

**COST BENEFIT ANALYSIS OF ADDING TECHNOLOGIES TO COMMERCIAL  
AIRCRAFT TO INCREASE THE SURVIVABILITY AGAINST SURFACE TO AIR  
THREATS**

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The Academic Faculty

By

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In theory, theory and practice are the same. In practice, they are not.

*A wise man or woman*

To my parents and step parents, Anthony Patterson Sr., Cheryl Drew, Lori  
Barksdale-Patterson, and Nelson Drew

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## SUMMARY

Flying internationally is an integral part of people's everyday lives. Most United States airlines fly internationally on a daily basis. The world continues to become a more dangerous place, due to improvements to technology and the willingness of some nations to sell older technology to rebel groups. In the military realm, there have been countermeasures to combat surface to air threats and thus increase the survivability of military aircraft. Survivability is defined as the ability to remain mission capable after a single engagement. Existing commercial aircraft currently do not have any countermeasure systems or missile warning systems integrated into their onboard systems. Better understanding of the interaction between countermeasure systems and commercial aircraft will help bring additional knowledge to support a cost benefit analysis. The scope of this research is to perform a cost benefit analysis on the addition of these technologies that are currently available on military aircraft, and to study the adding of these same technologies to commercial aircraft. The research will include a cost benefit analysis along with a size, weight, and power analysis. Additionally, a simulation will be included that will analyze the success rates of different countermeasures versus different surface to air threats in hopes of bridging the gap between a cost benefit analysis and a survivability simulation. The research will explore whether or not adding countermeasure systems to commercial aircraft is technically feasible and economically viable.

# CHAPTER 1

## INTRODUCTION

Over two million passengers fly domestically and internationally everyday [1]. Furthermore, international flights have increasingly become more dangerous, due to terrorist groups having access to surface to air missiles (SAMs) [23, 38, 2]. This research is about performing a cost benefit analysis on adding countermeasures to commercial aircraft to increase its survivability against surface to air threats. Survivability is defined as: the ability to remain mission capable after a single engagement [12].

### 1.1 Motivation

Currently, the types of threats used against commercial aircraft consist of surface to air missiles and man portable air defense systems (MANPADS)[3]. MANPADS are generally employed during take-offs and landings due to their limited range. While an aircraft is in cruise phase, a surface-to-air missile is more than likely to be used to try to shoot down a commercial aircraft. During the cruise phase of the flight profile, the parameters of an older surface to air missile will be used to model the survivability, because of the availability of older SAM missiles to rebel groups [23].

The motivation behind the topic stems from the increasing danger commercial aircraft face every time an international flight is attempted. There are over four million square miles of possible conflict zones and there have been over twenty-one malicious acts toward commercial airplanes since 1970. Hundreds of commercial planes fly over conflict zones every day. After the Malaysia airlines flight MH 17 was shot down in 2014, the U.S. made changes to flight plans for commercial aircraft. The regions of eastern Ukraine, Crimea, North Korea, northern Ethiopia, Libya, and Somalia are currently off limits to U.S aircraft. When travel-

ing over the Middle East, U.S airlines must fly at a minimum altitude of 20,000 feet. That is out of range for most, but as MH17 proved, not all missiles [23].

### 1.1.1 Past Events

In addition to the previously discussed flight, a Korean Air flight was shot down by the USSR on September 1st, 1983. There was also a Boeing 747 commercial aircraft from New York to Seoul that was shot down by a Soviet military aircraft just west of the Russian island of Sakhalin, killing all 269 passengers and crew, including U.S. congressman Larry McDonald [23].

On November 6th, 1987 an Air Malawi passenger flight was shot down en route to Lilongwe from Blantyre. It crashed near the town of Ulongwe, killing eight passengers and two crew members [36]. On patrol in the Persian Gulf on July 3rd, 1988, the USS Vincennes shot down an Iranian commercial aircraft that had been mistaken for a hostile Iranian military aircraft, which killed all 290 passengers aboard the commercial aircraft [37].

There have been similar attacks such as when the Ukrainian military shot down a Russian commercial jet containing 78 passengers on October 4th, 2001, over the Black Sea traveling from Tel Aviv in Israel to Novosibirsk, Russia. Russian crash investigators concluded the Tu-154 was hit by a Ukrainian surface to air missile [36].

## **1.2 Threats**

There are many possible threats that are capable and readily available that can destroy a commercial aircraft in flight. These potential threats include: surface to air missiles, air to air missiles, and directed energy weapons. The most popular type of threat used is the man portable air defense system (MANPADS) which is a type of surface to air missile [12]. These are the most popular, because they are relatively the easiest to obtain due to their low

cost and transportability. MANPADS are mainly used for attacking commercial aircraft during their take-off and landing. For the scope of this thesis the surface to air threat that will be studied is the long range surface to air missile, because the range of the MANPAD is limited to takeoff and landing. One could make the argument that the guardian developed by Northrup Grumman has solved the MANPAD threat to commercial aircraft during take off and landings, leaving cruise phase as the only phase that could be attacked by a radar guided surface to air threat.

### 1.2.1 Potential Threats

An example of potential MANPAD threat is the SA-7 GRAIL. The SA-7 GRAIL is equipped with an explosive warhead and IR missile guidance system. The system also comes equipped with RF headphones which can be used to determine the general location of an aircraft [37]. The SA-7 was first in 1968, but quickly upgraded to SA-7b. The SA-7 MANPADS has a slant range of 1.4 km and a speed of Mach 1.4 [38], which is on the slower side when compared to today's surface to air threats. An example of a long range surface to air missile is the SA-2 guideline which was developed in the 1960s during the cold war. Surface to air missiles at this time were beginning to be equipped with proximity fuses and command fusing capabilities. The SA-2 guideline is best known for downing a U-2 spy plane [38].

### 1.2.2 Access to Threats

According to Chow et al. over 700,000 MANPADS have been produced worldwide since the 1970s. The Middle East has since become the world's battleground giving way to cause and effect that has provided terrorist groups MANPADS from countries all over the world including the United States. Russian made MANPADS have been sold for as little as \$5,000 in the Middle East and Central Asian countries. As of late terrorist groups have been willing to collaborate to reach its goals. Due to this collaboration MANPADS now have the ability to be transported anywhere in the world.

## **1.3 Countermeasures**

The military currently has many methods and measures to defend itself from surface to air missile threats. The three countermeasures this thesis will focus on will be chaff, flares, and directed energy.

### 1.3.1 Missile Warning System

The Northrup Grumman AN/AAR-54(V) is a missile warning system capable of tracking and classifying multiple sources. The missile warning system utilizes the UV energy from surface to air threats to classify the threat as lethal or non lethal. The system is designed for wide-body aircraft, helicopters, and combat vehicles. The missile warning is currently used by U.S special operations and the system is currently equipped to Air Force One [3].

### 1.3.2 Chaff/Flare Dispenser System

The ALE-47 Countermeasure Dispenser System is an integrated computer controlled system, designed to employ electronic and infrared countermeasures [4]. The CMDS provides the aircraft with protection from air-to-air and surface-to-air heat-seeking missiles. The CMDS may be programmed to generate an optimum response to combat a single or multiple threat environment [4].

### 1.3.3 Chaff

Chaff was first developed in the early stages of the second world war. The two major types of military chaff in use are aluminum foil and aluminum-coated glass fibers. Chaff is a defensive mechanism employed from military aircraft to avoid detection by adversary air defense systems [5]. Chaff consists of small fibers that reflect radar signals and, when dispensed in large quantities from an aircraft, it forms a cloud that temporarily hides the aircraft from radar detection [4, 5, 6].

#### 1.3.4 Flares

Since the emergence of aircraft in the twentieth century, the control of airspace has become of major tactical importance in times of conflict [7]. This has led to the creation of anti-aircraft weapon systems that can be deployed from a variety of platforms. The infrared countermeasure (IRCM) flare has been developed to decoy heat seeking missiles [7].

Flares along with chaff is a countermeasure with goal of being a decoy and being a distraction for a surface to air threat. The main differences between chaff and flares are chaff are for radar guided SAMs and flares are for IR guided SAMs. Flares are high-temperature heat sources ejected from aircraft that confuse the IR sensors on the incoming missile. Once a flare is activated the IR signature is much greater than the aircrafts due to increased burn temperature causing the IR guidance system to become confused. [7].

#### 1.3.5 Directed Energy

In recent years the military has started to integrate directed energy counter measures on to some of its of aircraft. There are several countermeasure systems with the goal of misdirecting the IR guidance system with a high energy laser. These technologies are usually integrated onto the fuselage and tail of the aircraft. For example Northrup Grumman's Guardian is retrofitted the the fuselage of aircraft [9].

#### 1.3.6 Towed Decoys

The AN/ALE-55 Fiber Optic Towed Decoy (FOTD) is manufactured by BAE SYSTEMS and it is a radio frequency countermeasures system. IDECM incorporates receivers and countermeasures that include the high-powered FOTD and deployment canister. The towed decoy is going to provide electronic warfare defense for current and future RF surface to air threats for military aircraft [10].

### 1.3.7 Air Force One

The President of the United States must be ready to travel anywhere in the world on a moment's notice. Air Force one is currently a custom Boeing 747-200B. A commercial Boeing 747-200B can hold a maximum of 480 passengers [13]. Air Force One is relevant to this research because this type of Boeing aircraft is very common in commercial international flights. Air Force one is outfitted with some of the world's best defense technologies including antennas, radar, and a plethora of infrared countermeasures that disrupt missile guidance systems [13].

Specifically, Air Force One is outfitted with an AN/AAR-54(V) which is a missile warning system located at the tail of the aircraft [13]. Also, Air Force one is equipped with directional IR countermeasure system which can be controlled and optimized by the AAR-54 missile warning system, which fires flashes of IR energy to misdirect the incoming IR missile [13].

Air Force One is the most efficient way the President of the United States travels. Air Force One is one of the most protected vehicles in the United States by way of countermeasure technologies. The information provided by Air Force One is a way one can show the importance of these countermeasures and always displaying that these commercial aircraft can be retrofitted with these technologies. The current plane used for Air Force One is a Boeing 747. The Boeing 747 is a very popular commercial aircraft that is used globally. One can assume that all commercial aircraft can't become Air Force One, but one can assume that taking some of the countermeasure systems being used on Air Force One and applying them to commercial wide-body aircraft would increase their survivability against surface to air threats. To retrofit technologies similar to these, one could assume it would incur some cost. Chow et al. created a detailed cost model for retrofitting a similar countermeasure technology a commercial aircraft.

## **1.4 Research Objective**

The scope of this thesis will pertain to the cost of adding countermeasures to the commercial aircraft, operation and support costs (O&S), and maintenance costs. This research will include a cost benefit analysis along with a size, weight, and power analysis. A model and simulation will be implemented to study the success rates of different countermeasures versus different surface to air threats. The research objective of this thesis is to perform a cost benefit analysis for a given countermeasure technology and to quantify the effectiveness of the countermeasure through a survivability model. The survivability model will focus on the cruise phase of the flight profile. This thesis will focus on chaff as a countermeasure.

### 1.4.1 Challenges

The purpose behind the development of these technologies was to help defend military aircraft of all types for the countermeasures mentioned in this research, specifically wide body aircraft. Countermeasure technologies are becoming more popular in the commercial cargo transport space. There is a lack of historical data of countermeasure technologies being retrofitted to commercial aircraft, this absence does not allow one to use real system measurements to validate the survivability model.

### 1.4.2 Research Approach

The approach for achieving this research objective is finding the correlation between the cost benefit analysis of these technologies and to quantify the effectiveness of the given countermeasure. This relationship could be found through a detailed cost model and a survivability model.

## **CHAPTER 2**

### **BACKGROUND**

#### **2.1 Potential Losses**

A commercial airliner potentially being shot down is something no one would like to think about, but it has happened, and there is always the likelihood of its happening again. There have been papers written that have estimated the potential losses that go along with the shooting down of a commercial airliner, such as airport closures.

According to Chow et al., if there was a commercial aircraft that was to be shot down by a surface to air missile in the United States the cost of the plane and lives would result in a loss of approximately \$1 B. The loss of the aircraft would approximately cost \$200 - 250 M depending on the model and also be able to transport 300 or more passengers. They estimate the value per life would approximately be \$2 M [38].

According to Chow et al. the loss of a commercial aircraft stems beyond just the immediate loss of life and property. Another loss is the potential change in the gross domestic product (GDP) that may result from the airline shut down itself. The airline industry sustains many associated industries, slowdowns in the airline industry would have a negative cause and effect on the associated industries.

Even though airline operations would eventually restart following a shutdown. A large amount of the population would be uncomfortable with the idea of flying. Six months after September 11th attack the airline industry was experiencing wide sweeping layoffs affecting the industry from top to bottom. A year after September 11th the airline industry was

still down roughly 8%. To avoid this problem at the time Chow et al. estimated the country would be willing to pay \$12 B to avoid an incident that effected traveler confidence [40].

### 2.1.1 Potential Solutions

Chow et al. provided insight on some possible solutions to prevent the shooting down of a commercial aircraft. Solutions consisting of adding technologies to aircraft and also some changes to policies currently set in place. According to Chow et al. there isn't a countermeasure that currently exists that would bring the could bring the probability of a successful MANPADS attack on a commercial airliner to zero. Countermeasures in the military space have been extremely valuable. The idea of adding countermeasure technologies to commercial aircraft is less obvious, because the probability of an attempt to shoot down a United States commercial aircraft is extremely low.

To protect commercial aircraft from a MANPADS attack would take a multi-layered solution. This multi-layered solution would have the goal of decreasing the attacker's confidence of using a MANPADS [40]. Chow et al. believes that confronting the enemy would not only thwart MANPADS attacks, but threaten the terrorist network as a whole.

If that method does not work well enough Chow et al. provided four more methods in MANPAD attack prevention. The four methods consist of preventing MANPADS from being fired, preventing a launched missile from hitting the aircraft, minimizing the damage from a missile hit, and minimizing the consequences from an attack.

Along with Chet at al. Bolkcom and Elias provided insight regarding a variation in airport security to prevent a successful MANPADS attack, airport security could enforce a perimeter with a range larger than MANPADS being used in the attack. Current airport security is not capable of completing such a task, which would require other efforts being

made to help thwart the attack, such public education, neighborhood watch programs, security patrols in high risk areas. However, this could be the starting point in a multi-layered solution .

Bolkom and Elias have provided insight on possible solutions regarding improved pilot training and air traffic procedures. Airline pilots currently receive simulator training on handling loss of power to an engine during takeoffs and landings. The training they believe aircraft crews should receive should prepare crews to handle the loss of power due to a missile strike. Modern aircraft are designed with avionics and flight control systems, that if a missile strike does not destroy the aircraft it would like be able to survive if the flight crew is trained properly.

Bolkom and Elias provide techniques to mitigate the chances of a successful attack, but without a missile warning system, it is highly improbable the pilot would be made aware of a missile launch. Large cargo planes are generally not nimble aircraft making maneuverability less effective. Bolkom and Elias believe reducing the aircraft's heat signature and auxiliary power units when applicable may reduce the effectiveness of the MANPADS IR guidance system. The safety risk associated with reducing the aircraft's heat signature will need to be carefully analyzed before these methods are implemented.

Bolkom and Elias theorized that altering aircraft routes to decrease the amount of time the aircraft is vulnerable to a missile launch could be a viable mitigation technique. If one could change the approach routes and departing routes of the aircraft, it could decrease the chances of a successful MANPADS attack, because there would be less predictability in the routes. Currently, commercial aircraft rely on gradual descents along known approach routes. Departing aircraft with heavy cargo loads can be targeted up to 30 miles away before they eventually are out of the effective range of a MANPADS. One challenge

to implementing this technique is that commercial aircraft radio frequencies are not protected, and terrorists may be able gather intelligence regarding the change in aircraft routes.

If the layer attempting to prevent a missile launch fails, countermeasures might prevent the missile from making a successful hit. Each system has its own pros and cons. Some systems could provide highly effective protection under a wide range of conditions, but none are able to protect against the full range of threats. The three countermeasure systems Chow et al. considered adding to commercial aircraft are flares, laser jammers, and high-energy lasers.

## **2.2 Cost Benefit Analysis**

According to Watkins, a cost benefit analysis (CBA) has its origins in the water development projects of the U.S. Army Corps of Engineers. The Corps of Engineers had its origins in the French engineers hired by George Washington in the American Revolution [15]. Cost benefit analysis do have some limitations specifically in efforts that involve small to mid-level capital expenditures with fast approaching deadlines. A cost benefit analysis may be sufficient enough to make a well informed decision. Large projects with lengthy deadlines, some CBAs fail to take into account inflation, interest rates, changes in cash flow, and the present value dollar amount [15].

## **2.3 Costs**

The costs that come along with adding countermeasures to commercial vehicles can be quite expensive. The Chow et al. research breaks down its costs into two sub groups: installation costs, and operation and support (OS) costs, which stem from total life-cycle cost (LCC). They conclude their cost benefit analysis by considering total program costs in the context of the federal TSA budget.

