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COST-EFFECTIVENESS ANALYSIS OF AERIAL PLATFORMS AND SUITABLE COMMUNICATION PAYLOADS

by

Randall E. Everly
David C. Limmer

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Thesis Advisor:	Cameron MacKenzie
Co-Advisor:	Glenn Cook
Second Reader	John Gibson

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Randall E. Everly
Lieutenant Commander, United States Navy
B.S., United States Naval Academy, 1998

David C. Limmer
Lieutenant, United States Navy
B.S., Gordon College, 2001

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March 2014

Authors: Randall E. Everly

David C. Limmer

Approved by: Cameron MacKenzie
Thesis Advisor

Glenn Cook
Co-Advisor

John Gibson
Second Reader

Dan Boger
Chair, Department of Information Systems

Bill Gates
Dean, Graduate School of Business

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The goal of this research is to perform a cost-effectiveness analysis of selected aerial platforms and suitable communication payloads for use as communication relays in support of distributed military operations. Aerial platforms, for the purpose of this study, include UAVs, towers and aerostats. A multi-objective analysis is utilized to compare dissimilar attributes together among the alternatives. Cost data for each system considered is presented. To analyze the cost-effectiveness of alternatives for different mission sets, three hypothetical scenarios are used including disaster relief, long-range relay, and the tactical user. This research identifies the most cost-effective aerial platforms and communication payloads for each scenario based on the authors' preferences. Future decision makers can utilize this study as a decision tool to match their own preferences.

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LIST OF ACRONYMS AND ABBREVIATIONS

ANW2	Adaptive Networking Wideband Waveform
BAMS	Broad Area Maritime Surveillance
BCA	business case analysis
BY	base year
CBA	cost-benefit analysis
CEA	cost-effectiveness analysis
COMSEC	communications security
COTS	commercial-off-the-shelf
DDL	Digital Data Link
DoD	Department of Defense
FoV	field of view
HALE	high-altitude long-endurance
ISR	intelligence, surveillance and reconnaissance
LTE	Long Term Evolution
MANET	mobile ad hoc network
MOE	measure of effectiveness
MTBF	mean time between failures
MTTR	mean time to repair
NPS	Naval Postgraduate School
NOX	Network of Xiphos
N/A	not applicable
O&M	operations and maintenance
O&S	operations and support
PAUC	program acquisition unit cost
RAID	Rapid Aerostat Initial Deployment
RDT&E	research, development, test and evaluation
ROI	return on investment
STUAS	Small Tactical Unmanned Aircraft System
SUAS	small unmanned aerial system
SWaP-C	size, weight, power and cooling

TCP	transmission control protocol
U.S.	United States
UAS	unmanned aerial systems
UAV	unmanned aerial vehicle
UDP	user datagram protocol
USAF	U.S. Air Force
USB	universal serial bus
VoIP	Voice over Internet Protocol

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I. INTRODUCTION

A. U.S. MILITARY'S GROWING NEED FOR CONNECTIVITY

New information technology (IT) advancements on the battlefield are driving the increase in demand for connectivity. The modern U.S. warfighter is being equipped with more IT enabled gear each year. For example, the AN/PRC-152 Falcon III handheld and 117G manpacks, which support streaming video, messaging, voice, and data, are replacing older radios in special forces units (Selinger, 2013). The AN/PRC-154 rifleman radio is gaining popularity with the U.S. Army. General Dynamics is currently under contract to provide 22,000 of these hand-held units to the U.S. Army (Selinger, 2013). The AN/PRC-154 possesses simultaneous voice and data capability along with blue force tracking.

An increasing number of ships and aircraft are receiving upgraded modules enabling higher quality voice, higher resolution video and more robust data capability. For example, the EA-18G Growler, which replaces the aging EA-6B Prowler, comes equipped with Link 16 (DOT&E, 2012). Link 16 is a significantly more capable tactical data exchange network than previously employed systems. IT enhancements on the battlefield promise higher situational awareness to both the warfighter in combat and leadership in headquarters (Rosenberg, 2010). Decision makers will be able to make decisions faster with more accurate information, and these improvements can help reduce the fog of war for the entire Joint Force. However, these benefits are not guaranteed. Demand for high-speed data from supporting networks will increase, and networks must be ready to meet this demand.

B. SATELLITES CANNOT BE THE SINGULAR SOLUTION

Too often, military planners rely solely on satellites for connectivity. Satellites are an incredible asset for the modern warfighter and can enable world-wide communications, provide geospatial information, and reach nearly any user. However, satellites in geostationary orbit suffer from relatively large latency delays because of their distance from earth. They are very expensive to acquire and launch, and their vast development and planning requirements result in long lead times. Satellites cannot be launched quickly to meet the needs of a rapidly developing situation. The rapid development pace of computer hardware coupled with the necessary, yet rigorous testing process for space-based equipment all but eliminates the possibility of a satellite utilizing cutting-edge technology. Furthermore, it is difficult, if not impossible to repair a satellite or replace mission modules after launch. Finally, satellites are working in a finite space, and space junk and debris increasingly threaten satellites (Wall, 2013). Earth's orbits are limited and they are controlled by an international governing body, not the U.S. For all of these reasons, satellites cannot be the sole answer to the U.S. military's connectivity problem.

C. UAV COMMUNICATION RELAYS PROVIDE A POSSIBLE SOLUTION

With the advent of lightweight construction materials, high energy-density lithium battery technology, and rapidly increasing efficiency of modern microprocessors, unmanned aerial vehicles (UAV) capability is growing annually (DoD, 2013). As the U.S. military becomes more experienced with UAVs, they are becoming more consistent performers. UAV mishaps rates have dropped dramatically in recent years. Evolutionary improvements, such as engine upgrades, are being made to make them more reliable (Boeing, 2014). The civilian sector's interest and financial investment in UAVs are expanding, which will offer more efficient UAV alternatives for the military to utilize in the future. Consequently, the variety of ways UAVs are being employed is constantly expanding.

The communication relay mission is a logical next step for UAVs. The mission is mundane and tedious for which autonomous vehicles are well-suited (DoD, 2013). The larger payload capacities and longer endurance of modern UAVs combined with communication payloads that are more capable and efficient and lighter weight, make them more suitable to the communications relay role than their predecessors.

UAVs are more flexible than more permanent infrastructure like relay and cellular towers. They can be quickly repositioned to support warfighters on the move as depicted in Figure 1. Similar to cell towers or wired network infrastructure, multiple UAVs can enable multiple paths, redundancy, and ensure connectivity over a wide geographic range, essentially recreating cell-tower infrastructure in the sky. The U.S. military has begun to match UAVs with suitable communication payloads. In 2007 in Afghanistan, the U.S. Army experimented with pairing the RQ-7 Shadow 200 UAV with an AN/PRC-152-C radio to act as a communications relay with an expected 105 mile range (Defense Industry Daily, 2008).

Figure 1. Autonomous Future (from DoD, 2013)

D. ANY SOLUTION MUST BE COST-EFFECTIVE

Admiral Mike Mullen, Chairman of the Joint Chiefs of Staff said in 2011, "I believe the single, biggest threat to our national security is our debt, so I also believe we have every responsibility to help eliminate that threat" (American Forces Press Service, 2011). Since those comments, the debt has increased by $2 trillion to over $17 trillion in 2014 (Hall, 2014). Current increases in mandatory spending offer no relief to the national debt in the near future. Consequently, any discretionary spending in the U.S., especially the defense budget, is receiving intense scrutiny. More than a decade of combat operations and large cost overruns in defense projects, such as the F-35 Joint Strike Fighter, have put a tremendous budgetary strain on the Department of Defense (DOD). Any future acquisitions will need to be executed thoughtfully with special emphasis placed on value. Cost-benefit and cost-effectiveness analyses will need to be utilized to identify the best value for the warfighter.

E. RESEARCH HIGHLIGHTS

1. Problem Statement

There is a lack of cost-analyses of aerial platforms and communication payloads capable of connecting military units in support of operations in austere environments.

2. Purpose Statement

The purpose of this research is to perform a cost-effectiveness analysis (CEA) of selected aerial platforms and suitable communication payloads for use as a communication relay in support of distributed military operations.

3. Methodology

A multi-objective analysis is utilized to analyze and compare the cost-effectiveness of selected aerial platforms and communication payloads. Three scenarios are presented to analyze alternatives across different mission sets.

To analyze the cost effectiveness of aerial platforms and communication payloads, an objectives hierarchy is created that lists all the desirable goals or attributes for aerial platforms and communication systems. The objectives hierarchy leads to value measures and weights, which allow the effectiveness of each aerial platform and communication system to be quantified. This measure of effectiveness (MOE) and the estimated annualized life cycle cost (LCC) for each alternative can help the decision maker identify the most cost-effective solutions. This research identifies the most cost-effective aerial platforms and communication payloads for each scenario.

4. Scope

This study considers 11 different UAVs, 4 alternative platforms, and 9 communication payloads suitable for the mission of communication relay. UAVs range in size from the hand-launched Raven to the Triton with its 130-foot wingspan. The 4 alternative platforms such as aerostats and towers are included in the study to offer a contrast in capabilities and cost. Communication relay payloads under consideration vary in weight from less than a pound to over 250 pounds. Not all combinations of aerial platforms and communication payloads are compatible because of differences in size and weight of various alternatives considered in this study.

5. Limitations

This research is based on interviews with subject matter experts in UAVs and communications packages, publicly available reports and vendor technical capabilities. This research is hypothetical in nature and does not include experiments or testing. More technical analysis and field testing is needed to determine the feasibility and compatibility of the various aerial platforms and communication payloads considered.

F. ORGANIZATION

This section provides an overview of the remaining chapters of this thesis.

Chapter II begins with previous cost-analyses and business cases regarding UAV communication relays. Then, the authors describe each aerial platform studied in this research and list data pertinent to the study. Scientific theorems related to communications theory that the author considered germane to this research is discussed to provide background. Finally, the authors present the communication payloads considered in this research.

In Chapter III, the authors present the format for a cost-effectiveness analysis at the beginning of the chapter. In this section, the authors detail the steps necessary to conduct a multi-objective, cost-effectiveness analysis using a hypothetical new car buyer as an example. The chapter then transitions to a presentation of the hierarchies used in this research. One hierarchy is dedicated to aerial platforms, while the other hierarchy displays the communication payloads. Within each hierarchy, desired attributes are described and raw data for each attribute is listed. Finally, the chapter concludes with a summary of the costs of each system.

Chapter IV explores the authors' three hypothetical mission scenarios requiring communication relay support. Each scenario is critically examined to determine the appropriate value functions and importance weights necessary to accurately describe the hypothetical situation. For each scenario, the authors describe why certain attributes are important and why others are not. The compiled results, which depict MOE plotted against annualized cost, are analyzed to determine the equipment best suited to the scenario.

In Chapter V, the authors draw conclusions on their research and summarize the main findings and contributions of this research. Finally, the authors list any opportunities for future research.

Appendix A shows an enlarged view of the car, aerial platform, and communication payload hierarchies. Appendix B shows the reader how to approximate value functions with equations using Excel. Appendix C contains instructions for the authors' Excel files, otherwise known as the Tool, which allows future decision makers to conduct similar cost-effectiveness analysis using their own criteria. Finally, Appendix D provides the detailed MOE results of this study; specifically it provides the values of individual attributes for each alternative for each of the authors' three scenarios.

II. BACKGROUND

A. RELATED STUDIES

This section explores previous UAV financial studies related to this study. Although some of the following studies go into significant scientific detail, such as Ferguson and Harbold (2001), most studies are primarily financial in nature.

Ferguson and Harbold (2001) performed an in-depth, technical multi-objective analysis of high altitude long endurance (HALE) platforms available for communications relay, intelligence, surveillance and reconnaissance (ISR), strategic deterrence, Blue Force Tracking and GPS satellite augmentation missions. They considered the Global Hawk, the manned research vehicle Proteus, AeroVironment's solar powered Helios, and the solar powered high altitude airships (HAA) Sounder and Sky Station. The Global Hawk, Proteus and Helios are shown in Figure 2. They evaluated each platform and assessed a score for the following objective areas: instantaneous access area, cost, endurance, survivability, feasibility, flexibility, and responsiveness. Costs were exclusively acquisition costs for each flying vehicle. Ferguson and Harbold assigned weights to each objective compared to their relative importance to one another based on the authors' judgment. They also created value functions to allow a translation of a raw measurement to an appropriate relative value. The sum product of each objective's value score and the weight of the objective gave the vehicle's overall effectiveness score. Ferguson and Harbold used acquisition costs as one of several objectives in their multi-objective analysis.

Figure 2. Global Hawk, Proteus, Helios (left to right) (from Wikipedia.org, 2014)

This study serves as an update to Ferguson and Harbold's (2001) research, with a focus on the communication relay mission. For this study, the authors utilize LCC whenever available. LCC is a more accurate representation of total costs than acquisition costs, which was used in Ferguson and Harbold's analysis. Additionally, this study does not consider costs as an objective or benefit. Instead, the authors compare graphically an overall effectiveness score with the cost of each alternative.

Collier and Kacala (2008) performed a cost-effectiveness analysis of HALE airships, medium (Sky Warrior, aka MQ-1C Gray Eagle) and high altitude (Global Hawk) UAVs, and tactical satellites. The Gray Eagle is shown in Figure 3. They used a multi-objective framework to compare benefits of different platforms, which eliminated the need to monetize those benefits. To study each platform across a range of operating environments and mission sets, they developed different scenarios to test the relative effectiveness of each platform. However, the scenarios focused on the ISR mission as well as the communications mission. Benefits, called measures of effectiveness, were ranked in order of importance and assigned weights for each scenario individually. In most cases, acquisition and research, development, test and evaluation (RDT&E) costs were considered. Operations and support (O&S) costs were not included in the study. Collier and Kacala calculated the total number of platforms that could be purchased using fixed monetary amounts ($9.6B and $4.8B) and compared the total effectiveness of each fleet of platforms. For example, they compared the effectiveness of 192 HALE airships to the effectiveness of 54 Global Hawk UAVs, assuming the costs of both fleets to be the same at $9.6B. Additionally, Collier and Kacala also utilized mixes of platforms to determine which mix of the various platforms would give the highest effectiveness score for a given amount of money. Synergistic effects of different platforms when operated together were not considered.

Figure 3. MQ-1C Gray Eagle (from Wikipedia.org, 2014)

The authors of this study evaluate the effectiveness of individual platforms instead of the effectiveness of multiple platforms, as in Collier and Kacala (2008). As a result, total costs are not constant across different platforms. As opposed to the acquisition costs utilized in Collier and Kacala's research, this study utilizes LCC whenever practical. Similar to Collier and Kacala, this study also utilizes a multi-objective format across multiple scenarios to determine the most cost-effective solution for each case.

