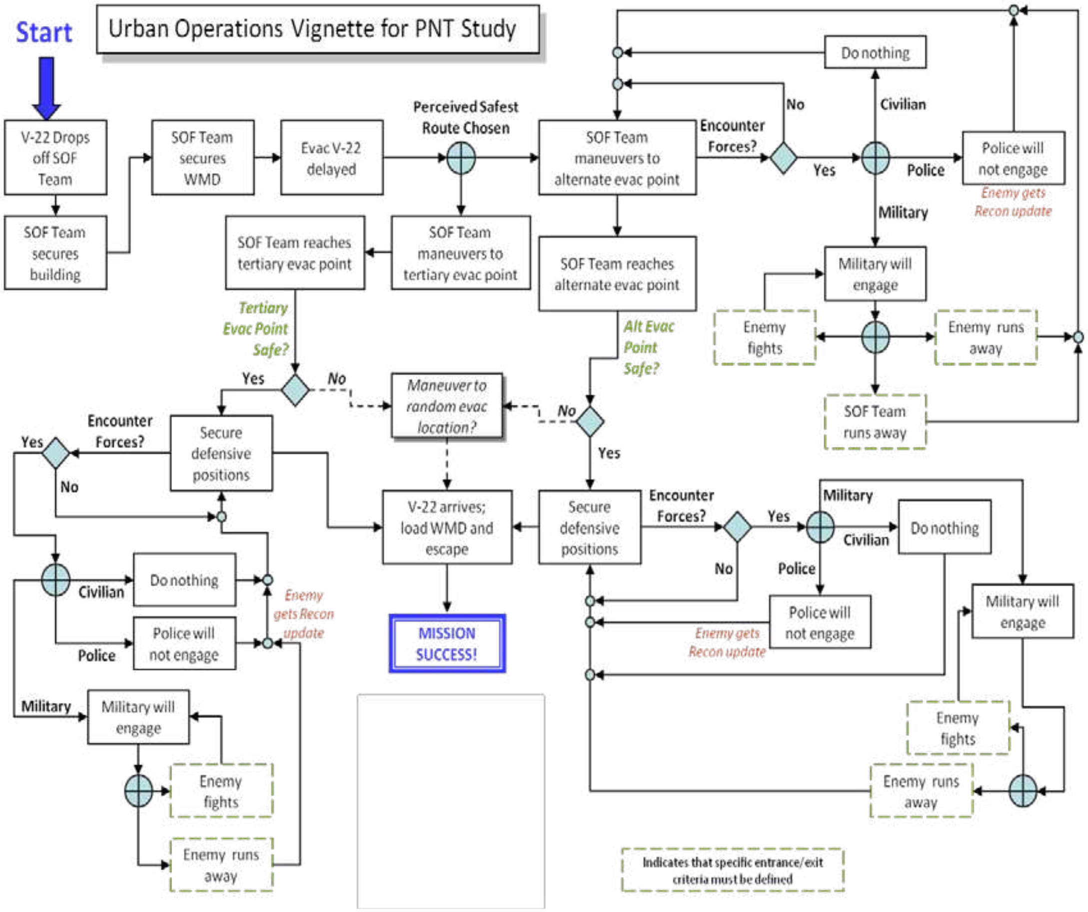

Figure 1: The urban canyon scenario logic flow chart (Dainty 2009).

The urban canyon scenario has several input parameters that can be changed to reflect different system characteristics of interest. Four parameters directly related to the GPS constellation include accuracy, availability, timeliness, and the number of satellites removed by enemy action. GPS accuracy ranges from five to 40 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 zero to one and represents the probability that the GPS constellation is able to provide geolocation information after the loss of signal. In our study, availability is specifically restricted between 0.34 and 0.95. 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. We chose to maintain the same value for timeliness at 5 seconds. The number of GPS satellites removed from zero to ten is the final parameter used to affect the constellation. For example, one design point 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 control of the GPS constellation capability. 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 model focuses on using the higher level input parameters to reflect the capabilities of the GPS constellation.

The principal component of the blue forces is the 50 soldier SOF team. Several rules of engagement govern the actions of the agents representing the SOF team. Each of the rules of engagement is processed at every time step in the simulation (SEAS 2014). 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 (SEAS 2014). 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. We specifically remove satellites within view of the SOF team during the simulation to represent directed enemy actions.

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 police and civilians will not engage the SOF team; however, they can communicate the location of the SOF team to the red military. If the civilians and police can communicate effectively, then the red military will be more successful at engaging the SOF team (SEAS 2014).