### 2.3.1 Installation Costs

Chow et al. made cost estimates for installing the most promising near-term countermeasure systems. All of the values and figures are based on the 2003 fiscal year (FY) and approximately 6,800 U.S. commercial aircraft. Those costs were based on modifying the most current set of cost data values from wide-body military IR countermeasure systems. Specifically Chow et al. adjusted weights and volumes calculated for the military version to meet the form and fit required to enclose all the electronics within the pod installed on the underside of the fuselage of the commercial aircraft. The direct energy countermeasure systems for commercial aircraft will consist of:

- Missile warning system of four two-color missile warning infrared sensors capable of detecting MANPADS
- System processor designed to military specifications using fifth-generation CPUs
- Electronic control unit
- Multi-band laser transmitter mounted within a small turret
- Command, control, and communications system to provide missile warning updates and intercept data to ground control operations
- Built-in-test hardware and software subsystem
- The canoe-type surface mounting hardware package and other A-kit interface hardware to enclose the preceding system components

Chow et al. estimated a total fleet installation cost of \$11.2 B. That includes:

- Research, development, test, and evaluation (RDTE) phase at \$445 M, consisting of the systems design, aircraft flight testing, and FAA certification for six fully configured prototype systems

- Manufacturing technology, capital, and facilities cost at \$165 M to build up the annual production rate needed through the end of low-rate initial production \$65 M, and the set-up tooling of a second final assembly and test manufacturing line for the entire production \$100 million
- Purchase of initial spares and test bench equipment at \$900 M
- Procurement and retrofit of approximately 6,800 directed energy B-kits and A-kits at \$9.75 B

Chow et al. assumed the development phase of a commercial DIRCM system beginning in FY 2004 and continuing until the end of FY 2007. The development estimate assumed the six flight-test prototypes that would be adequate for integrating across the most popular commercial aircraft models. In addition, the estimate included a sufficient number of prototype ground and flight tests to perform analysis on the acoustic and vibration effects on the system.

Finally, the total RDTE estimate includes an adequate number of reliability and maintainability demonstrations within commercially acceptable threshold and objective values. To prepare for these costs, Chow et al. estimated the commercial direct energy countermeasure system development cost by increasing the large aircraft infrared countermeasure RDTE total budget by 60%. That factor was based on the following considerations:

- Extent of repackaging of the B-kits to fit within the canoe structure
- Number of unique A-kit designs need for each commercial aircraft model
- Number of flight tests required for installing, testing, and certifying the systems on all the commercial aircraft models

Chow et al. projected procurement to begin in FY 2006 during the third year of the system development phase and continuing through FY 2009. By then, approximately 1,100 com-

mercial aircraft would be fitted with the new countermeasure technology, which would be enough to cover all three stages of the reserve commercial fleet, as well as all wide-body aircraft for international and domestic flights. The average unit production cost was estimated to be \$1.3 M (in FY 2003 dollars). This cumulative average unit production cost is the sum of the unit cost of the following:

- Airborne directed energy countermeasure system A-kit, B-kit, and system installation cost
- The cost of the initial spares, technical data, support equipment, and change orders, amortized on per-system basis by applying a 92 percent cost improvement curve or learning curve slope across the total quantity of approximately 6,800 systems.

### 2.3.2 Operation & Support Costs

Chow et al. estimated the annual O&S cost per aircraft of \$300,000 for a subtotal O&S cost of \$27 B through FY 2023. Those costs considered the following:

- Added fuel cost of \$45,000 needed due to the drag and additional weight that the commercial aircraft will be carrying over an assumed 3,000 hours per year
- Maintenance cost of \$140,000 per aircraft per year
- Airline mechanics labor, spares, and other material needed to perform airport ground maintenance
- Airline depot level or contractor logistics support activities for scheduled system overhauls and repairs
- Technology upgrade and sustainment cost of \$60,000 per aircraft per year
- Airplane delays \$15,000 per aircraft per year

The added fuel cost estimate stems from an increased drag estimate of 0.4% and added system-level total weight of approximately 500 lbs. The total O&S cost is thus \$27 B. Once all systems are installed, annual O&S costs would amount to a little over \$300,000 per airplane, or \$2.1 billion for a 6,800-plane fleet.

### 2.3.3 Benefit Analysis

Chow et al. performed their final piece of the cost benefit analysis by comparing the cost of adding technologies to commercial aircraft to the overall budget of the TSA. The OS costs amass about half of the TSA budget of \$4.4 B. Chow et al. provided the recommendation of postponing the adding of countermeasure technologies to commercial aircraft, due to the uncertainties in the cost of the countermeasures and their effectiveness in reducing the overall aircraft vulnerability. They claimed the current RDTE activities are the most important step toward both reducing significant cost uncertainties involved and minimizing the delay of the program.

The cost benefit analysis by Chow et al. acknowledges many threats to commercial aircraft and the possible solutions. One of the solutions mentioned by Chow et al. is a viable solution which, entails adding countermeasures to a commercial wide body aircraft. Chow et al. concludes that the countermeasures alone won't be effective enough. They state a multilayered approach would be necessary to actually thwart surface to air missile attempts on commercial aircraft.

## **2.4 Space Filling Designs for Computer Experiments**

Professor Jeff Wu suggests that if one observes a response and wishes to study how that response varies as one changes the input variables. One must determine if the response may be affected by outside factors. Unless one can control the effects of the outside factors, observations at the same values will vary as the outside factors vary [19].

### 2.4.1 Latin Hypercube Sampling

The Latin Hypercube Design spreads the points evenly over the design space based upon the value of each input variable. The LH could sample point distributed evenly along the diagonal of the design space. It is true the points along the diagonal have projections that are evenly spread out over the input values. One could not assume the points to be evenly spread throughout the entire design space [19].

## **2.5 Model Validation**

Jane Hillston concludes based up on the the performance analysis extracted from a model, it will only have some bearing on the real system being represented. Validation is the task of demonstrating that the model is a reasonable representation of the actual system. A model is usually developed to analyze a particular problem and may therefore represent different parts of the system at different levels of abstraction. As a result, the model may have different levels of validity for different parts of the system, due to the fidelity of part being studied [20].

Three key factors which should be considered during model validation:

- Assumptions
- Input parameter values and distributions
- Output values and conclusions

However, in practice it may be difficult to achieve such a full validation of the model, especially if the system being modeled does not yet exist. In general, initial validation attempts will concentrate on the output of the model, and only if that validation suggests a problem will more detailed validation be undertaken [20].

There are three approaches one could apply to perform model validation and any combination of them may be applied [20]. These approaches are:

- Expert intuition
- Real system measurements
- Theoretical results/analysis

Any time a research engineer creates a model/simulation one must also verify and validate their logic and procedures. For model validation expert intuition and real system measurements will be the approaches guiding the validation process. Throughout the data analysis process the results will be used as validation.

## **2.6 Literature Review Summary**

There are several reasons why the information above is important. Recognizing the threat to commercial wide body aircraft that fly over conflict zones on a daily basis. In these conflict zones there are terrorist groups that have access to older surface to air missiles. Several studies have shown that there is an underlying willingness for terrorist groups to these military capable threats against commercial aircraft.

After a review of the literature one could recognize a gap between quantifying the effectiveness of these countermeasures and their costs. This thesis addresses this gap with its own cost benefit analysis similar to the one in the literature, but also provides a survivability model that assesses the technology's effectiveness against surface to air threats. The simulation model will use Latin Hypercube Sampling, because it is an extremely efficient way for random sampling the interior of design spaces. LHS does have some weaknesses, such as placing sample points at the edges of the cube.

## CHAPTER 3

### METHODOLOGY

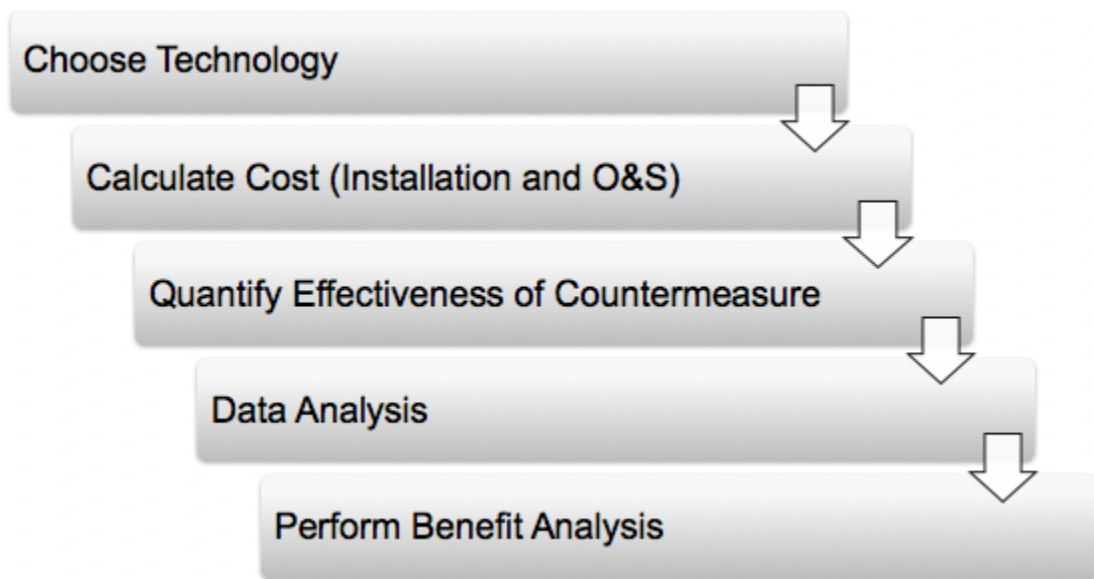


Figure 3.1: Steps in Methodology

### 3.1 Challenges

#### Lack of Historical Data

Major issues stem from the lack of historical data regarding adding these types of technologies to commercial aircraft, such as the lack of real system measurements. The lack of size, weight, and power analysis regarding the effects of adding these technologies to commercial aircraft such as the physical effects on the commercial aircraft. Fortunately, all of these technologies are at a technology readiness level (TRL) of 9 meaning the system is flight proven through successful mission operations, according NASA's TRL chart. Chaff, flares, directed energy, and towed decoys are commonly used in the defense sector today.

#### Physical and Virtual Testing

In order to select between different technologies for any given mission scenario requires, in essence, the ability to either physically test or virtually analyze them in a simulation environment. Adding technologies to a commercial vehicle and then physically testing those technologies is extremely expensive, leaving modeling and simulation as the only viable option.

### **3.2 Performance Prediction**

Chaff has been in use since World War II and is currently equipped to wide body military transport aircraft, such as the C-17 and C-130. One can assume the chaff countermeasure technology performs well enough to keep equipping it to modern military transport aircraft. The chaff countermeasure has operational results that would appear more favorable, than a commercial aircraft without any surface to air missile countermeasures. One must think about the odds of a U.S airliner under attack from the ground; one can assume these odds are extremely low. Another one being the effectiveness of the countermeasure not being high enough to commit the amount of capital that is required to retrofit wide-body aircraft with these technologies.

### **3.3 Observations**

In summary, a gap is observed in the literature between the effectiveness of these countermeasures and a cost analysis of these countermeasures. Chow et al.'s cost benefit analysis of adding countermeasures to commercial aircraft is very thorough and one could use their methodology as a basis for a similar methodology with slight changes in the fleet size, due to focusing only on wide body aircraft. The scope of this thesis will only focus on one countermeasure, and that will be chaff with a missile warning system developed by Northrop Grumman.

### **3.4 Research Questions and Hypothesis**

Chow et al. performed a cost benefit analysis that evaluated 6,800 domestic U.S airlines. Chow et al. and Bolkom provided a multi-layer system to attempt and thwart the attack of a surface to air missile on a commercial aircraft. The same cost benefit analysis methodology provided by Chow et al. will provide an in depth analysis that is adequate to successfully complete a cost benefit analysis on a smaller sample size of commercial aircraft.

#### **Research Question 1:**

How can one quantify the effectiveness of countermeasures deployed from commercial airliners against surface to air threats to capture the cost relationship for implementation of such countermeasures?

#### **Hypothesis 1:**

If the researcher uses a survivability model to describe the effectiveness of each countermeasure and a cost model to provide detailed cost analysis, then one could directly capture the correlation between cost and survivability between countermeasures.

#### **Research Question 2:**

By quantifying the effects of the countermeasure on a commercial aircraft using a SWAP analysis one could determine if the cost of implementation from both acquisition cost and performance decrements are justified. Further, how can one determine if adding countermeasures to commercial aircraft or simply avoiding conflict zones altogether is more cost effective over the lifespan of the vehicle?

#### **Hypothesis 2:**

If the rate of survivability is not high enough to justify the cost of adding these technologies to a commercial aircraft; avoiding conflict zones altogether will likely assert itself as the more viable alternative.

### **3.5 Task One: Cost Benefit Analysis**

The cost benefit analysis that will be performed will encompass adding countermeasure systems to the commercial aircraft. Where my cost benefit analysis slightly differs is Chow et al. added countermeasure systems to all of the United States commercial aircraft fleet. The CBA that will be performed here will only simulate the adding of countermeasure systems to planes that typically make international flights, which will greatly reduce the overall costs of installation and OS costs. The seven steps the researcher decided to go with to complete the CBA are:

1. Define the unit of cost. It is important to establish what exactly your CBA measures in terms of cost. The two types of cost my research will define will be time and money.
2. Itemize the tangible costs of the intended project. The two tangible costs that the researcher will consider will be installation cost and OS costs.
3. Itemize all intangible costs.
4. Itemize projected benefits; these are projected benefits that stem from adding countermeasure systems to commercial aircraft. For example, an unsuccessful SAM attack on a United States commercial aircraft, due to a countermeasure system. The projected benefits are the increase in confidence of travelers, money saved from the saving of lives and plane, and a possible increase in travelers who feared of a SAM attack on a commercial aircraft.
5. Add up and compare the project's cost and benefits. All of the installation costs and OS costs will be tabulated, and then all of the ongoing costs will be subtracted from the ongoing benefits determined in step 4.
6. Calculate a payback time for the venture. Unfortunately, for this venture to be worth it there would have to be an attack on a United States commercial aircraft. On top of

that, it is not guaranteed that the countermeasure system will always work against a SAM.

7. Use the CBA to make an informed decision about whether to pursue the project. After analyzing all of the information determined from the CBA, one would use the information to determine if adding countermeasure systems to commercial aircraft is technically feasible and financially viable.

### **3.6 Task Two: Size, Weight, and Power Analysis**

When adding technologies to a commercial aircraft one of the most important things along with cost, is the size, weight, and power of the technology. All of these things play a critical role in aircraft performance. The size of the technology can effect the aircraft in different ways depending on placement inside or outside of the aircraft. Size defined as a thing's overall dimensions or magnitude. If the technology is placed on the inside of the aircraft fuselage, it can reduce storage. If placed on the outside of the aircraft it can have a huge impact on aerodynamics. Negatively affecting aerodynamics can dramatically increase drag. Drag is the aerodynamic force that opposes an aircraft's motion through the air [21]. Increasing drag will decrease range and fuel efficiency ultimately costing time and money.

The weight of technology will not have a huge effect on drag, but will affect the lift of the aircraft. Weight is a body's relative mass giving rise to a downward force due to gravity. Lift is the force that directly opposes the weight of an airplane and holds the airplane in the air [22]. Decreasing lift will affect your fuel efficiency and have a negative impact on range. These technologies require some kind of power source for operation while the aircraft is in flight.

Along with adding the technology to the airplane, one would need to also add a power

source for the technology, contributing to weight. The SWAP analysis will consist of a comparison between the size, weight, and power required to operate the technology. The steps that will be taken to perform the SWAP analysis are:

1. Calculated size in comparison to the overall size of the plane
2. Calculated the forces of the system on the plane
3. Calculated the power needed to supply the system

Energy Consumption

$$E_{(\frac{kWh}{day})} = P_{(W)} * t_{(\frac{h}{day})} / 1000_{(\frac{W}{kW})} \quad (3.1)$$

Energy Cost Calculation

$$Cost_{(\frac{\$}{day})} = E_{(\frac{kWh}{day})} * Cost_{(\frac{cent}{kWh})} / 100_{(\frac{cent}{\$})} \quad (3.2)$$

### 3.7 Task Three: Model Survivability

Due to the expense of physically testing these technologies on commercial vehicles, testing their survivability through modeling and simulation is a less expensive option. Modeling the survivability will be done through parametric modeling. Parametric modeling is creating a model from known facts about a population [24].

#### 3.7.1 Simulation Design

The process of the development of the simulation environment consisted of the creation of the motion model, the surface to air missile guidance system, and then combining both

motion models into a simulation. Along with the motion models one must include the notification method and maneuver capabilities and the aircraft and missile constraints. Then one could perturb parameters for various case studies.

The simulation model will be object oriented in MATLAB and will contain four main classes the motion model for the aircraft, motion model for the missile, and the onboard radar and sensors. The sensor model for the missile simulates the perfect guidance system. One can assume the probability of success would increase as the sensor model fidelity increases. The motion model for the aircraft contains the parameters, maneuvers, and constraints. simulation parameters consist of number of times to vary initial parameters, altitude, initial position, type of aircraft, maneuver, missile location updates, direction, delay, and intensity.