Lawler (2010) analyzed the financial implications of the U.S. Navy's Broad Area Maritime Surveillance (BAMS) program fulfilled by the MQ-4C Triton UAV manufactured by Northrop Grumman shown in Figure 4. Specifically, Lawler focused on the cost effects of the Triton on the Navy's flight hour program and its operation and maintenance budget. He utilized cost estimation techniques to approximate Triton's LCC. Lawler concluded that operations and maintenance (O&M) costs would overshadow acquisition costs over a UAV's life cycle.

Figure 4. MQ-4C Triton (BAMS) (from Wikipedia.org, 2014)

Lawler's research emphasized the importance of utilizing LCC, as O&M costs can easily dwarf initial costs of RDT&E and acquisition costs. Similar to Lawler's study, the authors of this study utilize LCC whenever feasible as part of the determination for the most cost-effective platform.

Yilmaz (2013) conducted a cost-effectiveness analysis on UAVs used for surveillance and interdiction in a border security role. He compared the U.S. made General Atomics Predator B (MQ-9 Reaper) and Guardian (a U.S. Customs and Border Patrol variant of the MQ-9 Reaper) to the Israeli made Heron UAV. The Guardian and Heron are shown in Figure 5. Similar to LCC, Yilmaz used the procurement and operational costs of each UAV for comparison. He assumed benefits to be similar across the three UAVs and therefore, the benefits were not differentiated. He concluded the Predator B was the most cost-effective solution due to its lower cost per flight-hour than the Heron and lower acquisition costs than the Guardian.

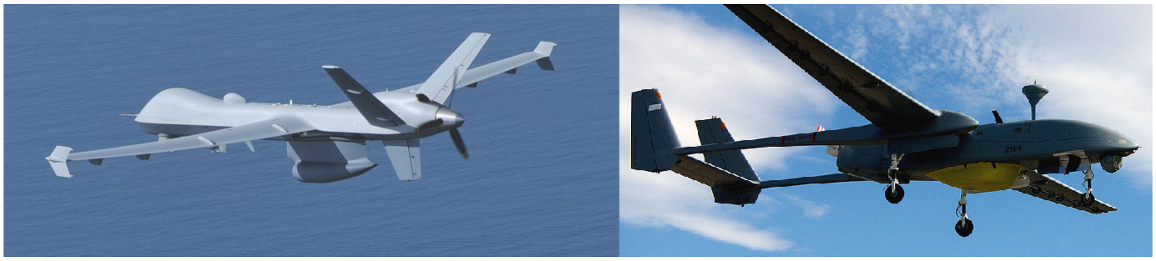

Figure 5. MQ-9 Guardian (left), Heron (right) (from Wikipedia.org, 2014)

While Yilmaz's (2013) research assumed the benefits across the three platforms in his study were the same, this study cannot realistically make that assumption due to the diversity of the platforms considered. Similarly this research also utilizes LCC in the determination of the most cost-effective solution.

Thiow Yong Dennis (2007) performed a business case analysis (BCA) of AeroVironment's Global Observer UAV program, which lost funding in late 2012. He created a hypothetical requirement for continuous 24/7 ISR and communications coverage over six different geographical locations around the world. Utilizing three separate airbases as possible points of origin and recovery, he compared the Global Observer to another HALE UAV: the U.S. Air Force (USAF) Global Hawk. Thiow Yong Dennis utilized a 35-hour endurance figure for the Global Hawk and a seven-day endurance for the Global Observer in his calculations. Using those endurance figures, he calculated that 20 Global Observers could fulfill the same requirements as 35 Global Hawks for the ISR and communications mission as described. The Global Observer is shown in Figure 6.

Figure 6. Global Observer (from Aviation Week, 2010)

Thiow Yong Dennis' (2007) LCC consisted of program acquisition costs and O&M costs. In his study, O&M costs were essentially fuel costs. Maintenance costs were estimated to be 10% of the acquisition costs of the platforms and associated equipment (ground control stations and payload) annually. Personnel costs were assumed to be the same across both platforms and are not considered. Over a 15-year life cycle, he estimated the Global Observer would cost approximately $880M and the Global Hawk would cost $3,951M. The primary cost drivers were the lower fuel costs and lower acquisition costs of the Global Observer. He performs sensitivity analysis on the results of his study by varying the discount rate, acquisition and maintenance costs, and finally fuel costs. The sensitivity analysis completed showed that none of the factors by themselves caused the Global Observer to be more expensive than the Global Hawk over the given period. In fact, the return on investment (ROI) of the Global Observer never fell below 8.5%, according to his calculations.

While Thiow Yong Dennis' study created one hypothetical scenario to test different platforms, the authors of this study utilize multiple scenarios and determine the most cost-effective platform for each scenario. Thiow Yong Dennis' (2007) study did not vary the payload of the platform. This study considers multiple communication relay payloads.

Fry and Tutaj (2010) continued Thiow Yong Dennis' research by adding the developmental Vulture program to the Global Observer and Global Hawk in a BCA. The Vulture was a developmental UAV that utilized solar cells on the upper surface of its wing to remain aloft for a claimed endurance of five years. The vehicle was designed to complete its five year flight and then be disposed of, therefore eliminating any O&M costs in theory. The Vulture is depicted in Figure 7.

Figure 7. Vulture (Artists' interpretations) (from Aviation Week, 2009)

Fry and Tutaj (2010) utilized one scenario with the requirement of providing 24/7 ISR and communication coverage over three geographical areas for a 15-year period. They allowed for two airports to be utilized for points of departure and recovery, with the nearest airport for each being utilized for each sortie. Fry and Tutaj calculated that the mission required 20 Global Hawks, 4 Vultures or 11 Global Observers to provide the same coverage. However, because the Vulture's planned service life was only five years, 12 Vulture UAVs needed to be purchased to satisfy mission requirements over the 15-year period. They estimated the lifespan of the Global Hawk and the Global Observer to exceed 15 years; therefore, no additional UAVs were needed to complete the 15-year mission. Fry and Tutaj estimated the acquisition cost of the Vulture at $200M per vehicle for their study, while the Global Hawk cost approximately $98M and the Global Observer was only $16M. Even with O&M costs of the Vulture set to zero, the total cost of the Global Observer of approximately $480M was approximately four times cheaper than the Vulture at about $1.6B. By their calculations, the Vulture was about three times cheaper than the Global Hawk's $5.1B price tag. Fry and Tutaj performed sensitivity analysis to test their assumptions, which just confirmed their initial findings.

Fry and Tutaj's (2010) study was significant because it examined the costs of a solar-electric powered HALE aircraft with flight endurances measured not in hours or days, but years. UAVs of this type have the potential to offer incredible capability. However, uncertainty in these programs is very high. The developmental programs bear monitoring going forward because their capabilities can be disruptive in the UAV field. That being said, as Fry and Tutaj's study showed, not all of the solar-electric HALE UAVs make sense financially. Furthermore, Fry and Tutaj's research demonstrates that cost data on programs such as the Vulture can be difficult to estimate accurately.

B. AERIAL PLATFORMS

The DOD currently has approximately 11,000 UAVs in their inventory. For a more detailed breakdown of their inventory, see Figure 8. For a depiction of UAV classifications, see Figure 9.

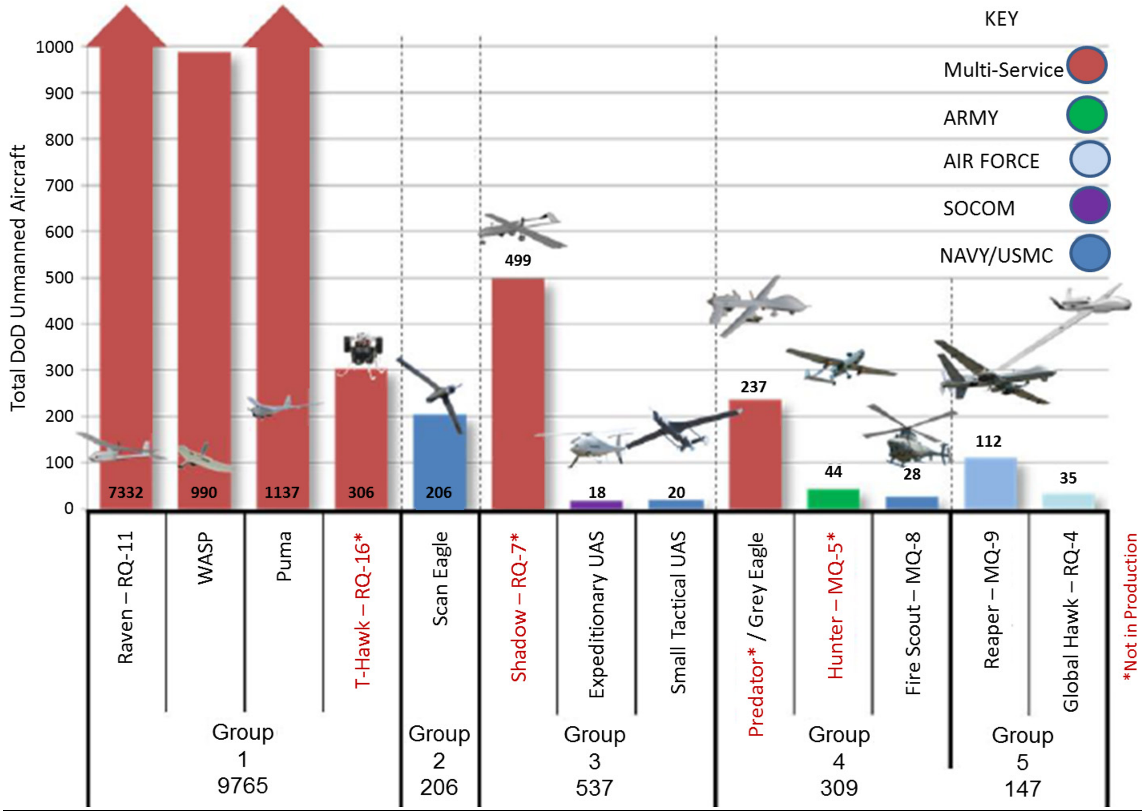

Figure 8. Inventory of DOD UAS, July 2013 (from DoD, 2013)

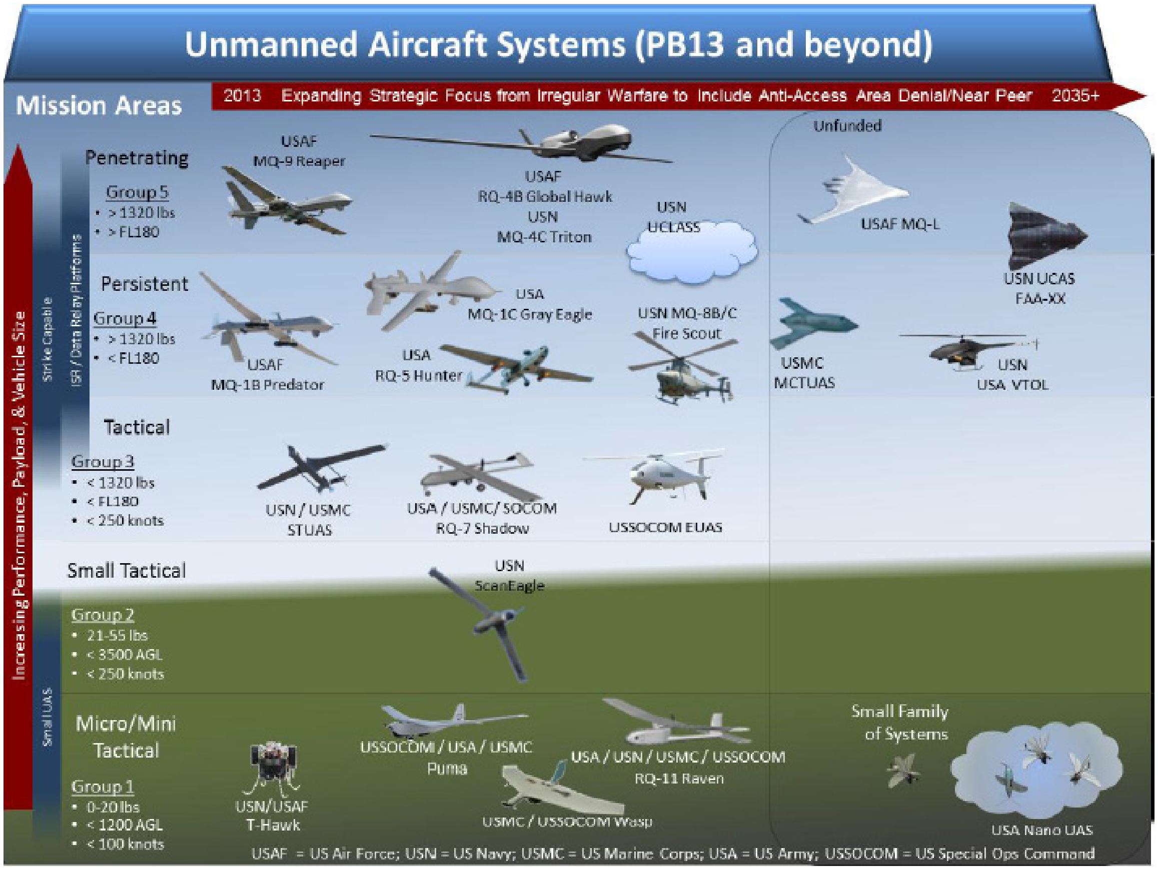

Figure 9. UAS (PB13 and Beyond) (from DoD, 2013)

The following sections provide a brief description and specifications of each aerial platform considered in this study, as well as some aerial platforms that were initially considered, but were ultimately not included in this research.

1. UAVs

This section present the various UAVs considered as aerial platforms in this study. UAVs are listed according to their size.

a. Small

Specifications for each small UAV are listed in Table 1.

(1) Wasp III. The Wasp III, made by AeroVironment, is a small hand-launched UAV, horizontal landing. Having a range of 3 miles, it represents the smallest

UAV examined that could perform the communications mission. The Wasp III is shown in Figure 10.

Figure 10. Wasp III (from AeroVironment, 2013)

(2) Raven. The RQ-11 Raven, made by AeroVironment, is a hand-launched, deep stall landing, unmanned altitude system (UAS) primarily used for low-altitude ISR (AeroVironment, 2014a). The Raven is shown in Figure 11.

Figure 11. RQ-11 Raven (after airforce-technology.com, 2011)

Name	Wasp III	Raven
Model Number	N/A	RQ-11
Dimensions: Length (ft)	1.3	3.0
Wingspan (ft)	2.3	4.5
Payload (lbs)	.2	.4
Maximum Speed (kts)	35	44
Maximum Range (nm)	2.7	5.4
Maximum Endurance (hrs)	.75	1.5
Ceiling (ft)	1,000	14,000

Table 1. Small UAV Specifications (after AeroVironment, 2014; Nicholas & Rossi, 2011)

b. Medium

Specifications for each medium UAV is listed in Table 2.