3.2 Modifications

One modification of the scenario removes available satellites from the scenario. Any number of satellites can be randomly or purposely selected within the model for omission. Removing satellites is 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 receives a decrease in overall travel speed if less than six GPS satellites are in view. 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. As the number of satellites in view increases the input parameters are changed through an increasing linear scale for GPS availability and a decreasing exponential scale for GPS accuracy. The multiplication factors for accuracy and availability are shown in Table 1. Specific parameter values for accuracy and availability use these factors for normal or degraded operations defined later.

3.3 Selected Metrics

Each of the selected metrics connects back to one of four campaign level priorities: WMD recovery at all costs, minimize blue force casualties, minimize mission duration, and GPS functioning as intended.

Table 1: The GPS unit parameter factors per the number of GPS satellites in view.

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

The first metric is mission duration that connects directly to the third campaign level priority. An extended mission duration can occur if the GPS constellation is degraded by having a fewer number of satellites, which decreases accuracy and availability while increasing the probability of the SOF team 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.

The number of blue casualties is the second metric, which connects to the second campaign level priority and provides insight into the SOF team losses. Any significant increases in the amount of blue casualties across scenarios reflects a weakness and lack of resiliency of the GPS constellation.

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. 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.

The percentage of time that less than four GPS satellites are in view is the final metric, which 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 (Parkinson 1996). 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.

3.4 Analysis Approach

The first method of analysis compares the metrics across unique design points using statistical difference tests. Each design point is defined by either a nominal or a 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 utilized the Paired T test to compare the metrics shown in Table 2. The Paired T test requires approximately normal data for analysis; however, it is robust to deviations in normality. Some of our data did not pass a formal Anderson Darling goodness-of-fit test; however, the deviations in normality were not severe.

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 0.95, respectfully. It is reasonable to assume that the GPS constellation is not perfect, but is highly accurate and readily available. GPS timeliness is kept at five seconds which is the fastest value used by the previous model developers.

The degraded operations reflect a minor loss of GPS capability. The only changes made to nominal operations are the reduction of GPS accuracy and availability. GPS accuracy is increased to 10 meters and the availability is reduced to 0.85. 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.

To simulate the loss of satellites due to the array of threats mentioned in the background, satellites are purposefully eliminated from the scenario. 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.

The second method of analysis is a full factorial designed experiment, which is performed to provide insight into the most important variables affecting the selected responses. The responses of interest are the metrics to assess resiliency. The designed experiment involves 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 affects overall resiliency.

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. Each replication only requires several minutes and the data for our responses was approximately normal with as few as 20 replications. Our final selection was based on providing a reasonable standard deviation relative to the mean values 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.

4 RESULTS

4.1 Initial Analysis

To gain a preliminary perspective on the data, an initial analysis composed of a variety of design points at the extreme and moderate levels of each factor is performed. The design points represent all possible combinations between nominal and degraded operations paired with zero, five, or ten satellites removed. The metrics for each design point are compared to determine if there is a statistically significant difference. The presence of a statistical difference indicates a metric impacted by the factor level changes to the simulation. Table 2 displays results which maintain the same nominal operations, but varies the number of satellites removed. Bolded difference confidence intervals indicate that there is a statistically significant difference in the metric at the individual 95% confidence level. Additional comparison tables are available in Burns (2015).

Table 2: Nominal scenario vs. number of satellites removed 95% confidence interval comparison.

Metric	Scenario Comparison		
	Nom-5 – Nom-0	Nom-10 – Nom-0	Nom-10 – Nom-5
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**

There are several trends which are nearly significant in comparisons included in Table 2 and in similar comparisons in Burns (2015). The first trend shows mission duration is always significantly different and always increases in value with increased degradation. Table 2 also shows that there is a large magnitude of difference between design points as indicated by the point estimators and half widths in the confidence intervals. This helps support the conclusion of a practically as well as statistically significant difference in the metric. A key insight from the trend is that the overall mission duration is highly sensitive to GPS performance. If the WMD needs to be removed in minimal time, then having the highest performing GPS constellation would be critical. As a result of the preliminary analysis, mission duration is the focus of more specific analysis presented in this paper.

The second trend is the significance difference that occurs when there are more satellites removed. The number of casualties and number of engagements are not significantly different in nominal operations when compared between zero and five satellites removed as shown in Table 2. However, the same metrics exhibit a significant difference when compared between zero and ten as well as with five and ten satellites removed. The pattern may be an indication of a nonlinear change in the metrics with increased satellite removals. While we show stronger statistical evidence of trends in Burns (2015), the two initially identified trends included here guide this paper toward sensitive response variables.