Table 3.1: Simulation Parameters

Simulation Parameters	Description
n	Number of times parameters are varied
Altitude	Z coordinate of the aircraft
XaircraftInt	X coordinate of the aircraft
YaircraftInt	Y coordinate of the aircraft
Aircraft	Boeing 777-300ER
Missile	SA - 2
Maneuver	Aircraft actions after missile launch
Update	Aircraft's missile awareness
Direction	Aircraft's starting direction
Delay	Delay between updates of the missile's position
Intensity	How close to max load factor

### 3.8 Code Architecture

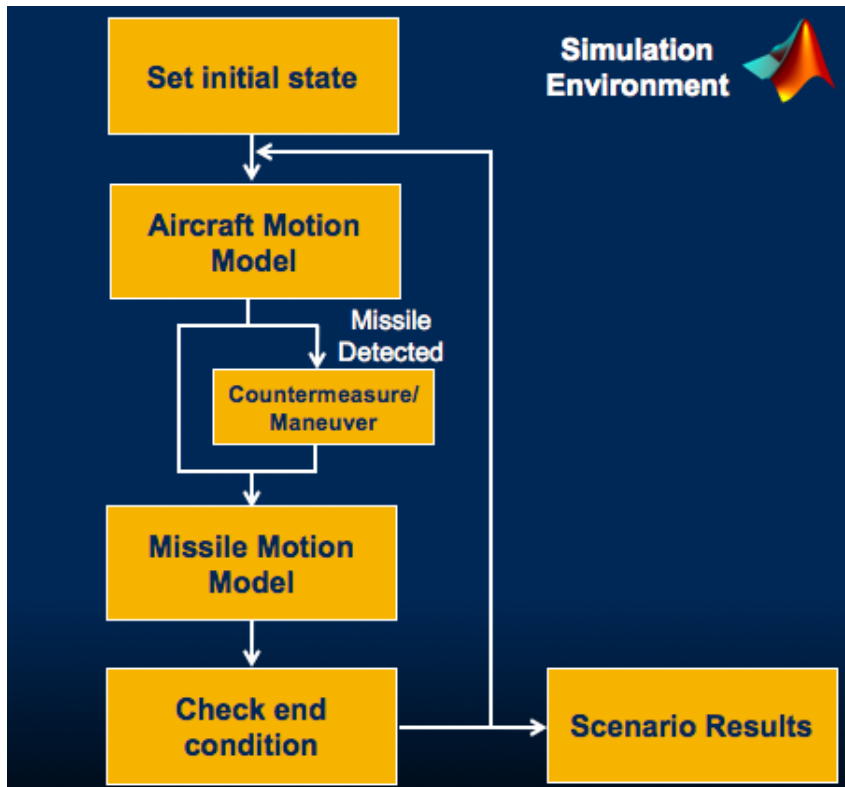


Figure 3.2: Code Architecture

The initial state was set by the simulation parameters regarding the aircraft's initial starting position and altitude using a Latin Hypercube Design [19, 25]. The reasoning behind only varying the starting position and not anything else such as cruise speed is because the cruise speeds would be so relatively close to each other that the change in cruise speed compared to the speed of the missile could be negligible.

The aircraft motion model was set by a wide-body aircraft that is very similar to a Boeing 777-300ER, which can hold up to 550 seats, has a max cruise speed of 587 mph, and a rate of climb of 3000 fpm [26]. The aircraft is constrained by the maximum number of G's and its cornering speed. The aircraft's maneuvers are constrained by the flight maneuvering envelope. The aircraft's power constraints for climbing are the pitch requirements and pos-

itive load factor, and the max rate of climb is constrained by the excess power. The physics based constraints such as the max velocity and loading factor limitations are determined from the V-n diagram.

$$E_h = H + \frac{1}{2g}V^2$$

$$ROC = \frac{ExcessPower}{W} \tag{3.3}$$

Table 3.2: Aircraft Parameters

Aircraft Parameters	Description
Cruise Speed	Aircraft's cruise speed
Climb Rate	Aircraft's rate of climb
Descend Rate	Aircraft's descend rate
Position Vector	Aircraft's initial position vector
Velocity Vector	Aircraft's initial velocity

Table 3.3: Boeing 777-300ER Properties

Aircraft Parameters	Description
Max Speed	Aircraft's cruise speed
W/S	Aircraft's rate of climb
Thrust Loading	Aircraft's descend rate
Coefficient of Drag	Aircraft's initial position vector
Aspect Ratio	Aircraft's initial velocity
Span Efficiency	Aircraft's span efficiency $W_{TO}$

Given the condition of a missile detection being true, the aircraft will begin its maneuver based on the given input parameters by the user. The aircraft will have two options regarding maneuvers; the first option will consist of absolutely no maneuver with the aircraft

Table 3.4: Boeing 777-300ER Constraints

Aircraft Parameters	Description
Corner Speed	Aircraft's corner speed
Acceleration	Aircraft's acceleration
Max g	Aircraft's maximum amount of g forces
Min g	Aircraft's minimum amount of g forces
Pitch Constraints	Aircraft's pitch limits

just continuing on its charted course. The second option will consist of a turn to the right, climbing, and increasing velocity. Along with the second maneuver option the aircraft will release the chaff slightly before it starts its maneuver. The chaff will then create a radar cross section large enough for the missile to then start approaching the chaff. Once the missile reaches the chaff it will then turn its bearing toward the aircraft, because it will then have the largest radar cross section.

Given the condition a missile is not detected the missile motion will take into effect. The missile being used in the simulation is very similar to the SA - 2 Guideline. This missile is constrained by its max speed, max g, mass, burn time, coefficient of drag, and drag polar. The turning model is based on the maximum structural acceleration and corresponding decrease in velocity. The missile motion model consist of the missile's position and velocity.

$$\begin{aligned}
 x_{new}(t) &= x(t) + t * v(t) \\
 v(t) &= v(t) * (updatedbearing)
 \end{aligned}
 \tag{3.4}$$

The simulation will have two options regarding the update of the missile's location with respect to the aircraft. The first option will be absolutely no alert of the missile launch which will simulate the lack of a missile warning system currently on commercial aircraft. The second option will simulate a missile warning system that will update the aircraft on

Table 3.5: Missile Parameters

Missile Parameters	Description
Max Speed	Missile's max speed
Max G's	Missile's max sustainable G forces
Mass	Missile's mass
Burn Time	How long missile is provided thrust
Missile's starting initial vector	Position Vector
Velocity Vector	Missile's starting initial vector
$C_d$	Missile's coefficient of drag
S	Missile's drag polar

the missile's time of launch and provide continuous updates of the missile's position. The missile warning system will also provide continuous updates to the aircraft regarding the missile's position.

Lastly, if the check end condition is satisfied by the missile being less than ten meters away from the aircraft or the velocity of the missile is less than mach one. If the given conditions are not met the scenario results will produced and then one could perform data analysis on the results.

## **CHAPTER 4**

### **RESULTS AND DISCUSSION**

For the results and discussion section this thesis will discuss the performed cost analysis which included the installation cost and operation and support costs for a wide body aircraft. Once the cost analysis is completed the researcher then performed a size, weight, and power analysis to understand the forces applied to the plane, compare the systems to the overall size of the plane, and calculate the cost of the power required. Then, the researcher will discuss the results of the effectiveness of a countermeasure and the lack thereof. Finally, the researcher synthesizes the above information into a benefit analysis, which will then lead to a recommendation based on the current state of the analysis. With the goal of bridging the gap between the cost of these technologies and quantifying their effectiveness.

#### **4.1 Cost Benefit Analysis**

According to fi-areoweb the United States fleet of commercial aircraft consisted of 7,126 vehicles and of that 7,126, 15.09% of those aircraft were wide body types. Therefore, there were 1,075 wide body aircraft in the United States fleet in 2016 [27]. The table below shows the entire make up of the United States commercial fleet by body type.

Table 4.1: U.S. Fleet 2016 — By Type

#	Type	# in Fleet	% of fleet
1	Narrow-Body Jet	3,934	55.21%
2	Regional Jet	1,639	23.00%
3	Wide-Body Jet	1,075	15.09%
4	Turboprop	386	5.42%
5	Business Jet	69	0.97%
6	Piston	23	0.32%

Using the methodology for the cost benefit analysis performed by Chow et al. at the RAND Corporation. The RAND Corporation is a research organization that develops solutions to public policy challenges to help make communities throughout the world safer and more prosperous [28]. One could assume the practices of the RAND corporation are sufficient, because of their reputation to produce acceptable results on a consistent basis.

#### 4.1.1 Installation Cost

The cost estimates are for installing the AN/AAR 54(V) missile warning system developed by Northrop Grumman that cost \$290k [29] and six ALE-47 Chaff/Flare dispenser systems developed by BAE systems that cost \$30k [30] each during the fiscal year (FY) 2018, on 1,075 U.S commercial aircraft. These costs were based on modifying the most current set of parametric data values from military systems.

The main assumption contributing to the cost benefit analysis is that these technologies can be retrofitted on to commercial aircraft; this assumption is derived from countermeasure technologies installed on Air Force One. One can estimate a total fleet installation cost of \$1.32 B. That includes the:

- Procurement of six ALE-47 Dispenser systems for 1,075 wide-body aircraft in the

Table 4.2: Installation Cost Estimate AN/AAR 54(V) ALE-47 FY 2018

Cost Name	Cost amount \$
Procurement (MWS & 6 units)	\$505,150,000
RDT&E	\$0
Production Start- Up	\$0
Spares	\$46,530,000
Retrofit Aircraft	\$769,648,690
Total	\$1,321,428,690

United States commercial fleet at \$505.25 M

- Procurement of approximately 99 missile warning systems and approximately 600 ALE-47 spare dispenser systems at approximately \$46.6M
- The value above may not reflect the exact value of retrofitting the ALE 47 dispenser systems and a MWS, but from the literature one can assume it may cost on the order of hundreds of thousands of dollars. Retrofitting approximately 1,075 wide-body aircraft in the United States commercial fleet at \$769.65 M

The two main differences between the current cost benefit analysis and the one performed by Chow et al. regarding the installation cost is Chow et al. included for \$445 M for research, development, test, and evaluation. These activities consisted of the systems design, aircraft flight testing, and Federal Aviation Administration certification for six fully configured prototype systems. Also, Chow et al. set aside \$165 M for manufacturing technologies, capital, facilities to build up the annual production rate needed through the end of low-rate initial production, and set-up tooling of a second final assembly and test manufacturing line for the entire full-rate production phase. The reason this current cost benefit analysis doesn't include those costs is because these technologies are off the shelf, and in this case BAE Systems and Northrup Grumman would be responsible for those costs.

The cost of procurement was calculated by the given cost of \$180,000 for six of the ALE

47 dispenser systems added to the \$290,000 for the Northrup Grumman missile warning system, to give a total value of \$470,000 per aircraft. Then multiplying it by 1,075, for the total number of wide-body U.S aircraft in the United States fleet, provide a total value of \$505.25M.

The cost of the spares was calculated from the information given from the Chow et al. cost benefit analysis; one could find the percentage of spares from the cost of the spares divided by the total cost of the procurement. Then once could multiply that percentage by the number of wide-body planes in the United States fleet to find the number of spares.

Chow et al. combined the cost of procurement and retrofitting their specified technology into one cost. One could calculate the cost of retrofitting by subtracting the cost of procurement from the total cost, which would determine the cost of retrofitting, which has a value of \$715,952. Multiplying that value by 1,075 yields the total value of approximately \$770 M.

#### 4.1.2 Operation & Support Cost

The cost estimates are derived from operating and supporting the AN/AAR 54(V) missile warning system developed by Northrop Grumman and six ALE-47 Chaff/Flare dispenser systems developed by BAE systems in the fiscal year (FY) 2018 of 1,075 U.S commercial aircraft. These costs were based on modifying the most current set of of parametric data values from military systems.

The differences between the current cost benefit analysis and the one completed by Chow et al. is Chow et al. included technology upgrade sustainment costs that maintain the capability of the countermeasures as different threats emerge, which does not account for dramatic shifts in threat capability. Chow et al. also included cost growth/uncertainty of 25%. The

Table 4.3: Operation and Support Cost Estimate AN/AAR 54(V) ALE-47 FY 2018

Cost Name	Fleet Cost Amount\$	Cost Amount Per Aircraft \$
Maintenance	\$273,240,390	\$254,177
Added Fuel	\$26,815,262	\$24,944
Cost Growth	\$0	\$0
Tech Upgrade and Sustainment	\$0	\$0
Airplane Delays	\$21,956,821	\$20,424
O&S (Ten Year Service)	\$268,356,875	\$249,634
Maintenance (Ten Year Service)	\$273,240,3897	\$2,541,771
Total	\$3,220,124,735	

reason behind not including these costs are because the technologies being retrofitted are at the top of their technology "S" curve, and one could conclude that it would not be logical to continue to invest in a technology when it is at the top of its "S" curve.

The value of \$29,944 for added fuel is needed due to the drag and additional weight that the aircraft will be carrying over an assumed 3,000 hours per year. One could calculate this value by using the values provided by the cost benefit analysis performed by Chow et al.. Chow et al. stated that it would cost \$45,000 per aircraft to carry an additional 500 lbs. Since the total weight of the missile warning system and ALE-47 dispenser system is approximately 225 lbs., one could assume the cost for additional fuel would be about half of what was stated in the original cost benefit analysis after moving the dollar amount to today's dollar value.

The maintenance cost of \$254,177 per aircraft per year stems from the airline mechanics labor and other material needed to do on-equipment airport ground maintenance. Airline contractor logistics support activities for scheduled system overhauls and unscheduled repairs of failed components sent back from the airport [38]. The maintenance cost was driven by a mean-time-between-failure(MTBF) estimate of 600 hours, based on projected

military system reliability. Chow et al. determined there would be a per aircraft maintenance cost of \$140,000 based on a mean-time-between-failure of 800 hours. After moving the dollar amount to today's value one could calculate the cost of maintenance based on the MTBF. Chow et al. determined there would be \$15,000 in operations cost in airport delays; moving that dollar amount to today's value one would obtain the dollar amount \$20,425 in airport delays. Propagating the operation and support cost and maintenance cost over a ten year period one would get the values of \$487,720,838 and \$2,732,403,897 respectively for a grand total of \$3,220,124,735.

#### **4.2 Size, Weight, and Power Analysis**

The purpose of the SWAP analysis is to study the countermeasure's physical effects on the wide-body aircraft. The wide-body commercial aircraft will be equipped with six ALE-47 dispenser systems and one AN/AAR 54(V). The reasoning behind equipping the commercial aircraft with six dispenser systems is because of the similarity in dimensions between a wide-body military aircraft and a wide-body commercial aircraft, they have similar radar cross sections, based on dimensions. Currently, C-130 aircraft are equipped with 12 ALE-47 dispensers, six for flares, six for chaff [32].

The values in the table above are pulled from the Navy's system training plan [6]. The total volume of all six ALE-47 dispenser systems is approximately five feet, which is not that large when you compare it to the size of the cargo hold capacity of a wide-body aircraft. The size and weights of the dispenser system are not negligible, because for any given aircraft there is a maximum take off weight.

The weight of the missile warning system developed by Northrop Grumman could not be determined. The size and weight of a different missile warning system is included below which was developed by BAE systems. The total weight of the six dispensers and one mis-

Table 4.4: Size, Weight, and Power Analysis of ALE - 47 Dispenser System

EQUIPMENT	LENGTH(IN)	WIDTH(IN)	HEIGHT(IN)	WEIGHT(LBS)	VOL(FT <sup>3</sup> )
Progammer	5.75	3.75	6.14	4.5	0.077
CDU	6.8	5.75	3.75	5.0	0.085
DCDU	4.22	5.675	3.00	2.3	0.042
Sequencer	6.53	6.57	2.89	3.75	0.072
Digital Sequencer Switch	6.00	4.00	1.80	1.5	0.025
Dispenser (D-56 or D-63)	9.83	10.13	7.77	4.00	0.448
Magazine (MX-11599)				6	
Safety Switch	4.61	3.64	2.55	2	0.025
Total 1 System	43.74	39.52	20.13	29.05	0.772
Total 6 Systems	262.44	237.09	120.78	174.3	4.634

sile warning system is approximately 225 lbs. The weight of the average human is 137 lbs; one can perform a tradeoff between losing two passengers, or if the airline company wants to keep its maximum amount of seats on board one can assume the weight would come from the fuel weight. The Boeing 777-300ER has a maximum range of approximately 9,000 miles, with a maximum fuel capacity of 47,890 gallons [26]. A naive calculation for mileage would therefore be approximately 0.188 mpg. There are aspects that are not included such as load, altitude, and winds [33]. Using the values from the source above the wide-body aircraft would lose approximately six miles based on the naive calculations above. The values in the table below come from forecasts international [35].

Table 4.5: Size, Weight, and Power Analysis of a NOTIONAL missile warning system

EQUIPMENT	LENGTH(IN)	WIDTH(IN)	HEIGHT(IN)	WEIGHT(LBS)	POWER(WATTS)
Receiver & Transmitter	20	10	8	49.6	425

### Energy Consumption

$$E_{\left(\frac{kWh}{day}\right)} = P_{(W)} * t_{\left(\frac{h}{day}\right)} / 1000_{\left(\frac{W}{kW}\right)} \quad (4.1)$$

## Energy Cost Calculation

$$Cost_{\left(\frac{\$}{day}\right)} = E_{\left(\frac{kWh}{day}\right)} * Cost_{\left(\frac{cent}{kWh}\right)} / 100_{\left(\frac{cent}{\$}\right)} \quad (4.2)$$

To calculate the cost of the power consumption from the missile warning system above one can use the mentioned the equations mentioned previously and based on the current kilowatt-hour cost of 12 cents. The energy cost of a system that consumes 425 watts used 24 hours a day is \$447 annually. One can also assume the system would only be used for for a few hours at a time, decreasing the cost drastically. Again, the calculation above assumes the system will be used for 24 hours a day to determine the cost of the absolute worst case scenario.