(1) Scan Eagle. The Scan Eagle, made by Insitu, a subsidiary of Boeing, is a catapult-launched, wire-arrested landing, UAS primarily used for long endurance, day and night ISR in nearly any environment (Insitu, 2013b). The Scan Eagle is shown in Figure 12. The authors did not include the Scan Eagle in this study due to lack of reliable cost data.

Figure 12. Scan Eagle (from Insitu.com, 2013)

(2) Shadow. The RQ-7 Shadow 200, made by AAI, is a catapult-launched, vertically arrested (by wire) UAS primarily used for reconnaissance, surveillance, target acquisition and battle damage assessment. The Shadow is shown in Figure 13.

Figure 13. RQ-7 Shadow 200 (from Wikipedia.org, 2007)

(3) Aerosonde. The MQ-19 Aerosonde, designed by Insitu and manufactured by AAI Corporation Aerosonde LTD, is a catapult-launched, net arrested Small Unmanned Aerial Systems (SUAS) primarily used to collect weather data, but is now being marketed to the military as a long-endurance ISR solution (Aerosonde, 2010). The Aerosonde is shown in Figure 14. Aerosonde is not considered in this study because reliable cost data was not available.

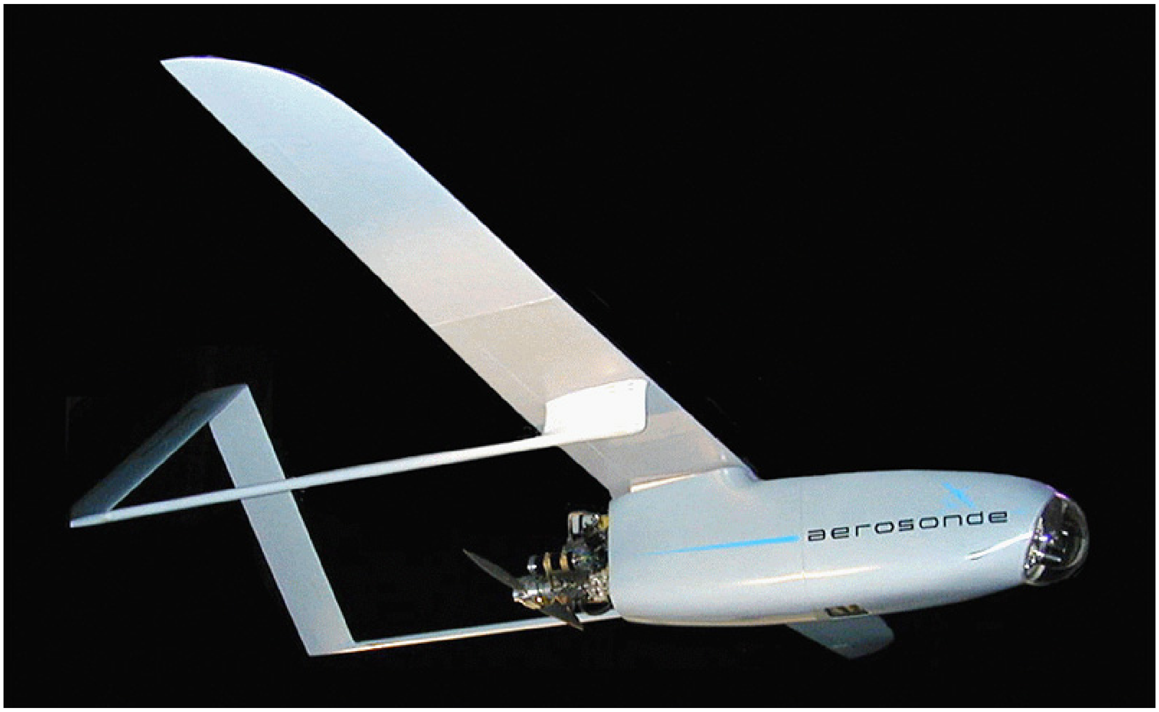

Figure 14. Aerosonde (from UAVConsultingGroup.com, 2014)

(4) Blackjack (formerly Integrator). The RQ-21 Blackjack, designed by Insitu of Boeing, is a catapult-launched, vertical-arrested (identical to the Scan Eagle) Small Tactical Unmanned Aircraft System (STUAS) designed to be multi-mission capable with six payload bays with power and Ethernet that can be fitted with cameras, communication capabilities, or other custom payloads. The Blackjack is shown in Figure 15.

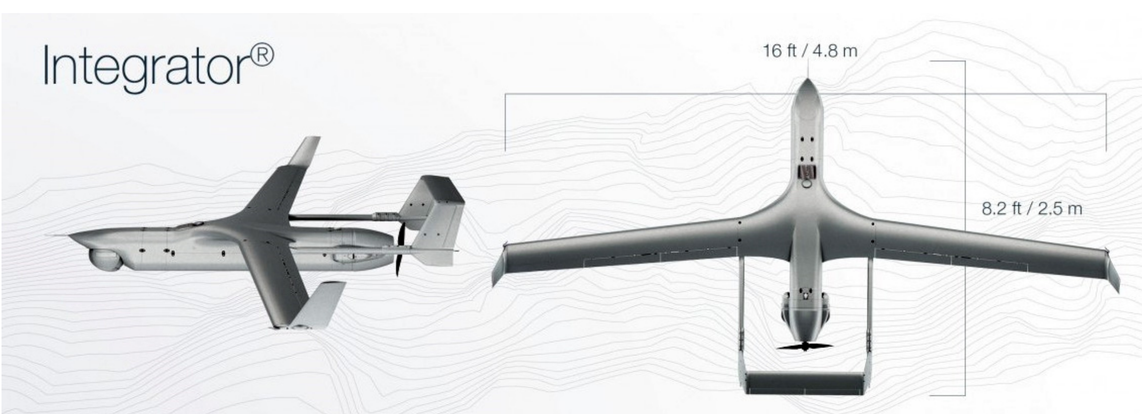

Figure 15. RQ-21 Blackjack (STUAS) (from Insitu.com, 2013)

Name	Scan Eagle	Shadow	Aerosonde	Blackjack
Model Number	N/A	RQ-7	MQ-19	RQ-21
Dimensions: Length (ft)	5.1	11.8	5.6	8.2
Wingspan (ft)	10.2	20.4	9.6	16
Payload (lbs)	7.5	80	10	39
Maximum Speed (kts)	80	110	80	90
Maximum Range (nm)	55 est.	59	Not Avail.	55
Maximum Endurance (hrs)	24	5	10	13
Ceiling (ft)	19,500	15,000	15,000	19,500

Table 2. Medium-Sized UAV Specifications (after Insitu, 2013a; Aerosonde, 2010; AAI Corp, 2013; Nicholas & Rossi, 2011)

c. Large

Specifications for each large UAV are listed in Table 3.

(1) Predator. The MQ-1 Predator, made by General Atomics, is a runway-capable UAS designed originally for ISR, but has been enhanced to be capable of taking on many roles to include targeting, forward air control, laser designation, weapons delivery, and bomb damage assessment (General Atomics, 2013b). The Predator is shown in Figure 16.

Figure 16. MQ-1 Predator (from General Atomics Aeronautical, 2013)

(2) Gray Eagle. The MQ-1C Gray Eagle, made by General Atomics, is a bigger version of the Predator used by the U.S. Army (General Atomics, 2012a). The Gray Eagle is shown in Figure 17.

Figure 17. MQ-1C Gray Eagle (from General Atomics, 2013)

(3) Reaper (Predator B). The MQ-9 Reaper, made by General Atomics, is a hunter-killer UAV designed to eliminate time-sensitive targets via onboard 500-pound bombs and Hellfire missiles (General Atomics, 2012b). The Reaper is shown in Figure 18.

Figure 18. MQ-9 Reaper (from General Atomics Aeronautical, 2013)

(4) Avenger (Predator C). The Avenger (also known as Predator C), made by General Atomics, is a runway-capable UAS that can use the same ground control station as the Predator and Reaper. It was designed with stealth in mind, including an internal weapons bay and radar and heat signature reducing features. Its missions include high-speed, long endurance covert ISR and precision strike (General Atomics, 2012c). Avenger is not considered in this study because reliable cost data was not available. The Avenger is shown in Figure 19.

Figure 19. Avenger (Predator C) (from General Atomics Aeronautical, 2013)

Name	Predator	Gray Eagle	Reaper	Avenger
Model Number	MQ-1	MQ-1C	MQ-9	N/A
Dimensions: Length (ft)	26.7	28	36	44
Wingspan (ft)	55	56	66	66
Payload (lbs)	450	1,075	3,850	6,500
Maximum Speed (kts)	120	167	240	400
Maximum Range (nm)	675	400	1,000	Not avail.
Maximum Endurance (hrs)	40	25	27	18
Ceiling (ft)	25,000	29,000	50,000	50,000

Table 3. Large UAV Specifications (after General Atomics, 2012a; General Atomics, 2012b; General Atomics, 2013b; Nicholas & Rossi, 2011)

d. HALE

Specifications for each HALE UAV are listed in Table 4.

(1) Global Hawk. The RQ-4 Global Hawk, designed by Ryan Aeronautical and manufactured by Northrop Grumman, is a runway-capable UAS designed for HALE, and long-range ISR operated by the USAF. The Global Hawk is shown in Figure 20.

Figure 20. RQ-4B Global Hawk (from Northrop Grumman, 2014)

(2) Triton. The MQ-4C Triton is the U.S Navy's version of the Global Hawk, manufactured by Northrop Grumman. The Triton has slightly different capabilities than its older brother, including de-icing capability which is important for flying in icing conditions. The Triton is shown in Figure 21.

Figure 21. MQ-4C Triton (from Northop Grumman, 2014)

Name	Global Hawk	Triton
Model Number	RQ-4	MQ-4C
Dimensions: Length (ft)	47.6	47.6
Wingspan (ft)	130.9	130.9
Payload (lbs)	3000	3200
Maximum Speed (kts)	310	331
Maximum Range (nm)	8,700	8,200
Maximum Endurance (hrs)	32	24
Ceiling (ft)	60,000	56,500

Table 4. HALE UAV Specifications (after Nicholas & Rossi, 2011; Northrop Grumman, 2014b)

e. Vertical Takeoff and Landing (VTOL)

Specifications for each VTOL UAV are listed in Table 5.

(1) Fire Scout. The MQ-8B Fire Scout is manufactured by Northrop Grumman and operated by the U.S. Navy. The Fire Scout is used on ships to provide situation awareness and targeting support. It can also operate as a communication relay or node. The Fire Scout is shown below in Figure 22.

Figure 22. Fire Scout (from Northrop Grumman, 2014)

(2) Hummingbird. The YMQ-18A Hummingbird is used for ISR, cargo, and other missions. It is manufactured by Boeing. The Hummingbird is shown in Figure 23.

Figure 23. Hummingbird (from Wikipedia.org, 2011)

Name	Fire Scout	Hummingbird
Model Number	MQ-8B	YMQ-18A
Dimensions: Length (ft)	30.03	35
Rotor Diameter (ft)	27.5	36
Payload (lbs)	600	2,500
Maximum Speed (kts)	115	165
Maximum Range (nm)	300	2,250
Maximum Endurance (hrs)	8	20

Table 5. VTOL UAV Specifications (after Nicholas & Rossi, 2011; Boeing 2014; Northrop Grumman, 2012) (Boeing, 2014) (Northrop Grumman, 2012)

2. Alternative Aerial Platforms

Non-UAV aerial platforms, such as balloons and towers, are described next.

a. Rapidly Erected Towers

Rapidly erected towers present an interesting alternative to UAVs. Data link and power can be supplied via cables from the ground, which can offer near limitless endurance. Additionally, running data over wired networks reduces wireless congestion. The most significant disadvantages of towers are the time it takes to erect them and the relative lack of mobility. Tower specifications are listed in Table 6.

(1) RAID (Rapid Aerostat Initial Deployment) Tower System. The RAID tower is a 105 foot rapidly deployable tower manufactured by various manufacturers including FLIR Systems Inc. and Raytheon. The RAID Tower is depicted in Figure 24.

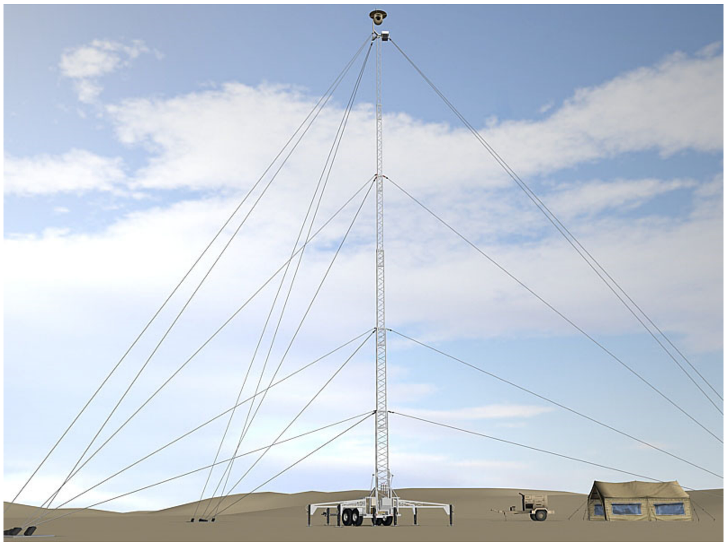

Figure 24. RAID Tower (from Halvorson, 2009)

(2) Cerberus Tower. The Cerberus Tower is a 30 foot mobile tower used by the U.S. military built by various manufacturers including FLIR Systems Inc., Manufacturing Techniques Inc. and Argon ST Inc. The Cerberus Tower is shown in Figure 25.

Figure 25. Cerberus Tower (after AR15.com, 2009)

	RAID	Cerberus
Height (ft)	105	30
Payload (lbs)	300 est.	300 est.

Table 6. Tower Specifications (Defense Update, 2008)

b. Tethered Multi-rotors

The authors conceived of multiple scenarios where tethered multi-rotors could be a viable alternative to a UAV (such as a quad-copter mounted to a Humvee). While multi-rotor aircraft are gaining much popularity in the radio-controlled hobby world, no multi-rotor UAVs seem to be currently in development for military use. Therefore, because of a lack of specifications and cost data, this interesting option will not be included in this study.

c. Tethered Balloons/Aerostats

Tethered balloons have the capability to carry power and data through the tether, and can go significantly higher, making them a very attractive alternative to a tower. Aerostats uses lighter than air gasses to inflate and fly them. Periodically, the aerostats require servicing, which is why they cannot remain airborne indefinitely. Aerostat specifications are listed in Table 7.