After the preliminary analysis, the full experiment is completed which involves collecting data from the remaining design points. The objective is to have data from every level of satellite removal from zero to ten for both the nominal and degraded operations. Table 3 depicts the runs configuration.

Table 3: Full production runs.

Factor	Levels	Design Points	Total Replications
Operations	2	22	550
Number of Sat Removed	11		

Using the complete data set, graphical insight is gained by comparing the confidence intervals across all of the design points. Figure 2 plots the individual 95% confidence intervals of the mission duration as the number of satellites removed increases. 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.

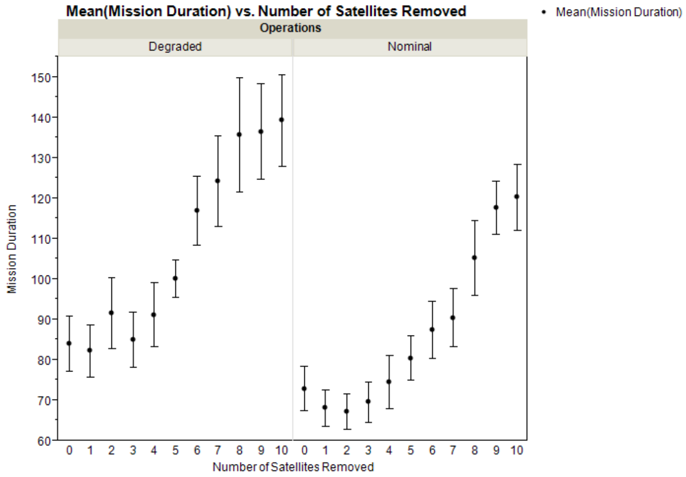

Figure 2: Mission duration individual 95% confidence interval graph.

4.2 Designed Experiment

Next, a designed experiment is performed to determine how the factors affect 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. (Montgomery 2013)

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. 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 zero and one. Each of the responses are analyzed through the ANOVA.

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 earlier. 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.

4.2.1 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. ANOVA model residuals are checked for constant variance and normality for all responses with some minor deviations from normality. More details can be found in Burns (2015).

Key results from the ANOVA include the $R^2 - adjusted$ value and the significance of the overall model along with the individual factors. The best models are based on the mission duration and the percentage of time there are fewer than four GPS satellites available. ANOVA enables insight into the specific situations that most affect GPS constellation resiliency. Summary statistics from each of the models are displayed in Table 4.

Table 4: 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
Satellites Removed	**<.0001**	**<.0001**	**<.0001**	**<.0001**

4.2.2 Tukey's Test

There are several unique groupings displayed in the Tukey's test results for the mission duration model shown in Figure 3. The first grouping displays that removing eight or more 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 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 extended mission durations above 100 minutes on average. If more than seven satellites are removed, then mission duration increases to 120 minutes on average. As a result, the different threshold levels provide information into satellite resiliency.

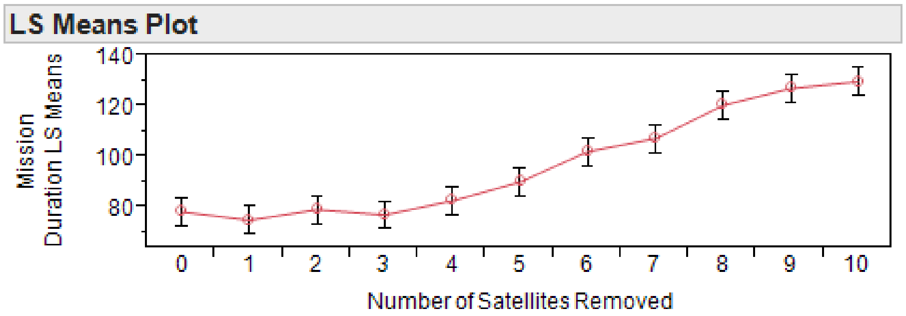

Figure 3: Mission duration Tukey's test results.

Each of the Tukey's plots for the remaining response variables provide similar 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's 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. More analysis details are available in Burns (2015).

5 CONCLUSIONS

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" (Air Force Space Command 2013).

One area for further research is the sensitivity of the GPS Unit logic structure in the SEAS code. 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. Another area for further research is incorporating the geometry of the GPS satellites instead of just the number in view as noted by Bell's (2010) research. A final area for further research is to model different satellite constellations. The GPS constellation is inherently resilient due to the large number of satellites in several different planes. Other constellations, however, are not as diverse and may not be able to provide the same capabilities under degraded scenarios.

Satellite constellation resiliency is an important consideration for the future. 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 provided 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. In addition, adding a geometry based geolocation algorithm is an important aspect of the SEAS code 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.

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