### 4.3 Survivability Model

The researcher performed three case studies simulating the wide-body aircraft without any countermeasure technologies and without performing a maneuver, the wide-body aircraft with just missile warning system and a maneuver, and the wide-body aircraft with only a missile warning system, countermeasure, and maneuver. The three case studies will use the same aircraft and missile parameters. There will be a trade off study on the effectiveness of the maneuver, missile warning system, and/or the countermeasure. The trade off study will include varying the parameters alert time and the use of a countermeasure. The MATLAB visual outputs consist of the initial position of the aircraft. The red dots indicate the aircraft was impacted and the green dots indicate the aircraft avoided impact. The aircraft and missile parameters above will be the parameters used for all three case studies.

Table 4.6: Aircraft Parameters

Aircraft Parameters	Description
Cruise Speed	$250.3 \frac{m}{s}$
Max Climb Rate	$10.2 \frac{m}{s}$
Max Descend Rate	$10.2 \frac{m}{s}$
Position Vector	Generated by LH
Velocity Vector	[250.3,0,0]

Table 4.7: Missile Parameters

Missile Parameters	Description
Max Speed	$877.9 \frac{m}{s}$
Max G's	50
Mass	2300kg
Burn Time	50.9s
Position Vector	[0,0,0]
Velocity Vector	[0,0,877.9]
$C_d$	0.1
S	$5 m^3$

### 4.3.1 Case Study # 1

Table 4.8: Simulation Parameters: No Alert and No Maneuver

Simulation Parameters	
n	5000
Altitude	Z coordinate of the aircraft
XaircraftInt	Generated by LH
YaircraftInt	Generated LH
Aircraft	Boeing 777-300ER
Missile	SA - 2
Maneuver	Stay current course
Update	None
Direction	Straight
Delay	N/A
Alert Time	Aircraft is not alerted
Intensity	1

For the first case study the researcher created a scenario that simulates a wide-body aircraft attempting to be shot down by a surface to air missile. The aircraft is completely unaware of the SAM site and is not alerted or updated about the missile's location. The simulation parameters are listed above.

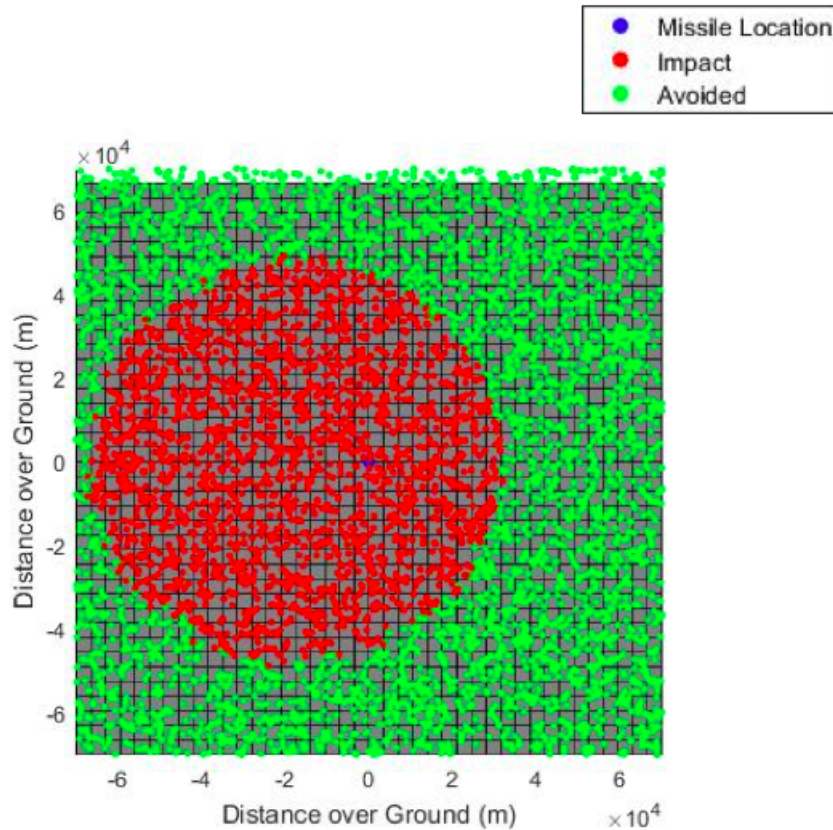


Figure 4.1: No Alert and No Maneuver Matlab Visual Output

The figure above is one of the outputs of the simulation and it describes the initial starting position of the aircraft relative to the missile. The SAM started to make impact with the aircraft that were located within 70km. The colors indicate if the aircraft was impacted or avoided. Due to the aircraft having zero indication of the location of the missile, the missile had an extremely high success rate against every aircraft within its range. One could expect an asymmetric plot, because the aircraft was flying straight in the positive x direction.

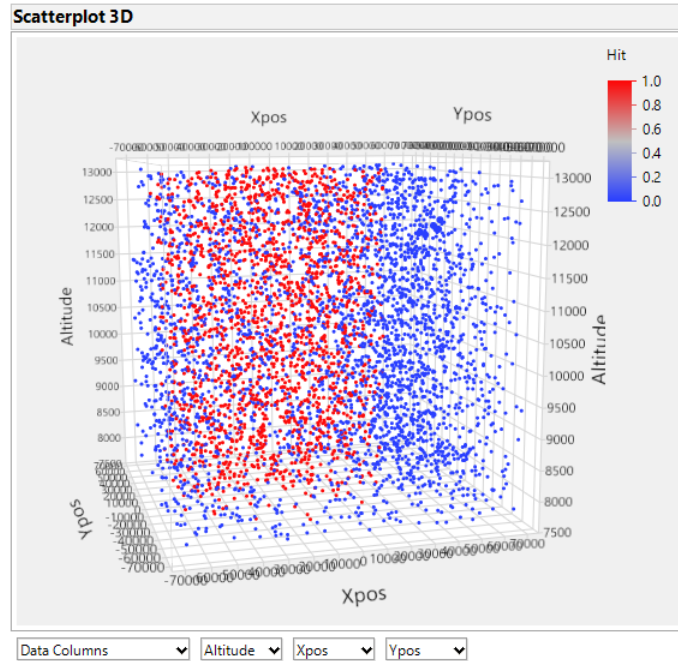


Figure 4.2: No Alert and No Maneuver JMP 3D Scatterplot

The scatter plot above shows a view of the effectiveness of the SAM based on altitude. One can see more successful hits against the aircraft heading towards the missile's initial location. The heading of the aircraft is the same for all 5000 runs in the positive x direction. One could expect this, because the initial positions created by the Latin Hypercube greater than 0 in the x direction gave the aircraft a slightly better chance of avoiding impact, because it is traveling away from the missile launch site. The data analysis completed in JMP Pro 14 displays a trend of decreasing effectiveness the greater the distance from the initial location of the missile.

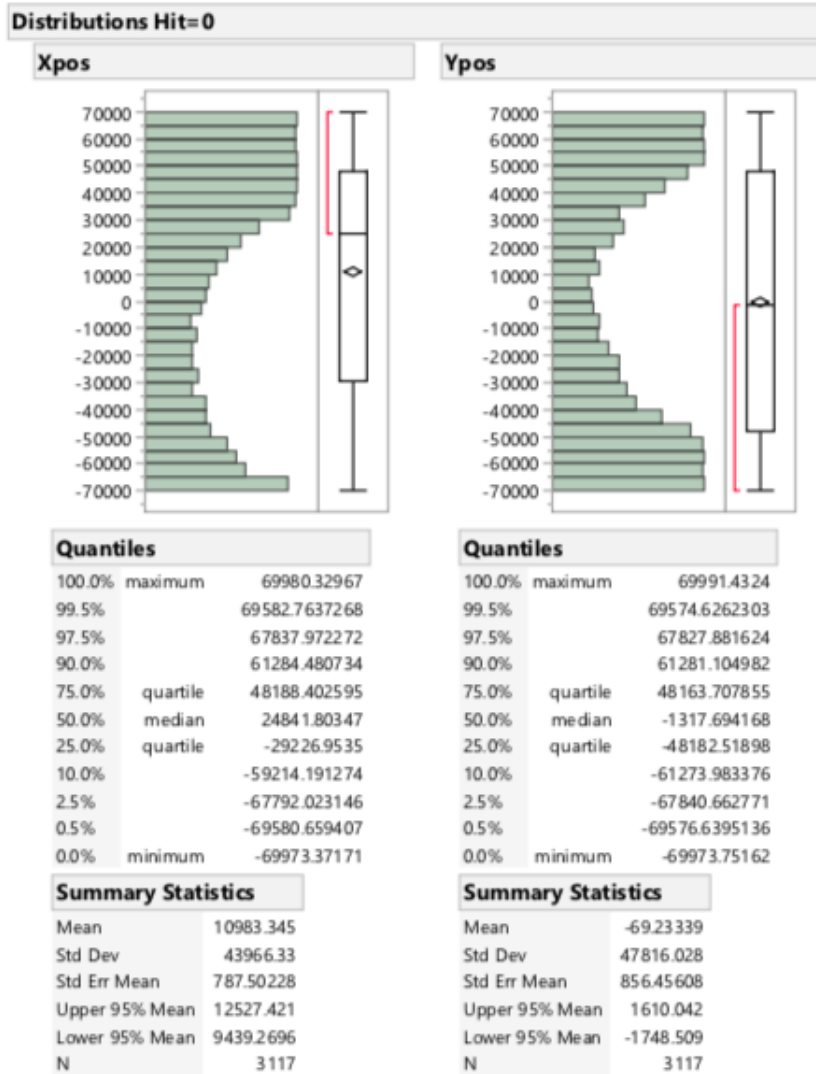


Figure 4.3: Non-Impact Distribution of X&Y initial location

The graphic above displays the Gaussian distribution of the non-impact scenarios based on the the airplanes initial X position and Y position. One can see the greatest chance of avoiding the surface to air missile is at 70km headed toward the missile's initial location and at 35km heading away from the missile's location. With the lowest chance of avoidance being in between the 0-20km range.

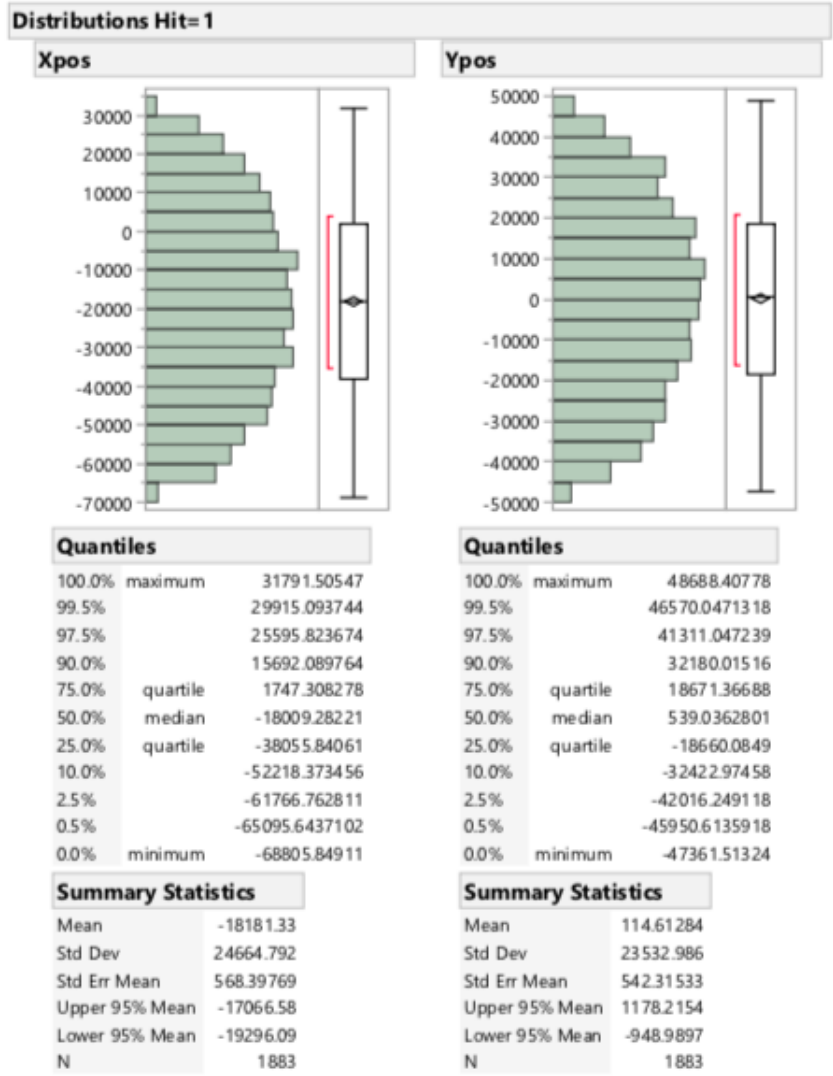


Figure 4.4: Impact Distribution of X&Y initial location

The graphic above displays the Gaussian distribution of the impact scenarios based on the the airplanes initial X position and Y position. One can see the missile starts making impact at approximately 70km, which also is the missile's lowest chance of impact.

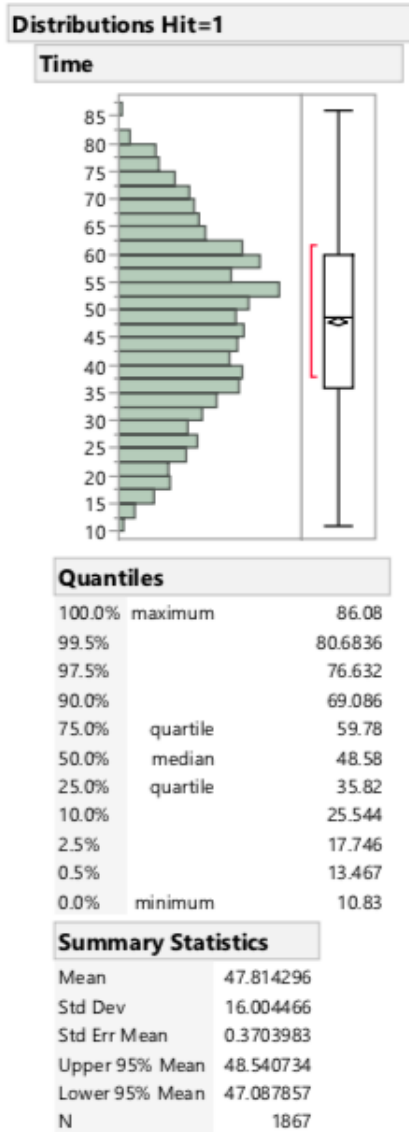


Figure 4.5: Time Impact Distribution

The graphic above displays the time until impact for 5000 runs. The number of importance calculated in JMP 14 pro is the average time until impact, the average time until impact is 47.8s.

### 4.3.2 Case Study #2

Table 4.9: Simulation Parameters: Full Alert and Maneuver

Simulation Parameters	
n	5000
Altitude	Z coordinate of the aircraft
XaircraftInt	Generated by LH
YaircraftInt	Generated LH
Aircraft	Boeing 777-300ER
Missile	SA - 2
Maneuver	Maneuvers to missile's bearing
Update	Missile location updates
Direction	Maneuvers to missile's bearing
Delay	N/A
Alert Time	Aircraft is alerted at missile launch
Intensity	1

For the second case study the researcher created a scenario that simulates a wide-body aircraft equipped with a missile warning system attempting to be shot down by a surface to air missile. The aircraft is completely aware of the SAM site and is alerted and updated about the missile's location. After the aircraft is alerted the aircraft attempted to maneuver. The simulation parameters are listed above.

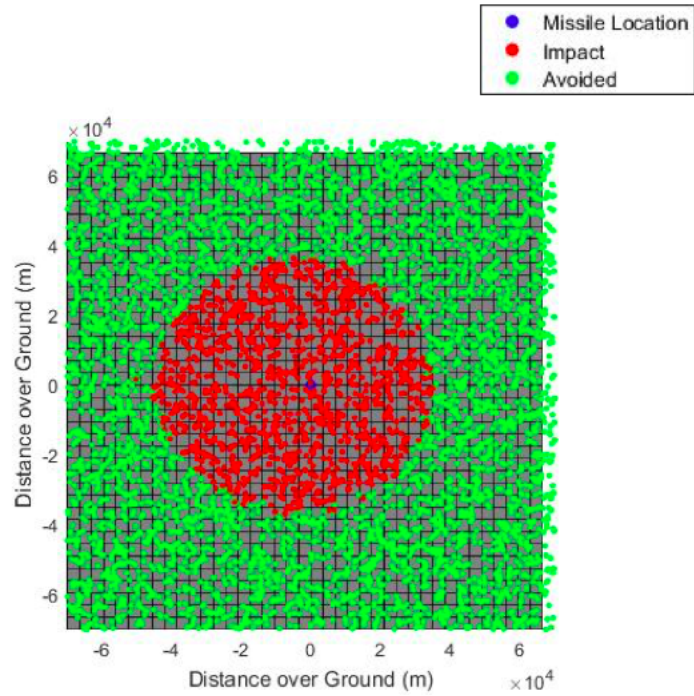


Figure 4.6: Full Alert and Maneuver Matlab Visual Output

In this case study, because the aircraft was aware of the missile launch it was able to make a maneuver. As one could see from the figure above that there was some improvement on the x-axis. The aircraft was able to get approximately 20km closer to the initial missile launch location when compared to case study # 1.