(1) TIF-25K Aerostat. The TIF-25K Aerostat is manufactured by Raven Aerostar and is shown in Figure 26.

Figure 26. TIF-25K (from Barker, 2013)

(2) PTDS-74K Aerostat. The PTDS-74K Aerostat is manufactured by Lockheed Martin. The PTDS-74K is shown in Figure 27.

Figure 27. PTDS-74K Aerostat System (from Defense Industry Daily, 2010)

Name	TIF-25K	PTDS-74K
Dimensions: Length (ft)	76	115
Diameter (ft)	25	36.5
Volume (ft^3)	25K	74K
Payload at 2000 ft (lbs)	468	-
Payload at 3000 ft (lbs)	302	-
Payload at 4900 ft (lbs)	-	1,100
Maximum Endurance (days)	14	20
Maximum Ceiling (ft)	3,000	4,900

Table 7. Aerostat Specifications (after Raven Aerostar, 2014; Defense Industry Daily, 2010)

d. Untethered Balloons – Google

Google is exploring an experimental airborne communications network, called Project Loon (Google, 2014), utilizing numerous untethered balloons in a complex communications relay system that utilizes different wind speeds and wind directions at different altitudes in an attempt to position the balloons for optimal communications, as shown in Figure 28. Since this application is still in the developmental phase, this alternative will not be explored in this study.

Figure 28. Project Loon (from decodingtech.com, 2012)

e. Unmanned Airships

Although conceptually interesting, unmanned airships are still in the developmental stage. Numerous developmental setbacks and funding cuts over the last few years have eliminated unmanned airships as viable solutions to the proposed mission in the authors' opinion. Therefore, unmanned airships will not be included in this study.

C. COMMUNICATION TECHNOLOGY AND PAYLOADS

This section will explore pertinent communication technology as well as various communication suites either previously employed by the DOD or currently being tested for use with UAVs.

1. Networking and Communications

Frew and Brown (2008) identified four communication structures applicable to small UAV applications: direct link, satellite, cellular, and mesh networking. The following sections explore those four communication structures and also another type of mesh networking called mobile ad hoc network (MANET).

a. Direct Link.

As the name implies, direct link architecture connects the transmitter and receiver directly as shown in Figure 29. An obstruction can block the signal and since the received power is inversely proportional to the distance squared, a high power transmitter is required at longer ranges as well as a directional antenna; otherwise data-rates will be significantly degraded. Furthermore, all spokes ($S_1 \ldots S_i$) share the bandwidth of the hub. Bandwidth is the amount of data, usually measured in bits, which can be transmitted in a unit of time.

If S_1 and S_2 need to communicate with each other, they must send their data through the hub, effectively doubling the bandwidth necessary (Frew, 2008).

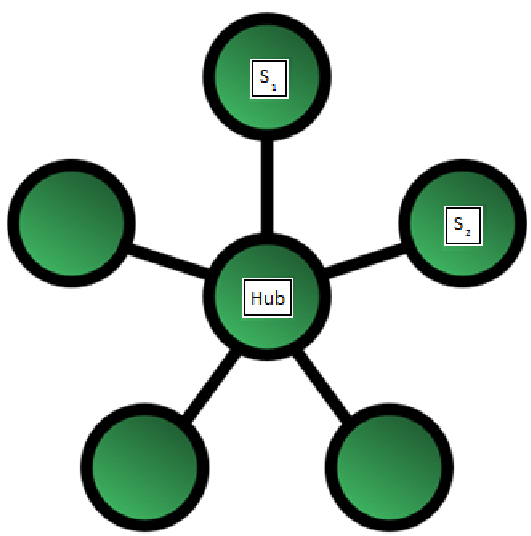

Figure 29. Star/Direct Link (after Wikipedia.org, 2014)

b. ***Satellite***

Satellites provide better coverage but still use the same hub and spoke structure and do not scale well due to their cost and latency. Terrain may also obstruct satellite view, and the ground equipment is unwieldy if mobility is desired (Frew, 2008).

c. ***Cellular***

Instead of utilizing a single hub, the cellular structure consists of multiple stationary towers, each with the ability to seamlessly connect with a device and transfer connections to a neighboring tower without interrupting the connection as shown in Figure 30. The benefits of this structure are increased capacity, redundancy, and scalability. The disadvantage of this structure is its fixed nature and expensive infrastructure, as the towers must be interconnected. Appropriate uses are high utilization, stationary areas such as border surveillance and agricultural monitoring (Frew, 2008).

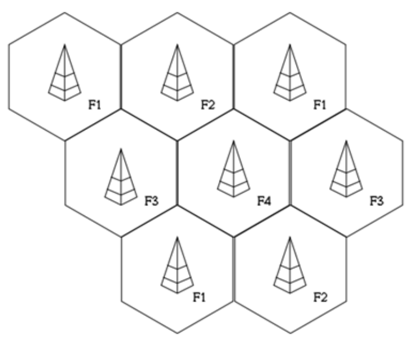

Figure 30. Cellular Network (from Wikipedia.org, 2014)

d. ***Mesh***

Mesh Network Topology is a network topology where each node not only sends and receives its own data but can also serve as a relay for other nodes, as shown in Figure 31. Self-healing algorithms are typically used to maintain paths between nodes to maintain connectivity when individual paths are blocked or broken. The benefits of this structure are exceptional redundancy, scalability, and since the nodes serve as the infrastructure, there is never a shortage (Frew, 2008). The cost of this topology is more complex routing algorithms.

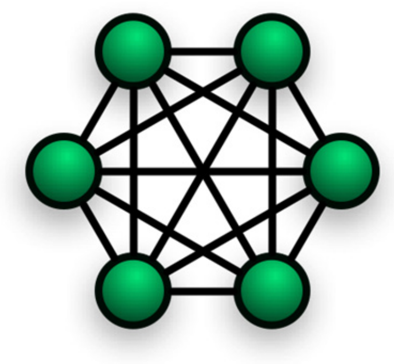

Figure 31. Fully Connected Mesh (from Wikipedia.org, 2014)

e. MANET

MANET is a self-forming meshed collection of mobile devices in a network topology that must also account for problems introduced by the mobility of the nodes. True MANET results in direct peer-to-peer connectivity between every node (Persistent Systems, 2012). However, multi-hop routing allows for easing of the requirement for direct peer-to-peer connections.

2. Technical Background

The following equations are used to determine the minimum operating altitude of a UAV and the theoretical maximum range of the communication payload in the scenarios in Chapter IV. Those requirements, along with size, weight, power [required] and cooling (SWaP-C), help distinguish the feasible solutions from the infeasible.

a. Link Budget

For communication to be effective, the signal containing data must travel from the transmitter to the receiver. The power necessary for that transmission is determined using a link budget. Numerous characteristics are used to determine the outcome, including transmitter power, antenna gain, receiver gain, and free space path loss (Ferguson & Harbold, 2001). Free space path loss is determined using the following equation:

$$L_s = \left(\frac{4\pi R}{\lambda}\right)^2$$

where λ= wavelength and R = distance between the transmitter and receiver.

Alternatively, λ is replaced with *c*/*f* where *c* = speed of propagation (speed of light assumed for free-space transmissions typical of radio or satellite links) and *f* = carrier frequency. Thus, the loss in terms of frequency and propagation speed is:

$$L_s = \left(\frac{4\pi Rf}{c}\right)^2$$

b. Shannon Limit

Higher frequencies are able to provide increased bandwidth. This is important because the warfighter will find it necessary to utilize higher frequencies in order to obtain greater throughput. The maximum throughput of a frequency can be determined using the Shannon Limit equation, as follows:

$$I = B\log_2\left(1+\frac{S}{N}\right)$$

where *I* = information capacity, *B* = bandwidth, and *S*/*N* = signal to noise ratio.

Combined with the free space path loss, it becomes clear that while higher frequency is desirable from a bandwidth perspective, a doubling of frequency necessitates a quadrupling in power to obtain the same link (Ferguson & Harbold, 2001).

c. Radio Horizon

The communication payloads explored in this study are "line of sight" and are limited by their radio horizon. According to Herbert, (2013), the simplified radio horizon equation is

$$\mathrm{R} = 1.23(h_t^{1/2} + h_r^{1/2})$$

where R is the distance to the radio horizon in nautical miles and h_t and h_r are the heights of the transmitting and receiving antennas in feet. In all of the cases examined in this study, one antenna is assumed to be at ground level, allowing for further simplification of the equation

$$R = 1.23h^{1/2}$$

This equation can be solved for h:

$$h = \left(\frac{R}{1.23}\right)^2$$

d. Size, Weight, Power and Cooling

SWaP-C requirements provide a number of challenges for both the aerial platform and the communication payload. Smaller aerial platforms have very small payload compartments (size) and minimal useful loads (weight). For example, the Raven UAV can only carry a 1 pound payload. AeroVironment combats this problem by manufacturing its own communication payload that specifically meets these requirements, the Digital Data Link (DDL) (AeroVironment, 2012a).

Increased power consumption decreases mission duration capability, while possibly improving transmission power (Altera, 2014). Furthermore, as waveform and processing complexity increases, functionality and power consumption increase as well. To compensate for the increase in power consumption and mission duration requirements, larger batteries are typically used, but larger batteries increase system weight (Altera, 2014). Additionally, larger batteries and the increased power drawn from them produce additional heat, sometime requiring the use of dedicated cooling units, which in turn draw more power and add more weight (Keller, 2013).

The ideal communication payload has low weight, high receiver sensitivity, low power consumption, high transmit power, and provide service for UHF, VHF and data. Each of the communications payloads considered in this study makes compromises to reach the manufacturer's idea of a good solution.

3. Communication Payloads

The following communication systems will be evaluated for cost-effectiveness and interoperability with appropriate platforms.

a. Persistent Systems Wave Relay

Wave Relay, manufactured by Persistent Systems, is a MANET solution that improves the standard "self-forming" and "self-healing" mesh network by continuously adapting to fluctuations in terrain and the environment to maximize connectivity and communication performance. The Wave Relay routing algorithm allows a large numbers of meshed devices to be incorporated into a network in which the devices (as relays), along with their associated radio links, are the infrastructure (Persistent Systems, 2011).

Wave Relay was designed to maintain connectivity among a large number of highly mobile nodes. According to Persistent Systems, their proprietary algorithms provide scalability that is over 10 times greater than that offered by other competitive options (Persistent Systems, 2012). Persistent Systems also claims that Wave Relay is the only solution that scales to a large numbers of continuously moving nodes utilizing an any-to-any topology. This capability removes the need to divide the mesh artificially into independent sub-networks. These capabilities result in providing a networking tool that should meet performance requirements under the most demanding situations.

The signal strength between two wireless devices in a mobile network decreases as the distance between them increases, as shown in the link loss calculation. Therefore, the capacity and reliability of the pathways through a network fluctuates continuously as each device moves. Wave Relay detects these changes and routes traffic according to the highest-capacity path, thereby delivering the best bandwidth for that particular moment. This algorithm-enabled route selection promises continual peak network performance (Persistent Systems, 2012).

The authors considered two of Persistent Systems' Wave Relay configurations for this study: Wave Relay Gen4 Board and the Wave Relay Quad Radio Router. The authors will refer to the Wave Relay Gen4 Board and the Wave Relay Quad Radio

Router as simply Wave Relay and Wave Relay Quad respectively. The specifications of both configurations are listed in Table 8 and an example of each is shown in Figure 32.

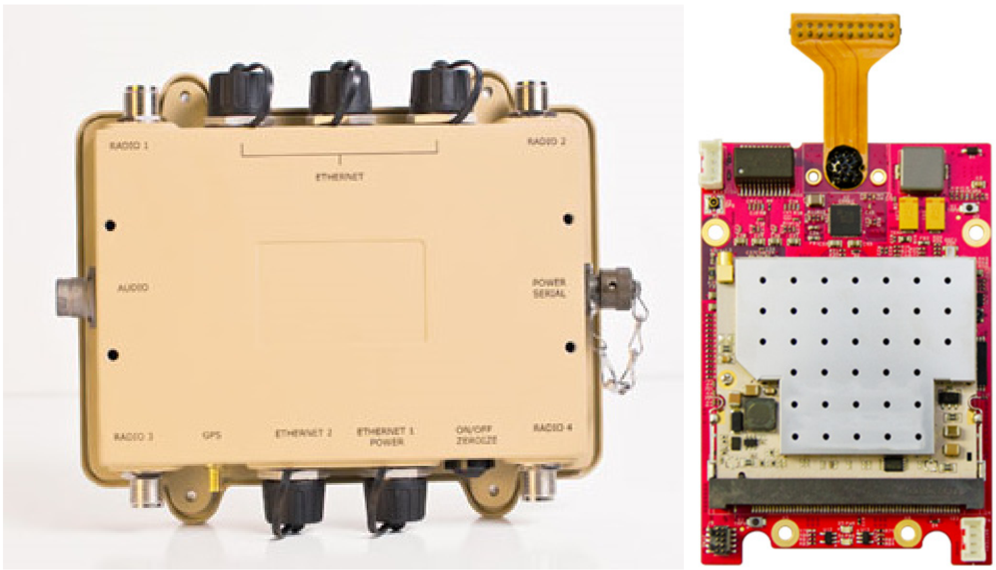

Figure 32. Wave Relay Quad and Wave Relay (from Persistent Systems, 2014)

Name	Wave Relay Quad	Wave Relay
Size	8.5”x6”x2”	3.9”x2.7”x.07”
Weight (lbs)	3.2	.2
Simultaneous Frequencies	4	1
Throughput (Mbps)	148	37
Power Consumption (Watts)	55	16.5
Power Output (Watts)	2	2

Table 8. Wave Relay Specifications (Persistent Systems, 2012)

b. TrellisWare WildCat II and Ocelot

WildCat II is one of TrellisWare’s Tactical MANET products. WildCat II has the capability to interact with two separate ground networks, bridge ground and airborne networks, or act as backhaul.

WildCat II contains two quad-band radios, GPS, Ethernet and universal serial bus (USB), and is capable of voice and data. TrellisWare claims data rates up to 40Mbps when fully aggregated. Like Wave Relay, WildCat II is also self-forming and self-healing, with routing changes being completely transparent to the operator (TrellisWare, 2014a). Ocelot is TrellisWare's small form factor module, similar to the Gen4 card previously described (TrellisWare, 2014b).

The specifications for TrellisWare's WildCat II and Ocelot are listed in Table 9 and each radio is shown in Figure 33.