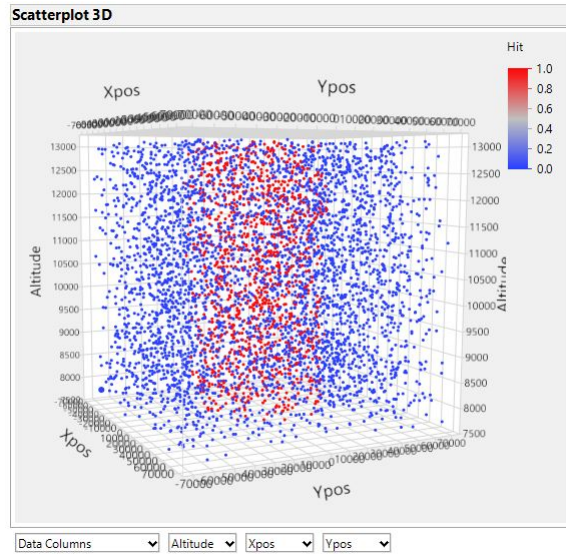


Figure 4.7: Full Alert and Maneuver JMP 3D Scatterplot

Again, the scatter plot above shows a view of the effectiveness of the SAM based on altitude. The plot above shows more successful hits against the aircraft heading towards the missile's initial location. This scatter plot reflects a significant change in the SAMs effective range when compared to case study #1. Again, one could expect the effectiveness of the SAM based on altitude would closely resemble a uniform distribution.

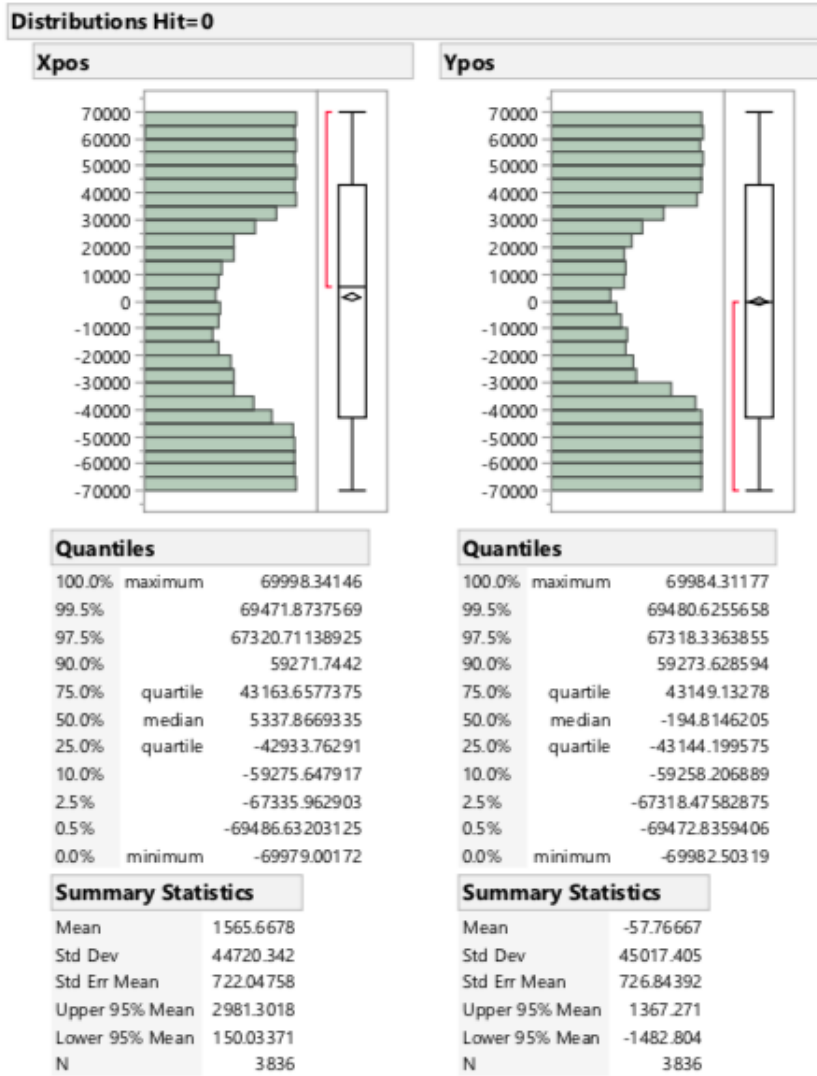


Figure 4.8: Non-Impact Distribution

The graphic above displays the Gaussian distribution of the non-impact scenarios based on the the airplanes initial X position and Y position. One can see the greatest chance of avoiding the surface to air missile is at 50km headed toward the missile's initial location and at 35km heading away from the missile's location. With the lowest chance of avoidance being in between the 0-20km range. Again, reducing the SAM's effective range to 50km when headed toward the SAM site.

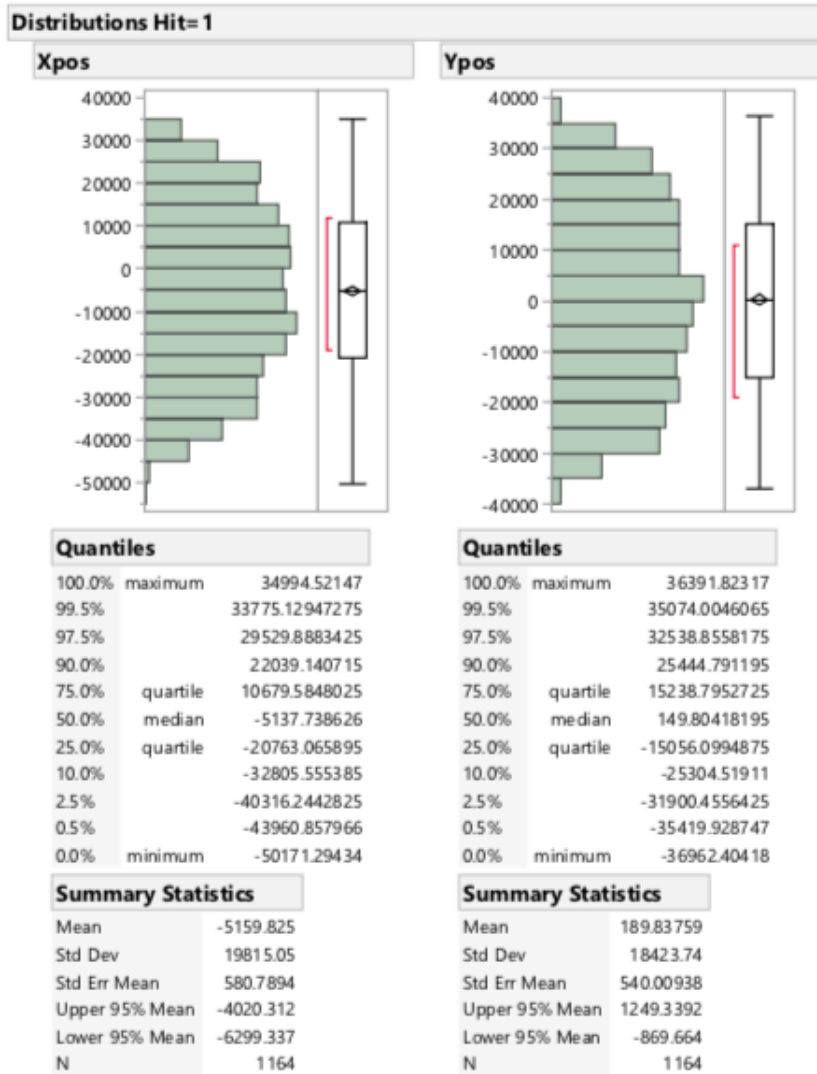


Figure 4.9: Impact Distribution

The graphic above displays the Gaussian distribution of the impact scenarios based on the the airplanes initial X position and Y position. One can see the missile starts making impact at approximately 50km, which also is the missile's lowest chance of impact.

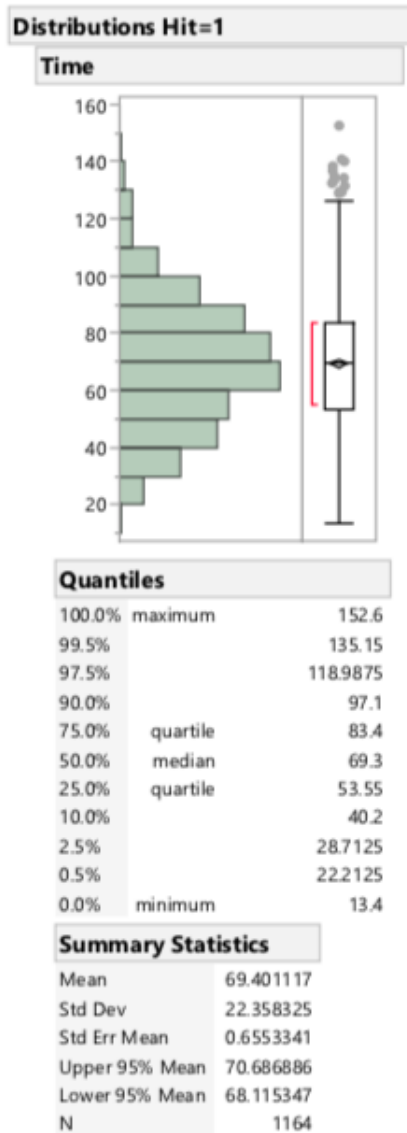


Figure 4.10: Time Impact Distribution

The graphic above displays the time until impact for 5000 runs. The average time until impact was 69.4s. The average time until impact increased from 47.8s to 69.4s. The time of survival increased by approximately 20 seconds when compared to case study # 1. One could use this number as validation, because as you increase the number of operations to avoid the surface to air threat, the time of survival would increase.

### 4.3.3 Case Study #3

Table 4.10: Simulation Parameters: Full Alert, Maneuver, Countermeasure: Chaff

Simulation Parameters	
n	5000
Altitude	Z coordinate of the aircraft
XaircraftInt	Generated by LH
YaircraftInt	Generated LH
Aircraft	Boeing 777-300ER
Missile	SA - 2
Maneuver	Maneuvers to missile's bearing
Update	Missile location updates
Direction	Maneuvers to missile's bearing
Delay	N/A
Alert Time	Aircraft is alerted at missile launch
Countermeasure	Chaff
Intensity	1

For the third case study the researcher created a scenario that simulates a wide-body aircraft equipped with a missile warning system and countermeasure, attempting to be shot down by a surface to air missile. The aircraft is completely aware of the SAM site and is alerted and updated about the missile's location. After the aircraft is alerted the aircraft attempted to make a maneuver. The simulation parameters are listed above. In this case study, because the aircraft was aware of the missile launch it was able to make a maneuver and release a countermeasure. The ALE-47 dispenser system comes with an automatic release setting which one can assume relieves the human in the system of responsibility, ultimately reducing the human error to zero.

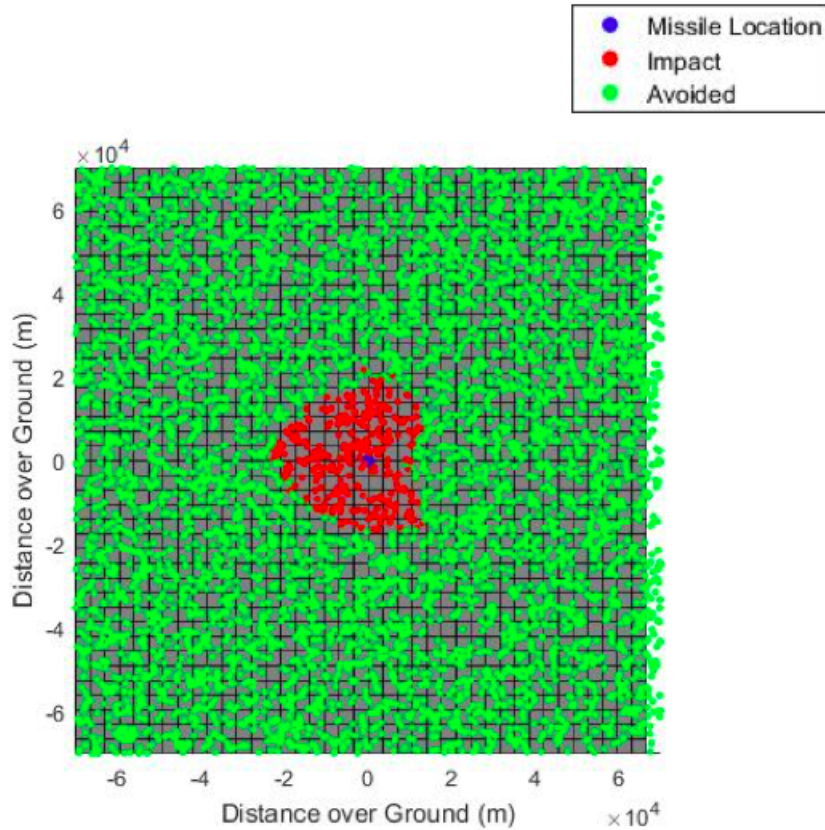


Figure 4.11: Full Alert, Maneuver, and Countermeasure Matlab Visual Output

In this case study, because the aircraft was aware of the missile launch it was able to make a maneuver and use a countermeasure. As one could see from the figure above that there was some improvement on the x-axis, but also in the y axis. The aircraft was able to get approximately 30km closer to the initial missile launch location when compared to case study # 2 and 50km closer compared to case study #1.

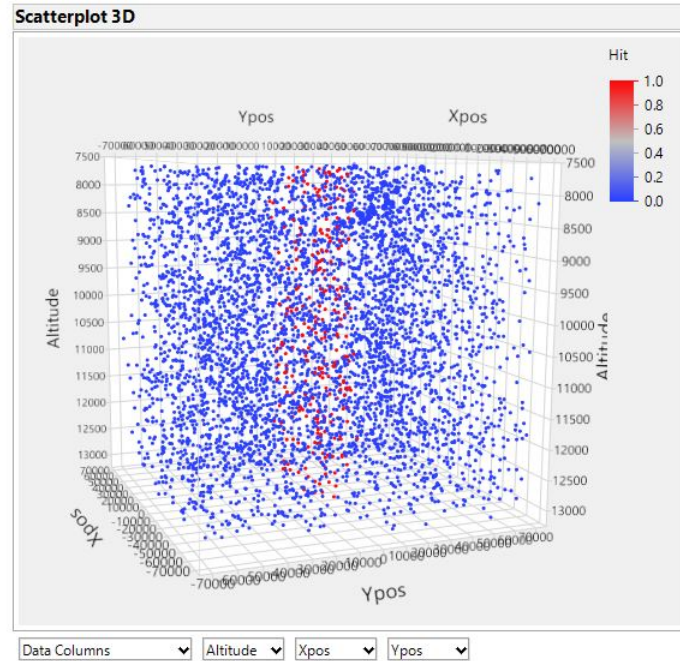


Figure 4.12: Full Alert, Maneuver, and Countermeasure JMP 3D Scatterplot

Again, the scatter plot above shows a view of the effectiveness of the SAM based on altitude. The plot above shows more successful hits against the aircraft heading towards the missile's initial location. This scatter plot reflects a significant change in the SAMs effective range when compared to case study #1 & #2. Again, one could expect the effectiveness of the SAM based on altitude would closely resemble a uniform distribution.

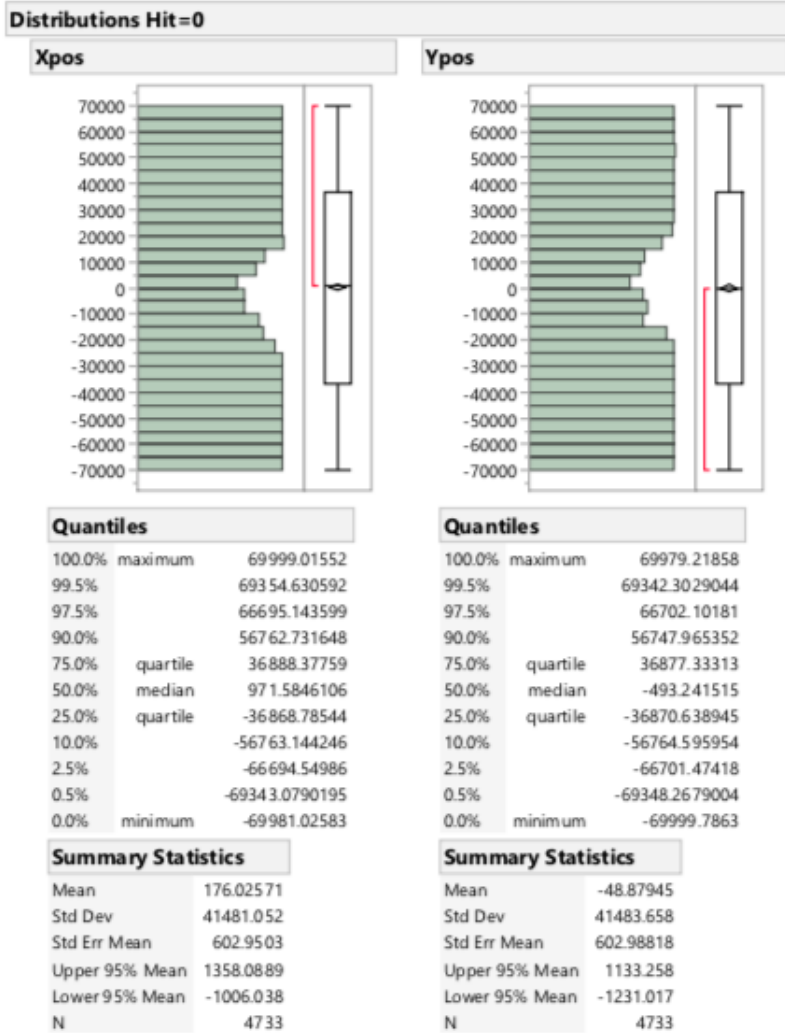


Figure 4.13: Non-Impact Distribution

The graphic above displays the Gaussian distribution of the non-impact scenarios based on the the airplanes initial X position and Y position. One can see the greatest chance of avoiding the surface to air missile is at 20km headed toward the missile’s initial location and at 15km heading away from the missile’s location. With the lowest chance of avoidance being in between the 0-5km range. Again, reducing the SAM’s effective range to 20km when headed toward the SAM site.

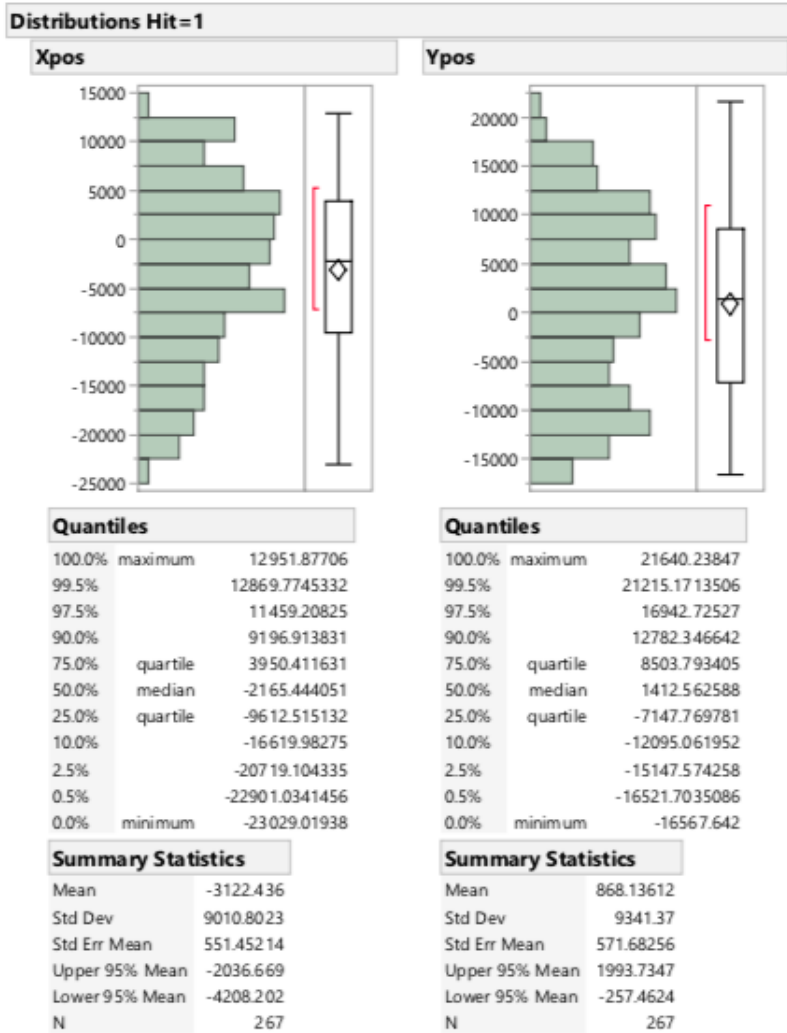


Figure 4.14: Impact Distribution

The graphic above displays the Gaussian distribution of the impact scenarios based on the the airplanes initial X position and Y position. One can see the missile starts making impact at approximately 20km, which also is the missile's lowest chance of impact.

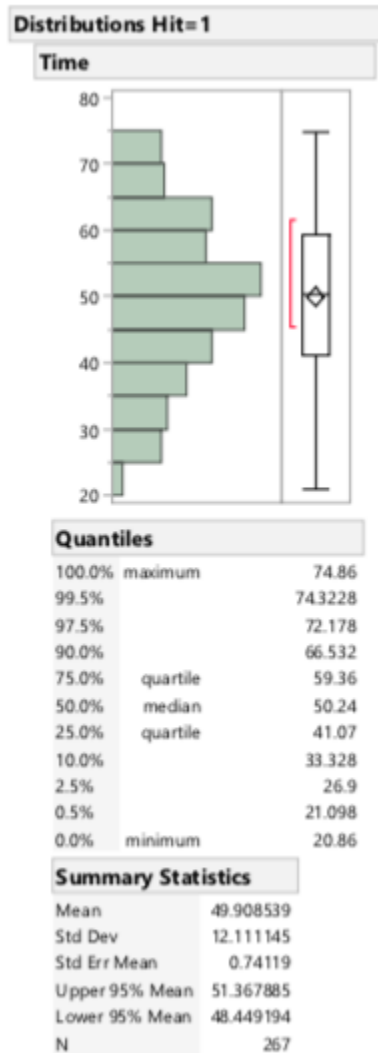


Figure 4.15: Time until Impact Distribution

The graphic above displays the time until impact for 5000 runs. The average time until impact was 49.9s. One could expect a decrease in survival time, because the aircraft that were hit were so much closer to the initial position of the missile. One could compare the time of survival of the aircraft between the range 0 - 20km to the survival time of the aircraft not equipped with countermeasures between the same range.

#### 4.3.4 Validation

There were several steps taken to validate the model created. Expert intuition and real system measurements were the guiding principles throughout the development process. When dealing with systems such as surface to air missiles, there is a lot of information that is available, but there is also a lot of information not available, causing one to make assumptions and perform rough naive calculations. Real system measurements were available for the aircraft and countermeasure systems individually. However, they were not real system measurements for the two systems combined. Making the real system measurement approach invalid. As another form of validation the researcher performed single runs with specific input parameter values, with foreseeable outcomes.

#### 4.3.5 Benefit Analysis

The researcher has calculated the costs of retrofitting commercial aircraft with countermeasure technologies and simulated the countermeasure's effectiveness at various altitudes, one can now perform a benefit analysis.

Any decision about government-mandated countermeasures installation aboard commercial airliners should thus consider the overall budget available for homeland security purposes [38]. The FY 2018 Transportation Security Administration budget is \$7.6 B [31]. One can assume the government would be responsible, because in a capitalistic society the state cannot force private industry to bear the cost. These cost estimates encompass only the period through the year 2028. As time goes on one could assume the technology available to terrorist groups will improve. The weapons systems of the future will have the capability of being radar guided and infrared guided, which would entail multiple countermeasure systems on board commercial airliners for there to be a slight chance of survival. At that point it may become desirable to increase the countermeasure capability on commercial aircraft. The total cost of installation and O&S is approximately \$4.5 B, which

encompasses about 59% of the current TSA budget. The technologies being considered only attempt to protect the aircraft against one type of surface to air missile. Another very important aspect not being considered is the taking off and landing portion of the commercial aircraft's flight profile. One could make the argument that that is currently the larger threat to commercial aircraft. The goal of this research was to bridge the gap between the performance of the countermeasure technology and the cost benefit analysis of the same technology. One could feel if the countermeasure technology improves the odds of aircraft survival by even one percent then it could be economically feasible and technically viable. One could also feel the price tag of integrating these technologies is economically feasible, because the chances of anyone actually attempting to shoot down an airliner are much less than one percent. A multilayered approach is important, because no single countermeasure can defeat all possible SAM attacks with high confidence. Nonetheless, substantial protection can be achieved by adding a missile warning system and a chaff dispenser system to a commercial aircraft.

#### **4.4 Summary of Findings**

The findings from this thesis include quantifying the effectiveness of the ALE 47 dispenser system and the AN/AAR 54 missile warning system along with a cost benefit analysis. The results from the CBA include approximately \$1.3 B for installation costs and approximately \$3.2 B for O&S costs through the year of 2028. The combined cost of both is \$ 4.5 B, which is approximately 60% of the current 2018 budget of \$7.6 B. The results from the SWAP analysis conclude adding these technologies to commercial aircraft is technically feasible. To add six ALE 47 dispenser systems and one MWS it would require approximately 5 cubic feet of space in the cargo area of the aircraft. The MWS system would use approximately 400 watts, which would cost approximately \$500 annually if the system is used 24 hours a day. The effectiveness of the SAM is extremely high when the aircraft is unaware of SAM

site. The SAM had an effective range up to 70km for aircraft headed towards the SAM site. The effectiveness of the SAM decreases when the aircraft is able to maneuver, reducing the effective range to 50km. Quantifying the effectiveness of the countermeasure resulted in reducing the effective range of the SAM to 20km. The table and figure below outlines the effect of taking actions against a surface to air threat and also comparing the benefits of countermeasures versus maneuvers.

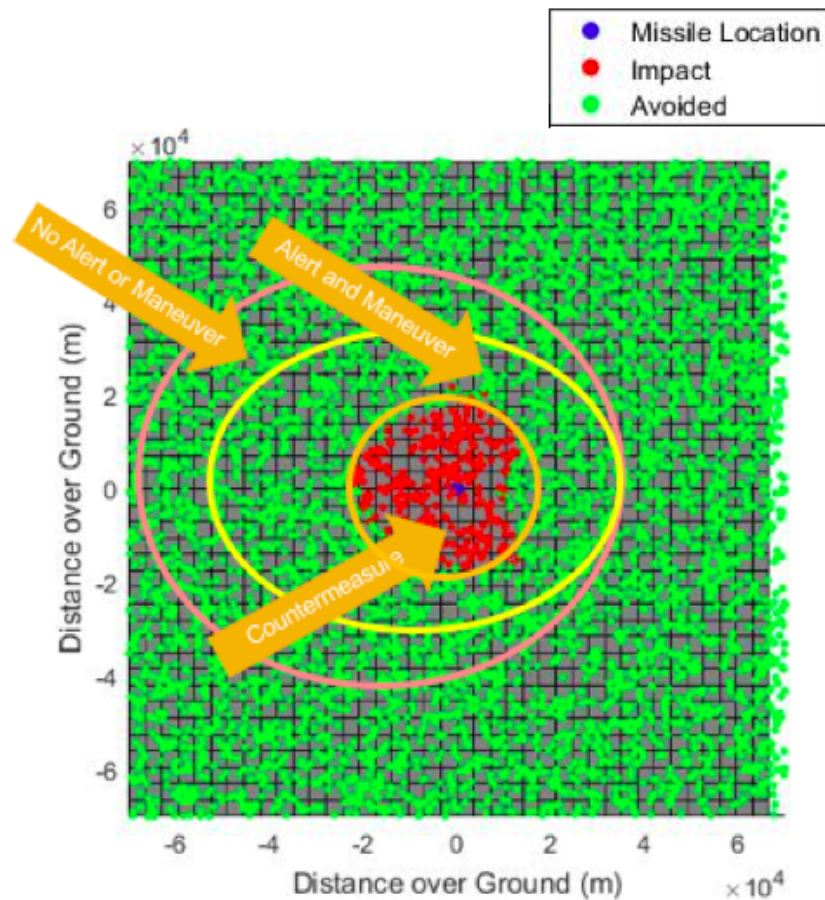


Figure 4.16: Effective range of SAM based on operation

The figure above displays the effective range of the SAM based on the aircraft operation. The area encompassed by the largest circle, represents when the aircraft is completely unaware of the SAM. The second largest area represents when the aircraft is equipped with the missile warning system and the aircraft is able to perform a maneuver. The smallest

area represents the effective range of the SAM when the aircraft is equipped with a missile warning system and countermeasure system.

Table 4.11: Current vs. Maneuver vs. Countermeasure

Current Setup	MWS & Maneuver	MWS & Maneuver & Countermeasure	
Effective SAM range	70km	50 km	20 km
Additional Cost	\$0	\$10's of thousands	\$4.5 B

Along with the figure above to compare the differences of the way current commercial aircraft are equipped, countermeasures, and maneuvers the data was tabulated to compare the three. In the table above one could see the effective range of the SAM for the aircraft headed toward the SAM site. The cost of the maneuver is based on the literature of training pilots to perform an optimized maneuver. One could assume that putting the aircraft in autopilot to perform the maneuver would drastically reduce the error in a high pressure situation. Again, addressing research question two and substantiating hypothesis two. Case study #1 verifies the effectiveness of a surface to air threat against a defenseless wide-body aircraft to be extremely high. The most important contribution this thesis makes is when one compares case study #2 to case study #3, one can recognize at the current state of the technologies being considered making a maneuver is a more viable alternative than adding technologies to commercial aircraft. Unless, one could determine a much smaller fleet size to add these technologies to, then one could make the argument adding technologies is a more viable option if one deems the difference in effectiveness to be worth it.

#### 4.4.1 Recommendations

Given the uncertainties of the effectiveness of the countermeasures when equipped to a commercial airliner and the pilot in a time of extremely high pressure. A decision to install

these technologies should be postponed for the following reasons. The current chance of a commercial airliner attempting to be shot down is extremely low, also the effectiveness of the countermeasure does not reduce the effective range of the SAM to zero, making the investment not currently worth it. As soon as there is a countermeasure that would allow a commercial aircraft to virtually fly over any conflict zone with 100% confidence and protect the aircraft in all three phase of flight takeoff, cruise, and landing. Then one can assume it would be worth it to add these technologies to a commercial aircraft. In the meantime flying around conflict zones will assert itself as the more viable option.

#### 4.4.2 Limitations

The cost benefit analysis does not incorporate the training of ground crews in maintaining the new countermeasure systems. There are limitations in the simulation specifically in the missile sensor model. The current missile sensor model always knows the location of the aircraft. An increased fidelity in the missile sensor model would include radar sensor error. Incorporating this error would slightly increase the odds of avoiding the surface to air threat. To perform an optimized maneuver to avoid a surface to air threat it would require the training of the pilots who are required to fly aircraft with countermeasure systems, which would incur some additional cost.

#### 4.4.3 Future Work

Future work for this research consists of increasing the fidelity of the model in the following places, such as the missile sensor model and the atmospheric physics surrounding the chaff cloud. Additional future work includes performing trade studies on the countermeasure effectiveness against different types of threats and countermeasures and also perturbing the delay and alert times.

## **CHAPTER 5**

### **CONCLUSION**

The United States has many airline companies and citizens that fly over millions of square miles of conflict zones on a daily basis [4], increasing the chances of an attempt to shoot down a commercial aircraft. As time goes on it is increasingly easier for rebel groups to acquire surface to air missiles. As a way to decrease the chances of a surface to air threat making contact with a commercial transport aircraft, there has been some research done by chow et al. that mentions a multilayered approach on how to mitigate some of this risk by adding technologies to these aircraft that would accomplish this task.

The objective of this research was to bridge the gap between the cost benefit analysis and to quantify the effectiveness of the ALE-47 chaff dispenser system integrated along with the AN/AAR 54(V) missile warning system. Bridging this gap involved answering the following research questions with their hypothesis:

#### **Research Question 1:**

How can one quantify the effectiveness of countermeasures deployed from commercial airliners against surface to air threats to capture the cost benefit relationship for implementation of such countermeasures?

#### **Hypothesis 1:**

If the researcher uses a survivability model to quantify the effectiveness of each countermeasure and a cost model to provide detailed cost analysis, then one could directly capture the correlation between cost and survivability between countermeasures.

**Research Question 2:**

By quantifying the effects of the countermeasure on a commercial aircraft using a SWAP analysis one could determine if the cost of implementation from both acquisition cost and performance decrements are justified. Further, how can one determine if adding countermeasures to commercial aircraft or simply avoiding conflict zones altogether is more cost effective over the lifespan of the vehicle?

**Hypothesis 2:**

If the survivability rate is not high enough to justify the cost of adding these technologies to a commercial aircraft; then avoiding conflict zones altogether will likely assert itself as the more viable alternative.

To capture the correlation between cost and effectiveness of the countermeasure technology, the researcher performed a cost benefit analysis on all of the technologies that would make the countermeasure technology most effective. The steps below were taken to perform the cost benefit analysis.

1. Define the unit of cost. It is important to establish what exactly your CBA measures in terms of cost. The two types of cost defined by my research will be time and money.
2. Itemize the tangible costs of the intended project. The two tangible costs that the researcher will consider will be installation cost and OS costs.
3. Itemize all intangible costs.
4. Itemize projected benefits, that stem from adding countermeasure systems to commercial aircraft. If there were an unsuccessful SAM attack on a United States commercial aircraft, due to a countermeasure system, the projected benefits are that the confidence of travelers will increase, money will be saved from the saving of lives

and the plane, and a possible increase in travelers who feared a SAM attack on a commercial aircraft.

5. Add up and compare the project's cost and benefits. All of the installation costs and OS costs will be added up, and then all of the ongoing costs will be subtracted from the ongoing benefits determined in step 4.
6. Calculate a payback time for the venture. Unfortunately, for this venture to be worth it there would have to be an attack on a United States commercial aircraft. On top of that, it is not guaranteed that the countermeasure system will always work against a SAM.
7. Use the CBA to make an informed decision about whether to pursue the project. After analyzing all of the information determined from the CBA, one would use the information to determine if adding countermeasure systems to commercial aircraft is technically feasible and financially viable.

Along with the cost benefit analysis the researcher used modeling and simulation to determine the effectiveness of the countermeasure. Through data analysis the researcher displayed the effectiveness of the countermeasure on a wide-body commercial aircraft. The simulation included motion models for both the aircraft and missile, and a low fidelity sensor model for the missile. The researcher concluded that cost of retrofitting these technologies to the aircraft were not worth it, based on the information provided in the cost benefit analysis, current budgetary restrictions, and the likelihood of the aircraft being attacked.