Figure 33. WildCat II and Ocelot (from TrellisWare Technologies, 2014)

Name	Wildcat II (TW-130)	Ocelot (TW-600)
Size	5.5"x5"x2"	3.4"x2.1"x.54"
Weight (lbs)	3.4	.19
Simultaneous Frequencies	4	1
Throughput (Mbps)	40	8
Power Consumption (Watts)	21	4.3
Power Output (Watts)	8	2

Table 9. WildCat II and Ocelot Specifications (TrellisWare, 2014a)

c. *Oceus Networks Xiphos*

Xiphos is Oceus Networks' 4G Long Term Evolution (LTE) tactical broadband solution for the mobile users communication needs. Oceus Networks claims a range of 5–7 miles on the ground, and up to 62 miles via airborne deployment with clear line of sight. While Xiphos is not MANET, it does utilize Oceus Networks' proprietary Network of Xiphos (NOX) capability allowing users to move between nodes without dropping active connections (Oceus Networks, 2014). Xiphos serves as an access point and users can use their own Long Term Evolution (LTE), commercial-off-the-shelf (COTS) cellular devices to access the network Xiphos provides.

A Xiphos radio is shown in Figure 34. The specifications for the two Xiphos radio configurations considered in this study are listed in Table 10.

Figure 34. Xiphos (after Oceus Networks Networks, 2011)

Name	Xiphos 1RU	Xiphos 6RU
Size	3x(4.4"x16.4"x18.8")	10x(4.4"x16.4"x18.8")
Weight (lbs)	25+33+20=78	25+6x33+13+2x20=276
Simultaneous Frequencies	4	24
Throughput (Mbps down)	150	346
Throughput (Mbps up)	50	112
Power Consumption (Watts)	855	3275
Power Output (Watts)	80	480

Table 10. Xiphos Specifications (Oceus Networks, 2014)

d. Harris Falcon III AN/PRC-117G and RF-7800W OU440

Falcon III is Harris Corporation's High Capacity Line-of-Sight platform that can send secure wireless IP data. Harris claims a range of over 100 miles given clear line-of-sight (Harris, 2014). The Falcon III RF-7800W OU440 is rated for operational use up to 15,000 ft and includes FIPS 140–2 Level 2 compliant encryption (Harris, 2012b). Harris also manufactures a manpack capable of UHF/VHF analog voice, and digital data called the AN/PRC-117G, shown on the left in Figure 35. The original family of Falcon III radios, still available, is Type 1 communications security (COMSEC) capable.

The specifications of AN/PRC-117G and RF-7800W OU440 are listed in Table 11. While the throughput for the AN/PRC-117G is listed as 16 Kbps, anecdotal field experiments conducted by Naval Postgraduate School (NPS) researchers in 2010 demonstrated a rate of 3-4 Mbps for the 117G over a 4 km range using the Adaptive Networking Wideband Waveform (ANW2) protocol (J. Gibson, personal communication, March 20, 2014).

Figure 35. Falcon III AN/PRC-117G and RF-7800W OU440 (from Wikipedia, 2013)

Name	Falcon III AN/PRC-117G	Falcon III RF-7800W OU440
Size	7.4”x3.7”x1.5”	10.23”x9.91”x2.53”
Weight (lbs)	12	5.5
Throughput (Mbps)	.016	90
Power Consumption (Watts)	55	22
Power Output (Watts)	20	.316

Table 11.
Falcon III – AN/PRC-117G and RF-7800W OU440 Specifications (Harris, 2014)

e. AeroVironment Digital Data Link (DDL)

DDL is AeroVironment's system designed specifically for SUAS. These exceptionally small systems can be installed on the smallest of UAS's and provide IP-based communication between a ground station and the aircraft (AeroVironment, 2012a). AeroVironment's Raven B UAVs can come equipped with DDL from the factory. An example of DDL is shown in Figure 36. DDL's specifications are listed in Table 12.

Figure 36. Digital Data Link (AeroVironment, 2012a)

Name	DDL
Size	2x5"x0.5"
Weight (lbs)	.2
Throughput (Mbps)	4.5
Power Consumption (Watts)	9
Power Output (Watts)	1.5

Table 12. Digital Data Link Specifications (AeroVironment, 2012a)

D. SUMMARY

This chapter started with a literature review of previous UAV cost analyses. Aerial platform backgrounds were presented. Pertinent communication theories were described to give the reader background information. Finally, communication payloads considered in this study were presented.

The next chapter will discuss the methodology utilized in this study, based on Wall and MacKenzie's (2013) work involving the initial organization of a multi-objective, cost-effectiveness analysis. The authors will focus on establishing a framework for evaluating the benefits and financial costs of each alternative and tailoring it to a decision maker's needs. The authors will include a hierarchical structure of benefits for both the included communications relay platforms and the possible communication payloads. Within each attribute description, data for each alternative will be provided. Finally, the chapter will provide cost data for each alternative and describe how each cost figure was derived.

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III. METHODOLOGY

A. MODELING APPROACH FOR CEA

In this section, the authors introduce the multi-objective framework used in this study.

1. Introduction to CEA

Traditional cost-benefit analysis (CBA) compares costs to benefits. Benefits in a CBA must be monetized, which in the private sector is easily achieved because almost all activities in business are geared toward increasing shareholder wealth and/or making a profit. In government, where the main goal of a system normally has nothing to do with earning a profit, monetizing benefits can be difficult, if not impossible.

Another method of analyzing costs and benefits is called a CEA. Like a CBA, a CEA also compares the costs and benefits of a system. However, unlike a CBA, the benefits in a CEA do not have to be monetized, which makes it more appropriate for government analysis (Wall & MacKenzie, 2013). With a CEA, benefits, such as creating security, aiding victims of a natural disaster or educating women can be measured and compared without the need to put a price on such actions. For example, a CEA can help determine the most cost-effective method of supplying network infrastructure to an amphibious landing force.

If a CEA only compares one type of benefit or metric between multiple alternatives, the analysis is relatively straightforward. For example, it is easy to compare the maximum speed of several automobiles. However, in most analyses, government officials desire more than one benefit from a system. In those cases, a method of comparing different types of benefits must be used. One method of comparing multiple benefits is called a multi-objective analysis. A multi-objective analysis allows a decision maker to compare dissimilar benefits in order to derive an overall effectiveness measure for each alternative. The effectiveness and cost of each alternative are used to derive the most cost-effective solution (Wall & MacKenzie, 2013).

A multi-objective CEA is used in this study. First, the authors will develop an objectives hierarchy which creates a structure and order to the desired benefits. Second, value functions are created based on the authors' research and best judgments in order to normalize the score of each objective between zero and one. Value functions for each objective can vary between different scenarios in order to accurately describe the importance of the specific benefit in completing a particular mission as specified in the scenario. Next, importance weights are given to each objective to determine how to compare different types of benefits to one another. Once complete, an overall effectiveness score can be determined for each alternative. A graph can depict the overall effectiveness score and the costs of each alternative. After plotting all alternatives on the two-dimensional graph, the decision maker can gain a better understanding about the cost-effectiveness of each alternative for a given scenario or mission-set (Wall & MacKenzie, 2013).

To test assumptions made in this study, the authors utilize sensitivity analysis to determine the effect of varying assumptions or estimates on the outcome of the study. The sensitivity analysis will demonstrate which assumptions are critical to the decision and which are not as important.

The overall effectiveness score rests largely on the value functions and importance weights of the objectives or benefits. Those parameters are based on subjective judgments by the decision maker. In this study, the authors will serve as the decision maker for each scenario. However, different decision makers will value different attributes more than others. Even the same decision maker may change how he values a particular objective as circumstances change. The authors provide a tool that will allow potential decision makers to add their own objectives and create their own value functions and importance weights. This will allow any future decision makers to specifically tailor the analysis to match the particular circumstances of their situation, as well as their individual preferences.

The following sections will describe the aforementioned multi-objective, CEA in more detail.

2. Objectives Hierarchy

A multi-objective analysis uses a hierarchy to structure layers of objectives or benefits. The hierarchy is determined by the individual or collective decision makers. Their needs and desires will help structure the hierarchy to accurately depict what they are looking for. The top layer of the hierarchy is the primary objective, which is normally to “maximize effectiveness.” For example, if an individual were trying to decide which car to buy, he could create a hierarchy of objectives for his goal. At the top of the hierarchy, he places maximize effectiveness of the car. However, how do you measure effectiveness? He would ask himself what he means by the “effectiveness.” He may answer that a car with maximum effectiveness maximizes performance, maximizes reliability, maximizes utility, maximizes efficiency, and finally, minimizes maintenance. He may then ask himself what he means by “maximizing performance.” He may answer that maximizing performance means maximizing speed and maximizing maneuverability. Another iteration of this process would break down speed into acceleration and highest top end speed. He then determines that maneuverability means the smallest turning radius and highest speed a driver could maintain while successfully negotiating one specific corner in an online review, which he will call skidpad test results. This process will continue for each objective until each objective can be measured (Wall & MacKenzie, 2013). When all objectives are determined, a hierarchy can be created. An example of a partially completed hierarchy is Figure 37. For an enlarged copy, see Appendix A.

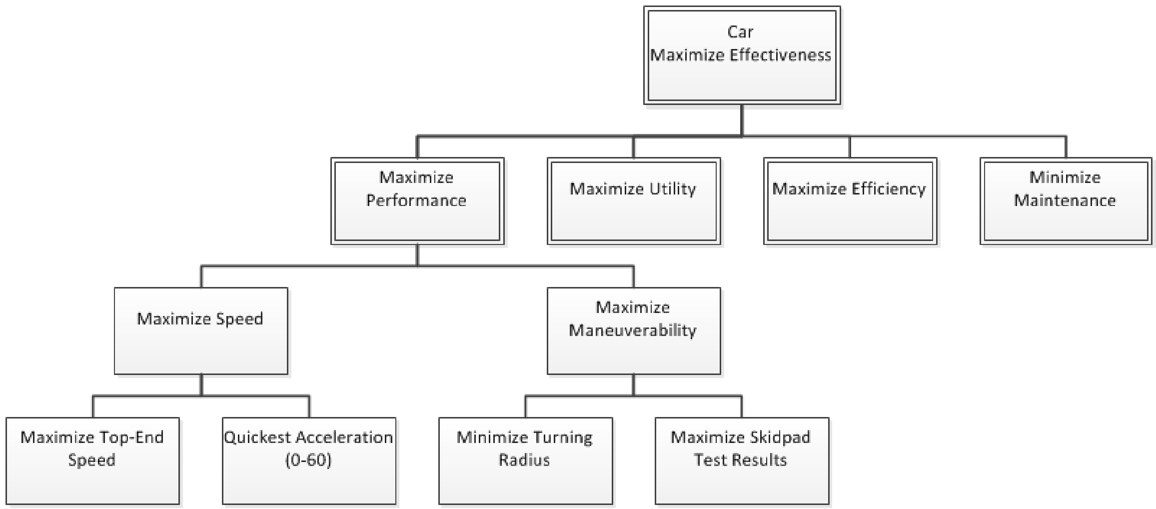

Figure 37. Car Hierarchy

Alternatively, a hierarchy of objectives can be derived by starting at the bottom of the hierarchy table with a specific set of measurable objectives. With each specific objective, the man would ask himself why is that there, which would then help him determine where it belongs in the structure (Wall & MacKenzie, 2013). For example, he already knows he want the car with the lowest 0–60 mph time and the highest top end speed. He could ask why those two objectives are there. He would answer he wants the fastest car (maximum speed). The process would continue until the hierarchy is connected from the bottom to the overall objective (maximum performance in this case).

In most cases both methods are used to derive an objective hierarchy. Each one has advantages and disadvantages that can be used together to ensure an accurate depiction of the layered set of objectives or benefits is achieved. When the hierarchy is complete it will have the following characteristics:

1. Mutually exclusive (each objective appears only once).
2. Collectively exhaustive (all important objectives are included).
3. Able to lead to measures that are operational (can actually be used). (Wall & MacKenzie, 2013)

The first two characteristics are self-explanatory. However, #3 deserves further explanation. The bottom-level of objectives in the hierarchy, called attributes, should be operational measures, which means that you can actually find values to measure (Wall & MacKenzie, 2013). In other words, speed is a good attribute because it can be measured in miles per hour. Beauty would not be a good attribute because you cannot measure beauty without breaking it down in terms of what you mean by beauty. It would be necessary to break beauty into other attributes which can be measured.

3. Value Functions

Each single objective or attribute in the bottom level of the hierarchy must be translated to a value scale ranging between 0 and 1. By mapping each attribute to a value scale, the decision maker can combine attributes measured in different units (e.g., mph and pounds). A value scale also reflects that a decision maker may value marginal changes in an attribute differently. For example, in the previous example, a car buyer may value increasing the top speed of the automobile from 50 to 99 mph more than he values increasing the top speed from 150 to 199 mph. The car buyer knows that most roads in his driving area do not have straight sections long enough to achieve more than 150 mph; therefore achieving a top-end speed in the 150–199 mph is of little additional value. Incremental values are derived from the top speed by measuring the importance a particular stakeholder places on each range. The car buyer assesses the incremental value that he receives by moving from one range to the next range. In this case, the car buyer rates the incremental value of the following speed ranges from 0–10 where 10 is the best and 0 has no incremental value as shown in Table 13.

Speed Range	Incremental Value
0–49 mph	10
50–99 mph	9
100–149 mph	6
150–199 mph	4
200+ mph	1

Table 13. Car Example Incremental Values

With the relative value for each range of speed determined, a value function can be created to score each attribute on a scale of 0–1. This is accomplished by calculating the cumulative value of each speed range and then dividing by the largest cumulative value (Wall & MacKenzie, 2013). For example:

$$Sum : 10 + 9 + 6 + 4 + 1 = 30$$

The speed cumulative values are listed in Table 14.

Speed Range	Cumulative Value	Value
0–49 mph	10	10/30 = .333
50–99 mph	10+9 =19	19/30 = .633
100–149 mph	10+9+6 = 25	25/30 = .833
150–199 mph	10+9+6+4 = 29	29/30 = .967
200+ mph	10+9+6+4+1 = 30	30/30 = 1

Table 14. Car Example Cumulative Values

While it is true that a car with a top-end speed over 200 mph would receive the highest score, a car that measured in the 100–149 mph range would only reduce the value by 16.7%. This relative range of values reflects the priority of the specific stakeholders and answers the question: "how much is enough?" Additionally, the value function eliminates units and scales each attribute according to a stakeholder's preferences (Wall & MacKenzie, 2013). This will help in comparing different attributes to one another. For the corresponding graph of the top-end speed value function, see Figure 38.