The researcher performed a size, weight, and power analysis on the technologies required for the countermeasure to be most effective. The SWAP analysis included:

1. Calculated size in comparison to the overall size of the plane

2. Calculated the forces of the system on the plane
3. Calculated the power needed to supply the system

The researcher concluded that the amount of space, forces, and power required for the systems was not low enough to be negligible, but was also not high enough to impede on any major aircraft operations. The researcher concludes that flying around conflict zones altogether is a more viable option than adding these technologies to the commercial wide-body aircraft, because it is technically possible to add these technologies, but is not economically feasible.

#### 5.0.1 Answers to Research Questions 1 & 2

The answer to research question one was answered in Tasks 1 and 3 by performing both tasks with enough fidelity one could correlate the cost and effectiveness. Hypothesis one is substantiated by the results from the detailed cost model and the countermeasure effectiveness simulation.

The answer to research question two was answered by case study # 3 by quantifying the effectiveness of the countermeasure, the countermeasure did reduce the SAMs effective range, but it did not make the SAM ineffective. Allowing the alternative of flying around conflict zones to assert itself as the more viable option substantiating hypothesis 2.

#### 5.0.2 Things to Consider

There are several things one may consider when developing a detailed cost model. Such as the amount of planes being considered. It is very possible that the number of aircraft being considered is too high. One could determine which planes fly over conflict zones by tail number and only add countermeasure technologies to those aircraft who fly the route. By greatly decreasing the number of aircraft that need to be retrofitted one could substantially reduce the cost allowing for more effective countermeasures. Then one could come to the

conclusion that adding countermeasure to commercial aircraft is economically viable. One could also consider adding technologies to a commercial aircraft that covers all three phases of the flight profile (takeoff, landing, and takeoff). One could look at this as a cause and effect scenario, an interesting study would be to look into the actual cause of the conflict zone and determine if that would be a more economically viable alternative.

### 5.0.3 Research Contributions

The research methodology above provides value on multiple levels with its largest contribution being to the airline industry. Contributions to the academic community would include providing case studies that would determine the effectiveness of the technologies being considered. Contributions to ASDL include an in-house tool for determining the success rate of countermeasure systems being retrofitted to commercial vehicles, along with a cost benefit analysis. In addition, a parametric motion model has been developed that is very customizable to any aircraft or missile. Contributions to the airline industry include an additional understanding of the consequences of adding missile defense technologies to commercial aircraft.

# Appendices

## **APPENDIX A**

### **THE SIMULATION (AIRCRAFT & MISSILE MOTION MODEL)**

The codes below include the simulation, classes for the the aircraft, missile, vehicle, update state, and the chaff cloud.

```
CHAFFSIM
```

```
% Anthony Patterson
```

```
% 2/23/2018
```

```
tic
```

```
clear;clc;clf;
```

```
close all
```

```
%To run cases use this for input:
```

```
n = 5000; % how many times it varies parameters
```

```
q = lhsdesign(n,3); %Latin Hypercube
```

```
H = repmat(7620,n,1) + q(:,1)*5486; %25,000 to 43,000 feet values in meters for initial Height
```

```
X = repmat(-70000,n,1) + q(:,2)*140000; %-70,000 to 140,000 for initial X
```

```
Y = repmat(-70000,n,1) + q(:,3)*140000; %-70,000 to 140,000 for initial Y
```

```
OutputPlot = 0; %keeps it from plotting each run while running
```

```
CaseRunPlot = 1; %outputs case run plot
```

```
M1_miss = [0,0,0];
```

```
M2_miss = [0,0,0];
```

```
M3_miss = [0,0,0];
```

```
M1_hit = [0,0,0];
```

```
M2_hit = [0,0,0];
```

```
M3_hit = [0,0,0];
```

```
if OutputPlot == 1 || CaseRunPlot == 1
```

```
    figure
```

```
    hold on
```

```
    if CaseRunPlot == 1
```

```
        [x,y,z] = meshgrid(min(X):0.05*max(X):max(Y),min(Y):0.05*max(Y):max(Y),0);
```

```
        plot3(0,0,0,'b.', 'markers', 15) %Plots initial position of missile launch site (0,0,0)
```

```
%        plot3(X,Y,H,'b.', 'markers', 15)
```

```
        hold on
```

```
    end
```

```
    if OutputPlot == 1
```

```
        [x,y,z] = meshgrid(-.25*X:.1*X:3.*X,-0.25*Y:.1*Y:3.*Y,0);
```

```
    end
```

```
    surface(x,y,z)
```

```
    colormap gray
```

```
end
```

```
for n = 1:n
```

```
% close all
```

```

timestep = .1;

Altitude = H(n); %meters
XaircraftInt = X(n); %meters
YaircraftInt = Y(n); %meters
% distanceplot(n) = norm([XaircraftInt YaircraftInt Altitude]);
aircraft =
boeing777_300er(250.342,10.16,10.16,[XaircraftInt,YaircraftInt,Altitude],[250.342,0,0]);
cloud = chaffcloud([XaircraftInt,YaircraftInt,Altitude],[0,0,0]);

aircraft.status = 1; % steps through a series of maneuvers (counter variable)

maneuver = [7,7,7]; %order of operations; 0 do nothing, 1 slowdown, 2 speedup, 3 turn, 4
climb, 5 dive, 7 combine them etc.
%maneuver = [0,0,0]; %order of operations; 0 do nothing, 1 slowdown, 2 speedup, 3 turn, 4
climb, 5 dive, 7 combine them etc.
update = 3; %0 no info only alert, 1 told initial launch site,
        %2 told missile location @ time of alert, 3 continuous updates
direction = [0,1,0]; %default direction: right [0,-1,0] or left [0,1,0]
delay = 0; %seconds of delay between the missile alert and missile location information
intensity = 1; %how close to max load factor - value from 0 to 1 decimal percent
alerttime = 0;

%dummy start values
AircraftMaxV = 0;
AircraftMinV = 5000;
AircraftMaxH = 0;

time = 0;

%% Initializing Missile

missile = S_75;
missile.bearing = (aircraft.pos-missile.pos)/((norm(aircraft.pos-missile.pos)));
chaff_cloud_RCS = 105;

%% Simulation
counter = 1;
while true

if time >= alerttime

```

```

    aircraft.missile_det = true;
end

if time >= (alerttime + delay) && time <= (alerttime + delay + timestep)
    %aircraft provided with this information
    switch update
        case 0
            %No missile info - commanded direction to head
            aircraft.goal = direction;
        case 1
            %Launch site of missile known (0,0,0) and current aircraft pos
            aircraft.goal = (aircraft.pos)/norm(aircraft.pos) - 0; %missile launch site @ (0,0,0)
        case 2
            %missiles current location known and current aircraft pos
            aircraft.goal = missile.bearing;
        case 3
            %continuous knowledge of missile bearing/location
            %updates within the maneuver function not here
    end
end

aircraft.UpdateState(timestep);

if aircraft.missile_det == true
    if aircraft.status > (ndims(maneuver) + 1)
        maneuver = zeros([1 aircraft.status]);
        %finished all the maneuvers asked to do for this case set maneuver
        %to zeros so it stops
    end

    switch maneuver(aircraft.status)
        case 0
            %    % DONT DO ANYTHING!
            aircraft.Turn(missile, timestep, update, direction, intensity, alerttime, delay, time);
            aircraft.Climb(missile, timestep, update, direction, intensity, alerttime, delay, time);
            if aircraft.status < 2
                aircraft.SpeedUp(timestep);
            end
        % case 1
        %    %slow down
        %    aircraft.SlowDown(timestep);
        % case 2
        %    %speed up
        %    aircraft.SpeedUp(timestep);
    end
end

```

```

% case 3
%   %turn
%   aircraft.Turn(missile, timestep, update, direction, intensity, alerttime, delay, time);
% case 4
%   %Climb
%   aircraft.Climb(missile, timestep, update, direction, intensity, alerttime, delay, time);
% case 5
%   %Dive
%   aircraft.Dive(missile, timestep, update, direction, intensity, alerttime, delay, time);
case 7
    chaff_cloud = cloud.pos;
%   aircraft.UpdateState(timestep);
    distance = norm(chaff_cloud-missile.pos);
    missile.bearing = (cloud.pos-missile.pos)/((norm(cloud.pos-missile.pos)));
    missile.CalcBearing(cloud, timestep, time);
%   missile.UpdateState(timestep);
    while distance > 0
        distance = distance - (norm(missile.vel) * timestep);
    end
    missile.UpdateState(timestep);
    missile.bearing = (aircraft.pos-missile.pos)/((norm(aircraft.pos-missile.pos)));
    aircraft.Turn(missile, timestep, update, direction, intensity, alerttime, delay, time);
    aircraft.Climb(missile, timestep, update, direction, intensity, alerttime, delay, time);
    if aircraft.status < 2
        aircraft.SpeedUp(timestep);
    end

end

end

%% Missile Physics
hi = missile.pos(3); %initial missile height before update

missile.CalcBearing(aircraft, timestep, time);
missile.UpdateState(timestep);

Energy = missile.pos(3) + norm(missile.vel)^2 / (2*9.81);

%Missile Energy Height Projectile Calculations
if time > missile.burntime
    hf = missile.pos(3); %height after update
    g = 9.81; %m/s

```

```

if hf > hi
    missile.vel = ((norm(missile.vel)^2 - 2*g*(hf-hi))^(1/2))*missile.bearing;
else
    %end of simulation since missile can't gain anymore height
end
%[~, theta, ~] = cart2sph(missile.bearing(1), missile.bearing(2), missile.bearing(3));
missile.DensityCalc(hf);
%a = -g*cos(theta)-
((1/(2*missile.mass))*missile.density*norm(missile.vel)^2*missile.Cd*missile.S);
a = -((1/(2*missile.mass))*missile.density*norm(missile.vel)^2*missile.Cd*missile.S);
%ignoring weight
missile.vel = (norm(missile.vel) + a*timestep)*missile.bearing;
Energy = missile.pos(3) + norm(missile.vel)^2 / (2*g);
end

if Energy < 1.5281e+04 || norm(missile.vel) < norm(aircraft.vel) %Missile energy is lost after
burnout or speed less than aircraft's speed
    result = 'Missile ran out of fuel and projectile energy';
    output(n) = 0;
    if CaseRunPlot == 1
%        if m == 1
%            M1_miss = [X(n), Y(n), H(n)];
%        elseif m == 2
%            M2_miss = [X(n), Y(n), H(n)];
%        elseif m == 3
%            M3_miss = [X(n), Y(n), H(n)];
%        end

        plot3(X(n), Y(n), H(n), 'g.', 'markers', 10) %Plots intial position of aircraft
%        plot3(aircraft.pos(1), aircraft.pos(2), aircraft.pos(3), 'g.', 'markers', 10) %Plots final
position of aircraft
        hold on
    end
    if OutputPlot == 1
        plot3(aircraft.pos(1), aircraft.pos(2), aircraft.pos(3), 'go', 'markers', 5) %Plots A/C position
    end
    break %If missile misses
end
if norm(aircraft.pos-missile.pos) < 10
    result = 'The missile hit the target';
    output(n) = 1;
    if CaseRunPlot == 1
        if m == 1
            M1_hit = [X(n), Y(n), H(n)];

```

```

elseif m == 2
    M2_hit = [X(n), Y(n), H(n) ];
elseif m == 3
    M3_hit = [X(n), Y(n), H(n) ];
end

plot3(X(n), Y(n), H(n),'r.', 'markers', 10) %Plots initial position of aircraft
% plot3(aircraft.pos(1), aircraft.pos(2), aircraft.pos(3),'r.', 'markers', 10) %Plots final
position of aircraft
hold on

end
if OutputPlot == 1
    plot3(aircraft.pos(1), aircraft.pos(2), aircraft.pos(3),'r*', 'markers', 8) %Plots A/C position
end
break; %if the sam comes within 10 meters of the a/c, it is destroyed
end

time = time+timestep;
%separation(counter) = norm(aircraft.pos - missile.pos);

end

if CaseRunPlot == 1
    xlabel('Distance over Ground (m)')
    ylabel('Distance over Ground (m)')
    zlabel('Altitude (m)')
    axis equal
end

M1_miss = [0,0,0];
M2_miss = [0,0,0];
M3_miss = [0,0,0];
M1_hit = [0,0,0];
M2_hit = [0,0,0];
M3_hit = [0,0,0];

% DATA ANALYSIS
resultsda(n,:) = [Altitude XaircraftInt YaircraftInt output(n) time];
end

```

```

%DATA ANALYSIS
sheet = 1;
filename = 'CaseStudyAlertManCount8.xlsx';
xlswrite(filename, resultsda, sheet);

axis([-70000 70000 -70000 70000 0 15000])

toc

BOEING 777-300ER
classdef boeing777_300er < Vehicle

    %Stats for a BOEING737
    properties (GetAccess = 'public', SetAccess = 'private')

end

    methods
        function obj = boeing777_300er(cruise_speed,climb_rate,descend_rate,pos_vec,vel_vec)

            if nargin > 0
                obj.cruise_speed = cruise_speed;
                % obj.climb_rate = climb_rate;
                % obj.descend_rate = descend_rate;
                obj.pos = pos_vec;
                obj.vel = vel_vec;
            end

            obj.max_speed = .84*340.29;
            obj.accel = 9.81*4; %m/s
            obj.max_g = 2.0;
            obj.min_g = -1.1;
            obj.bearing = [1 0 0];
            obj.pitch = [-20 30];
            obj.wingloading = 699.79*9.81; %N/m^2
            obj.thrustloading = 1/(353.87*9.81)*1000; %N/N
            obj.Cdo = 0.026;
            obj.aspectratio = 8.67;
            obj.span_eff = 0.87;
            obj.weightTO = 30516*9.81; %N
            % obj.RCS = 100; %meters squared
        end
    end

```

```
end
```

```
end
```

```
S_75 Missile
```

```
classdef S_75 < Missile
```

```
    %S_75 Dvina Russian SAM missile
```

```
    properties (GetAccess = 'public', SetAccess = 'private')
```

```
end
```

```
    methods
```

```
        function obj = S_75()
```

```
            VdepLF = 1;
```

```
            obj.burntime = 50.9 ; %sec
```

```
            %obj.max_range = 147840;
```

```
            obj.max_speed = 2.58*340.29;
```

```
            obj.turn_radius = 19.50;
```

```
            obj.max_g = 50;
```

```
            obj.pos = [0 0 0];
```

```
            obj.vel = obj.max_speed.*[0 0 1];
```

```
            obj.mass = 2300; %kg
```

```
            obj.Cd = 0.1;
```

```
            obj.S = 5; %for drag calculation
```

```
        end
```

```
    end
```

```
end
```

```
VEHICLE
```

```
classdef Vehicle < State
```

```
    properties
```

```
        max_range
```

```
        cruise_speed
```

```
        max_speed
```

```
        turn_radius
```

```
%    climb_rate
```

```
%    descend_rate
```

```
        max_g
```

```
        min_g
```

```

missile_det
bearing2
pitch
corner_speed
goal
accel
Energy_Height
wingloading
thrustloading
Cdo
aspectratio
span_eff
weightTO
ROC
RCS
countermeasure
end

methods
%% Specific Excess Power
function P_SExcess(obj,timestep, Height, Velocity, theta)
    %Input Parameters: Weight, K, S, Cdo, (Ta)0
    %Varies with Velocity, Height, & theta
%     Height = obj.pos(3);
%     Velocity = norm(obj.vel);
%     [~, theta , ~] = cart2sph(obj.bearing(1), obj.bearing(2), obj.bearing(3));

%     Height = 9000; %m
%     theta = 0; % radians
%     Velocity = 60; %m/s
%     m=0;
%     v=0;
%     figure
%     for v = 0:1
%     for m = 0:150
obj.DensityCalc(Height);
rho = obj.density;
rho_0 = 1.2266; %kg/m3

%ThrustA_sl = 120000; %N
ThrustA_sl = obj.weightTO*obj.thrustloading; %N
Pavail = (ThrustA_sl * (rho/rho_0)^0.6) * Velocity; %for turbofan engine

S = (obj.weightTO/obj.wingloading);

```

```

K = 1/(3.14159*obj.span_eff*obj.aspectratio);
Cd = obj.Cdo + (K*((obj.weightTO*cos(theta))/(0.5*rho*Velocity^2*S))^2) ;
Preq = Velocity *((0.5*rho*Velocity^2*S * Cd) + obj.weightTO*sin(theta));

Excess_Power = (Pavail - Preq)/obj.weightTO ;

obj.ROC = Excess_Power;

%theta = asin(ROC/Velocity) *180/3.14159
%
%     m = m + 1;
%     Velocity = Velocity + 2;
%     hold on
%     plot (Velocity, Preq,'b.')
%     plot (Velocity, Pavail,'r.')
%     xlabel('Velocity (m/s) ')
%     ylabel('Power (N*m/s)')
%     xlim([20 300])
%     ylim([0 3e7])
%     end
%     Height
%     Height = Height + 3000;
%     v = v + 1;
%     m = 0 ;
%     Velocity = 60;
%     end

end

%% DIVE Function
function Dive(obj, threat, timestep, update, direction, intensity, alerttime, delay, time)
    %update theta not psi & work in z direction

    obj.goal = [0,0,-1]; %down direction

    %switch from cartesian to spherical coordinates
    [psi, theta , ~] = cart2sph(obj.bearing(1), obj.bearing(2), obj.bearing(3));
    [~, thetaGoal , ~] = cart2sph(obj.goal(1), obj.goal(2), obj.goal(3));

    %end this maneuver & go to next once change in theta is very small
    if abs(theta-thetaGoal) < 0.003
        obj.status = obj.status + 1;
    end
end