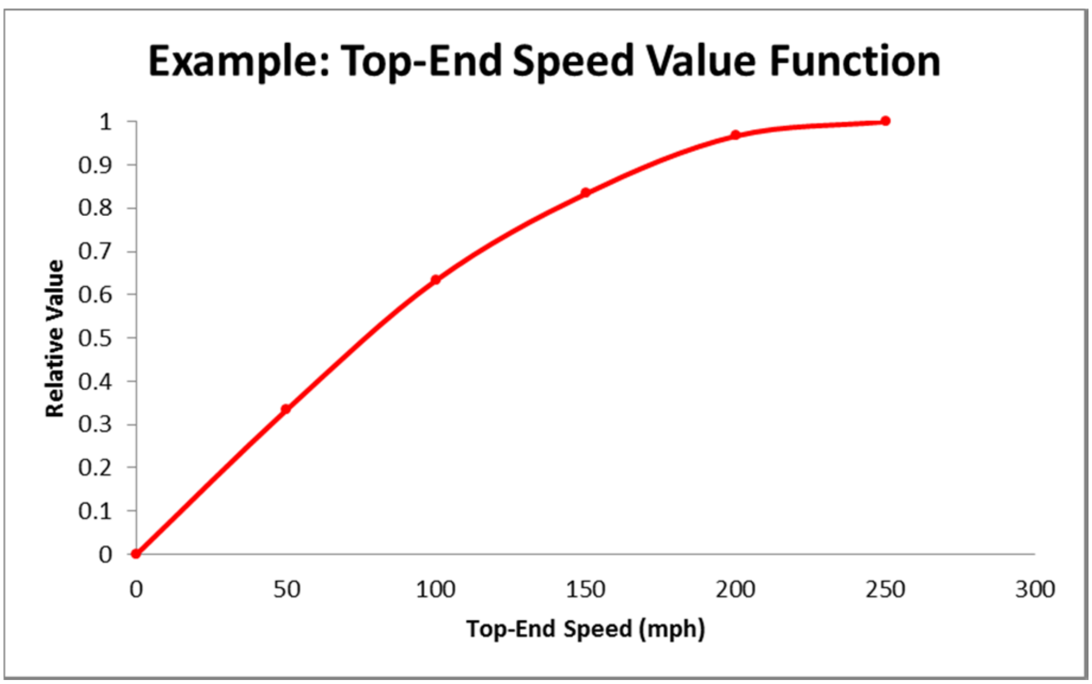

Figure 38. Car Value Function

Creating an equation that approximates the value function above can provide more granularity. The 2nd order polynomial equation below closely approximates the previously described value function.

$$v(x) = -1.51E - 05x^2 + .0078x$$

where x = speed in miles per hour.

The speed value function is shown in Figure 39. When necessary, a higher order function, piecewise linear function, or an exponential function may be used to best fit the assessed values. More complex equations can be seen in Chapter IV. Additionally, Appendix B contains an example of the step-by-step process in Excel.

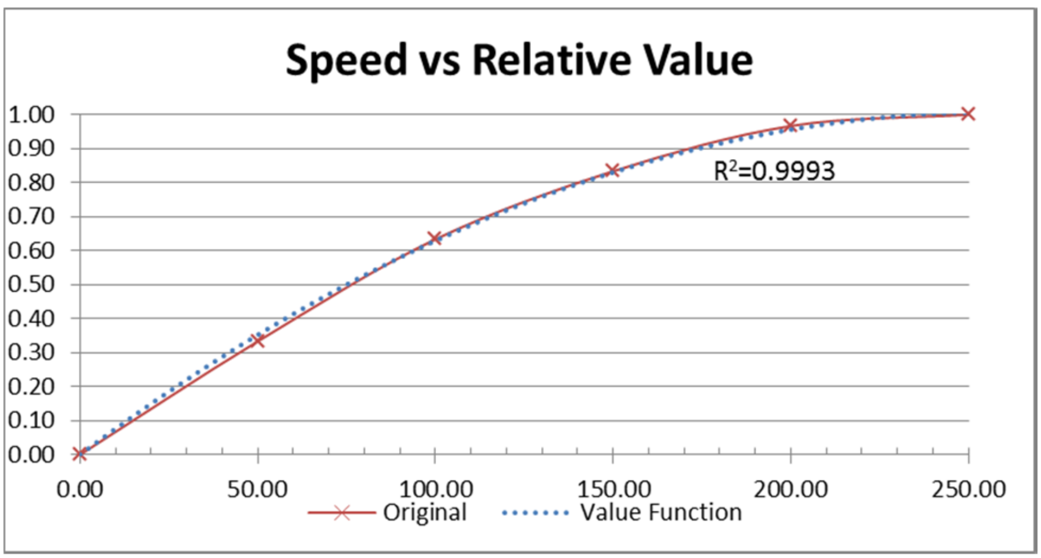

Figure 39. Speed Value Function (Using Equation)

While speed was easily measured, not all metrics are easily counted or physically measureable, which is referred to as a natural measure (Wall & MacKenzie, 2013). For instance, the decision maker may prefer one color car over another. In this case, the decision maker may prefer a silver car to a black car, since dust and scratches show more on the black car. The black car must be washed and touched-up more frequently. The decision maker could directly assign relative values to each color between 0 and 1 where the most preferred color has a value of 1 and the least preferred color has a value of 0.

4. Importance Weights

After each individual objective or attribute has been assigned a value function ranging between 0 and 1, the decision maker must decide on the relative importance of each objective or attribute compared to one another. The stakeholder rates the importance of each attribute by giving each attribute a weight. That weight must be a value between 0 and 1 and the sum of all attributes weights must equal 1. A larger weight value indicates that one attribute is more important than other attributes with lesser weights (Wall & MacKenzie, 2013). Weights will vary as decision makers and requirements change, but the methods by which the assessment is made should remain consistent.

The simplest approach is to assign each attribute the same weight. This is accomplished by evenly distributing the weight among N items. For example, given 5 attributes, each would be weighed by 0.20 or 1/5. However, this approach may not accurately reflect the decision maker's preferences. Two methods available are rank sum and rank reciprocal (Wall & MacKenzie, 2013) as shown in Table 15.

In the rank sum method, the first item receives a weight of N, where N is the total number of items being ranked. The second item gets N-1, and so on, until the last item gets a weight of 1. The normalized weight for each attribute is the weight (N, N-1,…,1) divided by the sum of all weights.

In the rank reciprocal method, the reciprocals of the ranks are used. The first item gets a weight of 1/1, the second = 1/2, the third = 1/3, the fourth = 1/4, and so on. The normalized weight for each attribute is its weight divided by the sum of all weights (Wall & MacKenzie, 2013).

Attribute	Ranked Order	Rank Sum	Rank Reciprocal
Top Speed	1	5/15 = .33	(1/1)/(137/60) = .438
0–60 Time	2	4/15 = .27	(1/2)/(137/60) = .219
Turn Radius	3	3/15 = .20	(1/3)/(137/60) = .146
Skidpad	4	2/15 = .13	(1/4)/(137/60) = .109
Color	5	1/15 = .07	(1/5)/(137/60) = .088

Table 15. Rank Sum and Rank Reciprocal

When the two methods are plotted graphically, it is easy to see the difference. See Figure 40. Rank sum produces a linear function, while rank reciprocal produces a more exponential function. The decision maker should use the method most consistent with the desired effect.

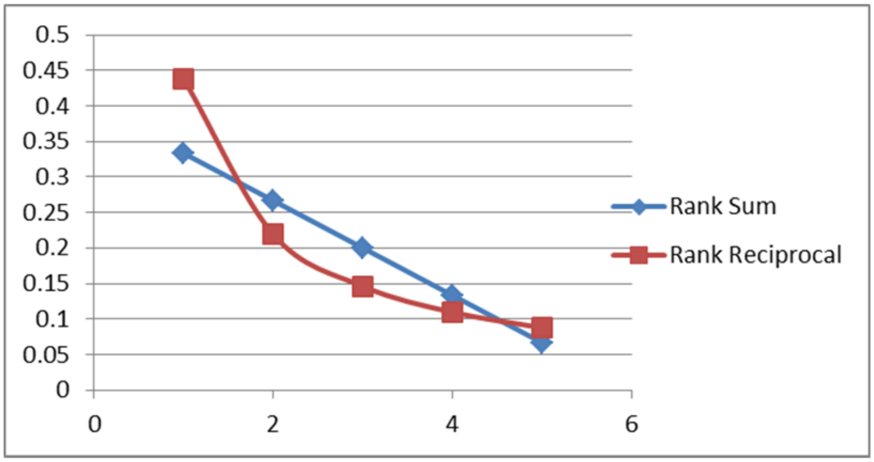

Figure 40. Rank Sum vs Rank Reciprocal Importance Weight Distribution

The decision maker can start with one method and then make minor adjustments to better approximate their preferences. For example, suppose the car buyer only cares about 5 attributes in the following order: top speed, 0–60 time, turn radius, skidpad results, and color. The decision maker then uses the rank sum method as a starting point. The decision maker then decides that the middle items are closer in weight than the rank sum method produced. He then manually adjusts the importance weights to better match his preferences while ensuring that the sum of importance weights remain 1. For the adjusted importance weights see Table 16.

Attribute	Rank Sum	Adjusted Weight
Top Speed	5/15 = .33	.33
0–60 time	4/15 = .27	.22
Turn radius	3/15 = .20	.20
Skidpad	2/15 = .13	.18
Color	1/15 = .07	.07

Table 16. Manually Adjusted Weights

Deciding importance weights is normally an iterative process with multiple adjustments made during the process. After each adjustment, the importance weights should be reviewed to determine if they meet the decision maker's intent. To make the process easier, it is sometimes helpful to graphically depict weights, as in Figure 41.

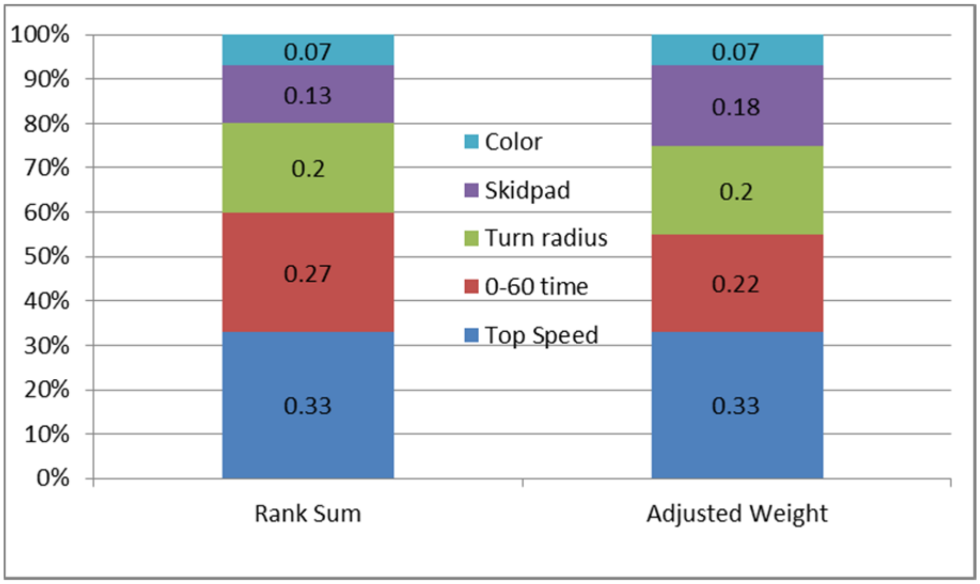

Figure 41. Distribution of Weight

When assigning importance weights, a decision maker must consider the relative desirability of the range of available alternatives for each attribute. For example, if the only car colors available to the car buyer are pink polka-dots and white, the decision maker may assign a much higher importance weight to color so they can avoid buying a car with pink polka-dots. Alternatively, if the available colors are all colors that the decision maker prefers, then he may place a significantly lower importance weight on color because any color available will be suitable.

After reviewing the importance weights, the decision maker can then ask himself questions similar to the following:

- Is top speed really five times as important as color?
- Is skidpad really almost as important as turn radius?
- Is top speed really more important than 0–60 time and color combined?

In this study, the authors primarily use a direct assessment approach for assigning importance weights. Once initial an assessment of importance weights for all attributes is made, the authors then make adjustments to refine each importance weight until the desired balance is achieved.

Once the decision maker is satisfied with the importance weights, they can be used with the raw data and value functions to determine a MOE for each alternative.

5. MOE

Once value functions and importance weights are determined, an overall rating or MOE can be calculated for a specific alternative (Wall & MacKenzie, 2013). MOE is calculated by adding the product of each value function and its corresponding importance weight as depicted in the formula below.

$$v(j)=w_1*v_1(x_1(j))+w_2*v_2(x_2(j))+...+w_n*v_n(x_n(j))$$

where $v(j)$ represents the MOE for alternative j, w_1 is importance weight for the 1st attribute, $v_1(.)$ is the value function for the 1st attribute, and $x_1(j)$ is the raw value for the 1st attribute for alternative j.

6. Determining a Cost-Effective Solution

Once the MOE is calculated, a graphical comparison of MOE vs cost can be made, allowing a decision maker to evaluate the cost-effectiveness of various alternatives. In the following sections, the authors explore a few methods of interpreting the results of a CEA and determining a cost-effective solution.

a. Superior Solution

A superior solution exists when one alternative possesses both the highest MOE and the lowest cost of all alternatives. When a superior solution exists, there is no need to interpret the data any further and it can be declared the most cost-effective solution (Wall & MacKenzie, 2013). Returning to the example of the car buyer, the data reveals that the Neon SRT-4 has the highest MOE and the lowest cost, a seen in Figure 42. Based upon the decision maker's input, the SRT-4 is the superior solution for his weighted combination of desirable attributes.

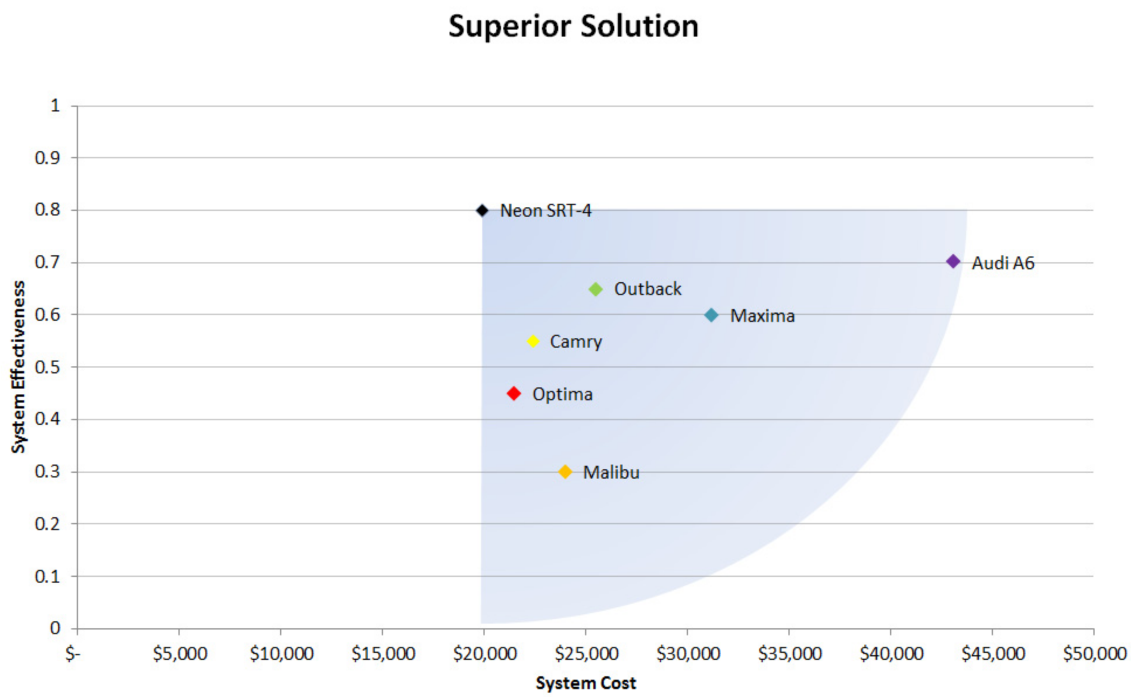

Figure 42. Superior Solution

Superior solutions make interpreting the results of a CEA much easier. However, superior solutions are relatively rare and other methods of determining a cost-effective solution are needed.

b. Efficient Solution

Efficient solutions are alternatives that are not dominated by other alternatives (Wall & MacKenzie, 2013). Going back to the car buyer example helps illustrate the concept of an efficient solution. If the Neon SRT-4 is no longer an alternative, the Malibu has a lower MOE and yet costs more than the Camry and Optima, as seen in Figure 43. Therefore, the Malibu is dominated by the Camry and Optima. The Malibu is not an efficient solution and can be eliminated from consideration. Further examination reveals that the Maxima is dominated by the Outback. Consequently, the Maxima is not an efficient solution and can be eliminated from consideration as well. That leaves the Optima, Camry, Outback and A6. All four cars can be considered efficient solutions since none of them are dominated by any of the others.

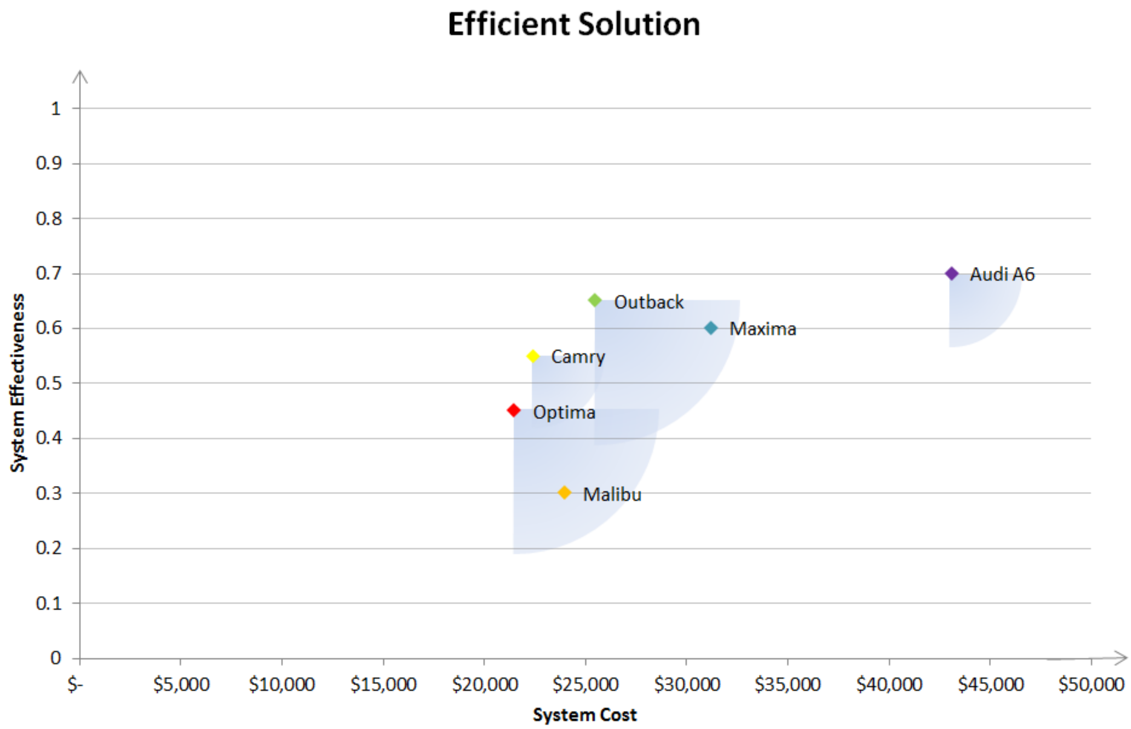

Figure 43. Efficient Solution

As in the car buyer example, the efficient solution method often still leaves a range of possible cost-effective alternatives to choose from. Narrowing down the alternatives any further requires examining the decision maker's preferences concerning MOE and costs.

c. *Satisficing Solutions*

Satisficing solutions represent the "good enough" solution. Satisficing solutions are alternatives that satisfy the decision maker's general preference for MOE and cost (Wall & MacKenzie, 2013). By determining the decision maker's minimum MOE and maximum cost, an acceptable window or quadrant can be developed. Any alternative that meets or exceeds the minimum MOE and is less than or equal to the maximum acceptable cost will be considered a satisficing solution. The Optima, Camry and Outback are all considered satisficing solutions, because their MOE is greater than the minimum MOE (.4) and their costs are lower than the maximum cost ($27,800) as determined by the car buyer, as shown in Figure 44.

Figure 44. Satisficing Solution

As is the case with efficient solutions, satisficing solutions often produce multiple acceptable cost-effective alternatives. In order to determine one winner out of these efficient and satisficing solutions, an additional examination of the decision maker's preference toward MOE and cost is needed (Wall & MacKenzie, 2013).

d. MOE and Cost Tradeoffs

When previous attempts at producing a cost-effective solution have left multiple acceptable alternatives, the decision maker must examine the tradeoff between each remaining alternative. The tradeoff or marginal difference between the Optima, Camry and Outback is apparent in Figure 45. From this graph, the car buyer must decide if the increase in MOE of 0.1 is worth the extra $900 of Camry compared to the Optima. If the answer is yes, then car buyer needs to determine if the additional 0.1 MOE of the Outback is worth the additional $3100 over the cost of the Camry. The authors use a marginal reasoning solution when determining if tradeoffs between platforms or payloads are worthwhile.

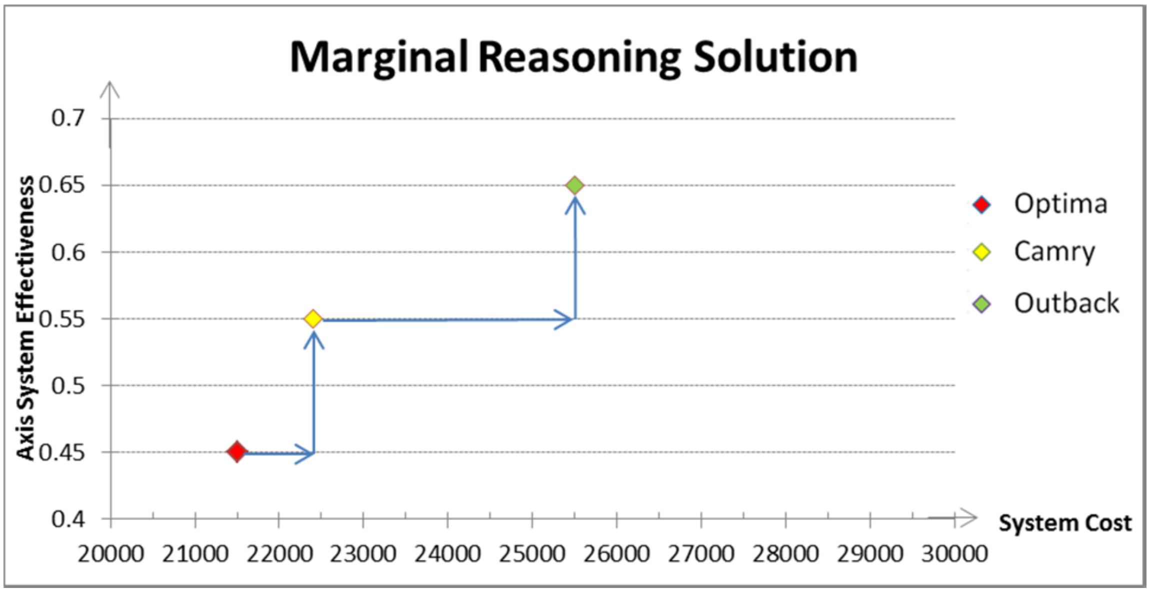

Figure 45. Marginal Reasoning Solution (Tradeoffs)

By exploring these relationships, the decision maker can determine a single cost-effective solution.

B. HEIRARCHIES

So far in this chapter, the authors have introduced the methodology of multi-objective CEA. For the remainder of this chapter, the authors will introduce the hierarchy for aerial platforms and the hierarchy for the communication payloads. Within each hierarchy description, individual attributes will be explained and the raw data for each alternative will be presented. Since the value function and importance weights will vary as conditions and requirements of the mission change, they will not be presented in this chapter. Each attribute value function and importance weight will be presented in Chapter IV within each of the four scenarios utilized in this study.

1. Aerial Platform Hierarchy

The hierarchy that is utilized in this study to individually evaluate the overall mission effectiveness of the selected aerial platforms within each proposed scenario considered in this study is depicted in Figure 46. For an enlarged copy, see Appendix A. It is important to note that this hierarchy was derived from the opinion of the authors after extensive research and discussions with experts in the field. Other decision makers may decide to add, subtract or reorganize the hierarchy to suit their own needs.

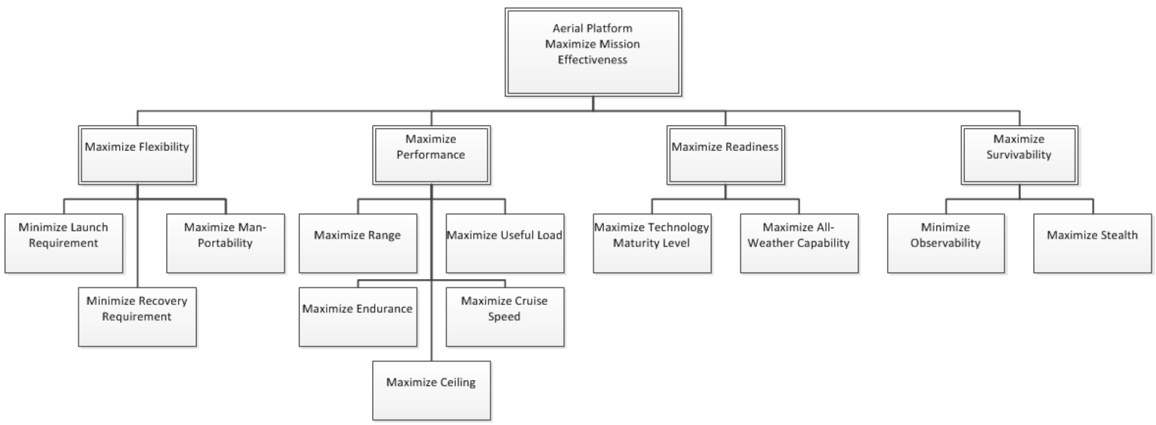

Figure 46. Aerial Platform Hierarchy

The overall objective of each aerial platform is mission effectiveness. The authors chose to break down mission effectiveness into flexibility, performance, readiness and survivability. The following sections will discuss flexibility, performance, readiness and survivability and their subcomponents in more detail.

a. Flexibility

The flexibility hierarchy for aerial platforms is depicted in Figure 47.

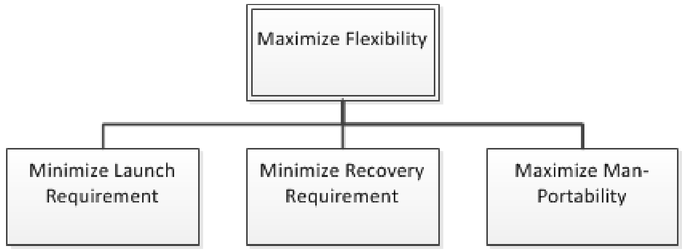

Figure 47. Aerial Platform Flexibility Hierarchy

Flexibility describes the ability to employ the aerial platform in different conditions. Flexibility is divided into launch requirement, recovery requirement and man-portability. Each aerial platform's raw data for the attributes included in the flexibility hierarchy are listed in Table 17. The following describes how each objective is measured across all scenarios.

(1) Launch Requirement. Launch requirement describes the type of launch required by the aerial platform. Launch requirement is an important attribute because it determines geographical requirements for deploying the aerial platform, which can have a big impact on the launch flexibility of the asset. Aerial platforms that need less space launching, such an aerostat due to its vertical launch, will be favored over assets that require more space for launch, such as the catapult launched Shadow, which will need a clear path for launch and climb to its operational altitude.

(2) Recovery Requirement. Recovery requirement describes the type of method utilized for recovering the aerial platform. Recovery requirement is an important attribute because it determines geographical requirements for recovering the aerial platform, which can have a big impact on the recovery flexibility of the asset. Platforms that need less space recovering, such as the Fire Scout with its vertical recovery, will be favored over assets that require more space for landing, such as the Global Hawk, which requires an approach path and paved runway for landing.

(3) Man-Portability. Man-portability is measured as a yes or no answer. In order for an aerial platform to be considered man-portable, it must have the capability of being transported and launched by an individual operator. If a single operator cannot carry and launch the platform, it is not considered man-portable for the purposes of this study. If an aerial platform can be carried and launched without a specialized platform, it

reduces the manning requirements and allows smaller sized units to employ the asset, thereby increasing flexibility of the asset. For the purposes of this study, the objective is to maximize man-portability.

Aerial Platform	Launch Requirement	Recovery Requirement	Man-Portable
Blackjack	Catapult	Vertical Wire	N
Cerberus Tower	Vertical	Vertical	N
Fire Scout	Vertical	Vertical	N
Global Hawk	Runway	Runway	N
Gray Eagle	Runway	Runway	N
Hummingbird	Vertical	Vertical	N
Predator	Runway	Runway	N
PTDS-74K Aerostat	Vertical	Vertical	N
RAID Tower	Vertical	Vertical	N
Raven	Hand Launch	Deep Stall	Y
Reaper	Runway	Runway	N
Shadow	Catapult	Arrestment (170ft)	N
TIF-25K Aerostat	Vertical	Vertical	N
Triton	Runway	Runway	N
Wasp III	Hand Launch	Deep Stall	Y

Table 17. Aerial Platform Flexibility[1]

b. Performance

The performance hierarchy for aerial platforms is depicted in Figure 48.