```

```

%Find the diff between where aircraft is and where it wants to be
%This is amount needed to turn (but might be more/less than structurally allowed)
thetaDiff = thetaGoal - theta;

%take into account a V-n Diagram
if norm(obj.vel) >= obj.corner_speed && norm(obj.vel) <= obj.max_speed
    %on V-n diagram past corner velocity & before max vel
    N = -obj.min_g*intensity;
elseif norm(obj.vel) < obj.corner_speed
    N = (-obj.min_g/(obj.corner_speed^2))*(norm(obj.vel))^2; %n~Kv^2 where K is some
constant
end

%Find turn rate allowed from structural limit on turn (max g's)
%v=wr & a=v^2/r ==> w=a/v
maxLonTurn = (N - 1).*9.81./(norm(obj.vel)); %for pitch up

%Find amount of angle allowed to turn for this timestep
delTheta = maxLonTurn.*timestep;

%Compare angles needed to turn for goal with angle allowed to turn structurally
if abs(thetaDiff) > delTheta
    theta = theta - delTheta;
else
    theta = thetaGoal;
end

%Check max and min pitch limitations
if theta > obj.pitch(2).*pi/180 %Max and min pitch conditions
    theta = obj.pitch(2).*pi/180;
elseif theta < obj.pitch(1).*pi/180
    theta = obj.pitch(1).*pi/180;
end

%Convert angles for turning to bearing for next update
[x,y,z] = sph2cart(psi, theta, 1);
NewBearing = [x,y,z];

%Check ROC doesn't exceed power limitations
vel = norm(obj.vel).*NewBearing;
DescentRate = vel(3);

[x,y,z] = sph2cart(psi, theta, 1);
obj.bearing = [x,y,z];

```

```
end
```

```
%% CLIMB Function
```

```
function Climb(obj, threat, timestep, update, direction, intensity, alerttime, delay, time)
```

```
    %update theta not psi & work in z direction
```

```
    %set goal direction for turn
```

```
    if time >= alerttime + delay
```

```
        switch update
```

```
            case 3
```

```
                obj.goal = [0,0,threat.bearing(3)]; %update every loop/timestep after alert
```

```
                obj.goal = obj.goal/norm(obj.goal); %normalize it
```

```
            end
```

```
        else %if haven't recieved any info about missile yet cause of delay time
```

```
            obj.goal = direction;
```

```
        end
```

```
    %switch from cartesian to spherical coordinates
```

```
    [psi, theta, ~] = cart2sph(obj.bearing(1), obj.bearing(2), obj.bearing(3));
```

```
    [~, thetaGoal, ~] = cart2sph(obj.goal(1), obj.goal(2), obj.goal(3));
```

```
    %end this maneuver & go to next once change in theta is very small
```

```
    if abs(theta-thetaGoal) < 0.003
```

```
        obj.status = obj.status + 1;
```

```
    end
```

```
    %Keep angles nonnegative (between 0 and 2pi) to avoid errors
```

```
    if theta < 0
```

```
        theta = theta + 2*pi;
```

```
    end
```

```
    if thetaGoal < 0
```

```
        thetaGoal = thetaGoal + 2*pi;
```

```
    end
```

```
    %Find the diff between where aircraft is and where it wants to be
```

```
    %This is amount needed to turn (but might be more/less than structurally allowed)
```

```
    thetaDiff = thetaGoal - theta;
```

```
    %Again keep values nonnegative
```

```
    if thetaDiff < 0
```

```
        thetaDiff = thetaDiff + 2*pi;
```

```
    end
```

```

%take into account a V-n Diagram
if norm(obj.vel) >= obj.corner_speed && norm(obj.vel) <= obj.max_speed
    %on V-n diagram past corner velocity & before max vel
    N = obj.max_g*intensity;
elseif norm(obj.vel) < obj.corner_speed
    N = (obj.max_g/(obj.corner_speed^2))*(norm(obj.vel))^2; %n~Kv^2 where K is some
constant
end

%Find turn rate allowed from structural limit on turn (max g's)
%v=wr & a=v^2/r ==> w=a/v
maxLonTurn = (N - 1).*9.81./(norm(obj.vel)); %for pitch up

%Find amount of angle allowed to turn for this timestep
delTheta = maxLonTurn.*timestep;

%Compare angles needed to turn for goal with angle allowed to turn structurally
if abs(thetaDiff) > delTheta
    if thetaDiff > pi
        theta = theta - delTheta;
    else
        theta = theta + delTheta;
    end
else
    theta = thetaGoal;
end

%Check max and min pitch limitations
if theta > obj.pitch(2).*pi/180 %Max and min pitch conditions
    theta = obj.pitch(2).*pi/180;
elseif theta < obj.pitch(1).*pi/180
    theta = obj.pitch(1).*pi/180;
end

%Convert angles for turning to bearing for next update
[x,y,z] = sph2cart(psi, theta, 1);
NewBearing = [x,y,z];

%Check ROC doesn't exceed power limitations
vel = norm(obj.vel).*NewBearing;
ROC = vel(3);

Height = obj.pos(3);

```

```

Velocity = norm(obj.vel);
angle = 0;
obj.P_SExcess(timestep, Height, Velocity, angle);
angle = asin(obj.ROC/norm(obj.vel));
if obj.ROC < 0
    obj.ROC = 0;
    theta = 0;
end
if ROC < obj.ROC
    obj.ROC = ROC;
    theta = angle;
end

[x,y,z] = sph2cart(psi, theta, 1);
obj.bearing = [x,y,z];

obj.ROC ;
end

%% TURN Function (change this to Level turn psi only, not theta update)
function Turn(obj, threat, timestep, update, direction, intensity, alerttime, delay, time)
    %set goal direction for turn
    if time >= alerttime + delay
        switch update
            case 3
                obj.goal = threat.bearing; %update every loop/timestep after alert
            end
        else %if haven't recieved any info about missile yet cause of delay time
            obj.goal = direction;
        end

        %switch from cartesian to spherical coordinates
        [psi, theta, ~] = cart2sph(obj.bearing(1), obj.bearing(2), obj.bearing(3));
        [psiGoal, ~, ~] = cart2sph(obj.goal(1), obj.goal(2), obj.goal(3));

        %end this maneuver & go to next once change in theta is very small
        if abs(psi-psiGoal) < 0.003
            obj.status = obj.status + 1;
        end

        %Keep angles nonnegative (between 0 and 2pi) to avoid errors
        if psi < 0
            psi = psi + 2*pi;
        end
    end
end

```

```

if psiGoal < 0
    psiGoal = psiGoal + 2*pi;
end

%Find the diff between where aircraft is and where it wants to be
%This is amount needed to turn (but might be more/less than structurally allowed)
psiDiff = psiGoal - psi;

%Again keep values nonnegative
if psiDiff < 0
    psiDiff = psiDiff + 2*pi;
end

%take into account a V-n Diagram
if norm(obj.vel) >= obj.corner_speed && norm(obj.vel) <= obj.max_speed
    %on V-n diagram past corner velocity & before max vel
    N = obj.max_g*intensity;
elseif norm(obj.vel) < obj.corner_speed
    N = (obj.max_g/(obj.corner_speed^2))*(norm(obj.vel))^2; %n~Kv^2 where K is some
constant
end

%Find turn rate allowed from structural limit on turn (max g's)
%v=wr & a=v^2/r ==> w=a/v
maxLatTurn = 9.81.*N/norm(obj.vel); %rad/s

%Find amount of angle allowed to turn for this timestep
delPsi = maxLatTurn.*timestep;

%Compare angles needed to turn for goal with angle allowed to turn structurally
if abs(psiDiff) > delPsi %if goal > structural
    if abs(psiDiff) > pi
        psi = psi - delPsi;
    else
        psi = psi + delPsi;
    end
else %if structural limit less than goal turn
    psi = psiGoal;
end

if psi > 2*pi
    psi = psi - 2*pi;
end

```

```

        %Convert angles for turning to bearing for next update
        [x,y,z] = sph2cart(psi, theta, 1);
        obj.bearing = [x,y,z];
    end

%% Speed Up
function SpeedUp(obj, timestep)
    if norm(obj.vel) < obj.max_speed
        if norm(obj.vel + (obj.accel * timestep)*obj.bearing) > obj.max_speed
            obj.vel = obj.max_speed*.999; %slightly less than max to eliminate errors
            obj.status = obj.status + 1; %end this maneuver & go to next
        else
            obj.vel = obj.vel + (obj.accel * timestep)*obj.bearing;
        end
    end
end

%% Slow Down
function SlowDown(obj, timestep)
    norm(obj.vel - (obj.accel * timestep)*obj.bearing)
    if norm(obj.vel) > obj.corner_speed
        if norm(obj.vel - (obj.accel * timestep)*obj.bearing) < obj.corner_speed
            obj.vel = obj.corner_speed*0.999; %slightly more than min to eliminate errors
            obj.status = obj.status + 1; %end this maneuver & go to next
        else
            obj.vel = obj.vel - (obj.accel * timestep)*obj.bearing;
        end
    end
end
end
end
end

```

STATE

```

classdef State < handle

```

```

    properties

```

```

        pos

```

```

        vel

```

```

        bearing

```

```

        % translational_state

```

```

        status

```

```

        density

```

```

    end

```

```

    methods

```

```

function obj = State()

end

function UpdateState(obj, timestep)
    obj.pos = obj.pos + timestep.*obj.vel;
    obj.vel = norm(obj.vel).*obj.bearing;
end

function DensityCalc(obj, Height)
    Temp = 15.04 - .00649 * Height;
    p = 101.29 * (Temp + 273.1)/288.08]^5.256;
    obj.density = p / [.2869 * (Temp + 273.1)];
end

end

end

CHAFF CLOUD
classdef chaffcloud < Vehicle

    %Stats for a chaff cloud
    properties (GetAccess = 'public', SetAccess = 'private')

end

    methods
        function obj = chaffcloud(pos_vec,vel_vec)

            if nargin > 0
                obj.pos = pos_vec;
                obj.vel = vel_vec;
            end

        end

    end

end

end

```

## REFERENCES

- [1] *Air traffic by the numbers*, <https://www.faa.gov/airtraffic/bythenumbers/>, Accessed: 2017-09-19.
- [2] T. Hunter, “The proliferation of manpads. *janes intelligence review*,” pp. 42–45, 2001.
- [3] *Sa-7*, <http://www.globalsecurity.org/military/world/russia/sa-7.html>, Accessed: 2017-09-06.
- [4] *Protecting airliners from terrorist missiles. library of congress washington dc congressional research service*, <https://fas.org/irp/crs/RL31741.pdf>, Accessed: 2017-09-06.
- [5] *An-aar-54*, <https://www.globalsecurity.org/military/systems/aircraft/systems/an-aar-54.htm>, Accessed: 2018-04.
- [6] *An/ale-47 countermeasure dispensing system*, [https://www.globalsecurity.org/military/library/policy/navy/ntsp/ale-47-p\\_v2\\_2002.pdf](https://www.globalsecurity.org/military/library/policy/navy/ntsp/ale-47-p_v2_2002.pdf), Accessed: 2018-04.
- [7] B. C. Butters, “Chaff. in *iee* proceedings f-communications, radar and signal processing,” *IEE*, vol. 129, pp. 197–201, 3 1982.
- [8] *Chaff*, <http://www.globalsecurity.org/military/systems/aircraft/systems/chaff.htm><http://www.globalsecurity.org/military/systems/aircraft/systems/chaff.htm>, Accessed: 2017-09-06.
- [9] M. D. Withey, “Infrared countermeasure flares,” *The Imaging Science Journal*, vol. 58, pp. 295–299, 5 2010.
- [10] *Flares*, <http://www.globalsecurity.org/military/systems/aircraft/systems/flares.htm>, Accessed: 2017-09-06.
- [11] *Infrared countermeasure*, <http://www.globalsecurity.org/military/systems/aircraft/systems/ircm.htm>, Accessed: 2017-09-06.
- [12] Robert E. Ball, *The fundamentals of aircraft combat survivability analysis and design*. AIAA (American Institute of Aeronautics Astronautics)., 2003.

- [13] *An-ale-55*, <http://www.globalsecurity.org/military/systems/aircraft/systems/an-ale-55.htm>, Accessed: 2017-09-07.
- [14] *Boeing air force one*, <http://www.boeing.com/defense/air-force-one/index.page>, Accessed: 2017-09-07.
- [15] *Air force one has new defensive systems, antennas*, <https://www.defensemedianetwork.com/stories/air-force-one-has-new-defensive-systems-antennas/>, Accessed: 2017-09-07.
- [16] *Patent*, <http://www.uspto.gov>.
- [17] *An introduction to cost benefit analysis*, <http://www.sjsu.edu/faculty/watkins/cba.htm/>, Accessed: 2017-09-14.
- [18] *Cost benefit analysis*, <http://www.investopedia.com/terms/c/cost-benefit-analysis.asp>, Accessed: 2017-09-22.
- [19] *Space filling designs for computer experiments*, <https://www2.isye.gatech.edu/~jeffwu/isy7400/Unit2010.pdf>, Accessed: 2018-06.
- [20] *Model validation and verification*, <http://www.inf.ed.ac.uk/teaching/courses/ms/notes/note14.pdf>, Accessed: 2018-06.
- [21] *Nasa: What is drag?* <https://www.grc.nasa.gov/www/k-12/airplane/drag1.html>, Accessed: 2017-09-22.
- [22] *Nasa: What is weight?* <https://www.grc.nasa.gov/www/k-12/airplane/weight1.html>, Accessed: 2017-09-22.
- [23] D. Von Winterfeldt and T. O’Sullivan, “Should we protect commercial airplanes against surface-to-air missile attacks by terrorists?” *Decision Analysis*, vol. 3, pp. 63–75, 2 2006.
- [24] *Parametric modeling definition and examples*, <http://www.statisticshowto.com/parametric-modeling/>, Accessed: 2017-09-22.
- [25] *Design of experiments*, ADM Lecture Slides by Professor Mavris, Accessed: 2018-06-15.
- [26] *Boeing 777-300er*, <https://www.aircraftcompare.com/helicopter-airplane/Boeing-777-300ER/23>, Accessed: 2018-06-15.

- [27] *U.s commercial fleet*, <http://www.fi-aeroweb.com/US-Commercial-Aircraft-Fleet.html>, Accessed: 2018-05-25.
- [28] *Rand corporation*, <https://www.rand.org>, Accessed: 2018-06-15.
- [29] *Anaar-54*, [http://www.deagel.com/Protection-Systems/ANAAR-54\\_a001551001.aspx](http://www.deagel.com/Protection-Systems/ANAAR-54_a001551001.aspx), Accessed: 2018-06-15.
- [30] *Anale-47*, [http://www.deagel.com/Protection-Systems/ANALE-47\\_a001395001.aspx](http://www.deagel.com/Protection-Systems/ANALE-47_a001395001.aspx), Accessed: 2018-06-15.
- [31] *Tsa fy 2018 budget*, [https://www.dhs.gov/sites/default/files/publications/DHS\\_0FY18\\_20BIB\\_20Final.pdf](https://www.dhs.gov/sites/default/files/publications/DHS_0FY18_20BIB_20Final.pdf), Accessed: 2018-06-15.
- [32] *Chaff c-130*, [https://commons.wikimedia.org/wiki/File:C-130\\_Hercules\\_flare\\_and\\_CHAFF\\_dispensers.JPG](https://commons.wikimedia.org/wiki/File:C-130_Hercules_flare_and_CHAFF_dispensers.JPG), Accessed: 2018-06-15.
- [33] *Boeing 77-300er fuel efficiency*, <https://www.quora.com/What-kind-of-fuel-mileage-does-a-jet-airliner-say-A320-B777-ER-achieve>, Accessed: 2018-06-15.
- [34] *Many flights soar over conflict zones*. <http://www.cnn.com/2014/07/22/travel/conflict-area-flights/index.>, Accessed: 2017-09-06.
- [35] *Alq-156 archived*, [https://www.forecastinternational.com/archive/disp\\_old\\_pdf.cfm?ARC\\_ID=646](https://www.forecastinternational.com/archive/disp_old_pdf.cfm?ARC_ID=646), Accessed: 2018-06-15.
- [36] *A history of passenger aircraft that have been shot down*. <https://www.theguardian.com/world/2014/jul/17/history-of-airlines-shot-down-malaysia-airlines-mh17>, Accessed: 2017-09-06.
- [37] *U.s. warship downs iranian passenger jet*. <http://www.history.com/this-day-in-history/u-s-warship-downs-iranian-passenger-jet>, Accessed: 2017-09-06.
- [38] J. Chow, J. Chiesa, P. Dreyer, M. Eisman, J. Kvitky, and C. Shirley, “Protecting commercial aviation against the shoulder-fired missile threat,” pp. 11–64, 2006.
- [39] *Sa-2 (guideline)/s-75 dvina high-altitude surface-to-air missile system (sam)*, [https://www.militaryfactory.com/armor/detail.asp?armor\\_id=133](https://www.militaryfactory.com/armor/detail.asp?armor_id=133), Accessed: 2017-09-26.

[40] *Surface to air missile effective in past conflicts*, <http://www.ausairpower.net/APA-SAM-Effectiveness.html>, note = Accessed: 2017-09-26.