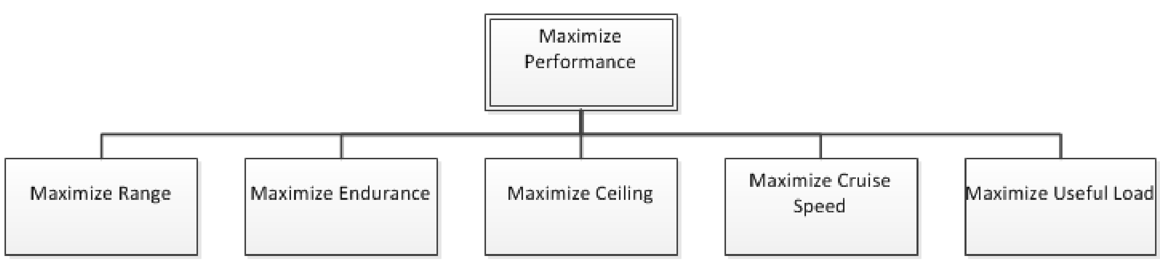

Figure 48. Aerial Platform Performance Hierarchy

[1] Table compiled (after Nicholas & Rossi, 2011; AeroVironment, 2014a; Army Technology, 2012; AeroVironment, 2012b; Boeing, 2014; Insitu, 2013a; Raven Aerostar, 2014; Defense Update, 2008; Northrop Grumman, 2014b; Barker, 2013)

Performance describes the potential of an aerial platform to perform the mission if conditions are optimal. Performance is divided into range, endurance, ceiling, cruise speed and useful load. Each aerial platform's raw data for the attributes included in the performance hierarchy are listed in Table 18. The following describes how each objective is measured.

(1) Range. Range describes how far an aerial platform can travel from its point of departure. Range is measured as the listed range in the available literature. It is important to note that for smaller UAVs lacking a satellite receiver, range is limited by control signal range and not by flight range. Alternative platforms that are not mobile are given the minimum possible score. When range is considered important, greater ranges will be given higher scores in this study.

(2) Endurance. Endurance is measured by the maximum number of hours a UAV can remain aloft. Alternative platforms such as aerostats and towers are considered as continuous and persistent assets and therefore, will receive the maximum endurance score. Higher endurance can increase the coverage time an asset can devote to its assigned mission area, increasing its performance. Higher endurance will receive higher scores in this study.

(3) Ceiling. Ceiling is measured by the highest altitude above the ground an aerial platform can achieve in sustained operations, where the ground is considered to be mean sea level in order to simplify the calculations used in this study. Higher ceilings allow for more coverage area and can increase the range of the communication relay because it will increase line of sight range. Higher ceilings are considered better for the purposes of this study.

(4) Cruise Speed. Cruise peed is measured by the highest sustained operational speed a UAV can maintain measured by ground speed with no wind. Cruise speed is measured in nautical miles per hour or knots. Stationary platforms will receive the minimum possible score. Cruise speed allows quicker repositioning of the asset and also allows for longer percentage of its endurance spent on station performing its assigned mission. Higher cruise speeds will be graded higher than slower speeds.

(5) Useful Load. Useful load describes the amount of weight an aerial platform can operationally carry. Useful load is an important attribute because it largely determines what communication payload can be carried by the aerial platform. A large useful load will allow more robust communication gear to be employed which can enhance the capability of the communications relay. More useful load is considered better.

Aerial Platform	Range (nm)	Endurance (hrs)	Ceiling (ft)	Speed (kts)	Useful Load (lbs)
Blackjack	55	13	19,500	90	39
Cerberus Tower	0	Unlimited	30	0	300 est.
Fire Scout	300	8	20,000	115	600
Global Hawk	8700	32	60,000	310	3000
Gray Eagle	400	25	29,000	167	1075
Hummingbird	2250	20	20,000	165	2500
Predator	675	40	25,000	120	450
PTDS-74K Aerostat	0	480	4,900	0	1100
RAID Tower	0	Unlimited	105	0	300 est.
Raven	5.4	1.5	14,000	44	0.4
Reaper	1000	27	50,000	240	3850
Shadow	59	5	15,000	110	80
TIF-25K Aerostat	0	336	3,000	0	302
Triton	8200	24	56,500	331	3000
Wasp III	2.7	0.75	1,000	35	0.2

Table 18. Aerial Platform Performance[2]

c. Readiness

The readiness hierarchy for aerial platforms is depicted in Figure 49.

[2] Table compiled (after Nicholas & Rossi, 2011; AeroVironment, 2014a; Army Technology, 2012; AeroVironment, 2012b; Boeing, 2014; Insitu, 2013a; Raven Aerostar, 2014; Defense Update, 2008; Northrop Grumman, 2014b; Barker, 2013)

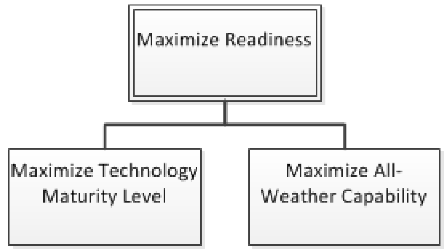

Figure 49. Aerial Platform Readiness Hierarchy

Readiness determines how prepared an aerial platform is to support the mission. Readiness is divided into technology maturity level and all-weather capability. Each aerial platform's raw data for the attributes included in the readiness hierarchy are listed in Table 19. The authors originally explored using other attributes including mishap-rate and availability to measure readiness for aerial platforms, but the data was not available and those attributes are not included as a result. The following section describes how each objective is measured across all scenarios.

(1) Technology Maturity Level. Technology maturity level is measured by the number of years in service for the aerial platform based on initial operating capability (IOC). If an aerial platform has not entered service yet, it is given a negative score based on the estimated number of years before it will enter service. Aerial platforms that are low in technology maturity lack the field testing and refinement of older, more tested designs. New technology can be unreliable or not perform as promised. Platforms without an estimated date to enter service receive the lowest score for this attribute. For this study, higher technology maturity levels will be considered better and given higher scores in this category.

(2) All-Weather Capability. All-weather capability is scored as yes or no. The platform must have de-icing capability to receive a yes score. Many UAVs cannot operate in visible moisture, and most cannot operate in icing conditions. However, many operating regions will include these environmental conditions during operations. When those conditions are experienced, aerial platforms not equipped with an all-weather capability are simply grounded. Across all scenarios, the objective for this study is to maximize all-weather capability.

Aerial Platform	IOC	Years in Service	All-Weather Capability
Blackjack	2014	0	N
Cerberus Tower	2007	7	Y
Fire Scout	2009	5	N
Global Hawk	2005	9	N
Gray Eagle	2012	2	N
Hummingbird	Unknown	-	N
Predator	2005	9	N
PTDS-74K Aerostat	2004	10	N
RAID Tower	2004	10	Y
Raven	2003	11	N
Reaper	2009	5	N
Shadow	2002	12	N
TIF-25K Aerostat	2010	4	N
Triton	2015	-1	Y
Wasp III	2007	7	N

Table 19. Aerial Platform Readiness[3]

d. Survivability

The observability hierarchy for aerial platforms is depicted in Figure 50.

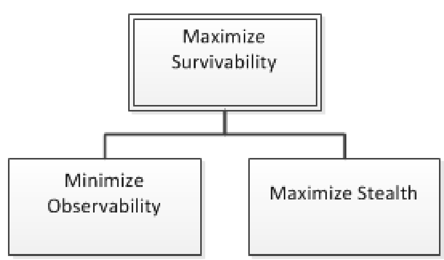

Figure 50. Aerial Platform Survivability Hierarchy

Survivability is the ability of an aerial platform to perform its mission without being harmed by the enemy. Survivability is divided into observability and stealth. Each aerial platform's raw data for the attributes included in the survivability hierarchy are

[3] Table compiled (after Nicholas & Rossi, 2011; AeroVironment, 2014a; Army Technology, 2012; AeroVironment, 2012b; Boeing, 2014; Insitu, 2013a; Raven Aerostar, 2014; Defense Update, 2008; Northrop Grumman, 2014b; Barker, 2013)

listed in Table 20. The following describes how each objective is measured across all scenarios.

(1) Observability. Observability is included in this study to describe the ability for enemy combatants to detect the aerial platform with the naked eye. If a UAV can evade visual detection by enemy soldiers, it has a better chance of not being targeted, which increases survivability. Observability is measured as the number of degrees in the observer's field of view (FoV) and utilizes the Pythagorean Theorem (Wolfram Alpha, 2014).

Using the geometry of an isosceles triangle, it is possible to determine the portion of the observer's FoV that the aerial platform occupies. The equation is derived from Figure 51.

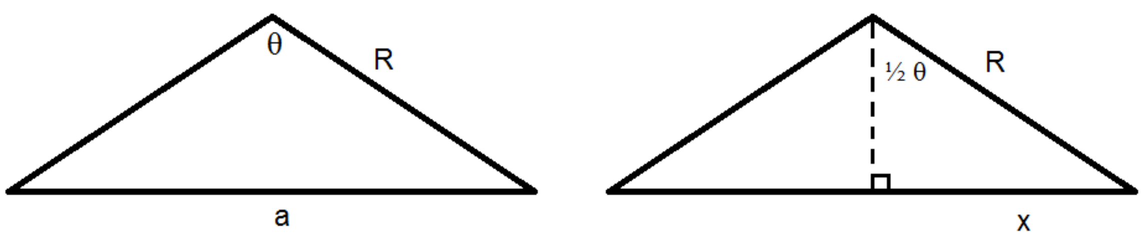

Figure 51. Isosceles Triangle (from Wolfram Alpha, 2014)

The FoV in degrees is

$$2 * \arctan\left(\frac{x}{h}\right)$$

where a is the largest dimension (length or wingspan) of the aerial platform in feet, x is ½ of a, h is the ceiling of the platform in feet, and θ is the FoV in degrees.

In all scenarios, the objective is to minimize observability. Alternative platforms that are physically connected to the ground, such as an aerostat or tower, are considered to be the most observable, will receive a maximum score for observability, and will therefore receive zero value for observability.

(2) Stealth. Stealth will serve as a measure of the radar cross section. If a platform uses radar absorbent materials similar to modern stealth aircraft, it is given a yes

score. Otherwise it is given a no score. Aircraft made of wood or foam will not be considered as stealth because their payload would still reflect any radar transmissions. Also, size of the UAV will not be considered in this objective. Stealth greatly increases the aerial platform's ability to evade detection by enemy radar. The objective is to maximize stealth in all scenarios.

Aerial Platform	Stealth	Longest Dimension (ft)	Ceiling (ft)	Observability (degrees FoV)
Blackjack	N	16	19,500	.047
Cerberus Tower	N	30	30	Maximum
Fire Scout	N	30.03	20,000	.086
Global Hawk	N	130.9	60,000	.125
Gray Eagle	N	56	29,000	.111
Hummingbird	N	36	20,000	.103
Predator	N	55	25,000	.126
PTDS-74K Aerostat	N	115	4,900	Maximum
RAID Tower	N	107	105	Maximum
Raven	N	4.5	14,000	.018
Reaper	N	66	50,000	.076
Shadow	N	20.4	15,000	.078
TIF-25K Aerostat	N	76	3,000	Maximum
Triton	N	130.9	56,500	.133
Wasp III	N	2.3	1,000	.132

Table 20. Aerial Platform Survivability[4]

2. Communication Payload Hierarchy

The hierarchy utilized in this study to individually evaluate the overall mission effectiveness of the selected communication payloads within each of the proposed scenarios considered is depicted in Figure 52. For an enlarged copy, see Appendix A. As in the UAV hierarchy, this communication payload hierarchy was derived from the research, discussion with experts, and best judgment of the authors. Other decision makers may decide to modify this hierarchy to suit their needs.

[4] Table compiled (after Nicholas & Rossi, 2011; AeroVironment, 2014a; Army Technology, 2012; AeroVironment, 2012b; Boeing, 2014; Insitu, 2013a; Raven Aerostar, 2014; Defense Update, 2008; Northrop Grumman, 2014b; Barker, 2013)

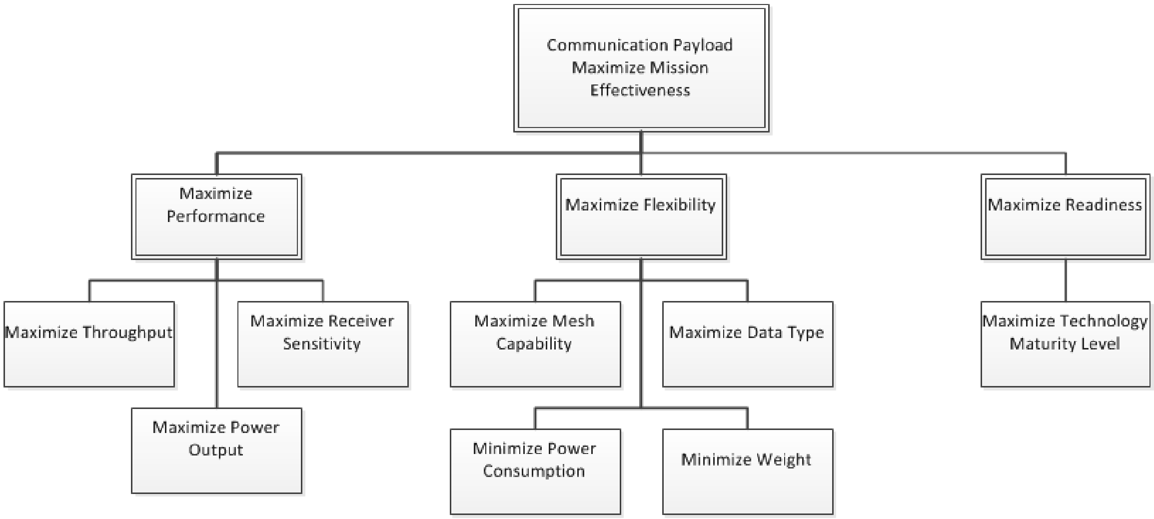

Figure 52. Communication Payload Hierarchy

The overall objective of each communication payload is mission effectiveness. The authors chose to break down mission effectiveness into performance, flexibility and readiness. The following sections will discuss performance, flexibility and readiness and their subcomponents in more detail.

a. Performance

The performance objective for communication payloads is depicted in Figure 53.

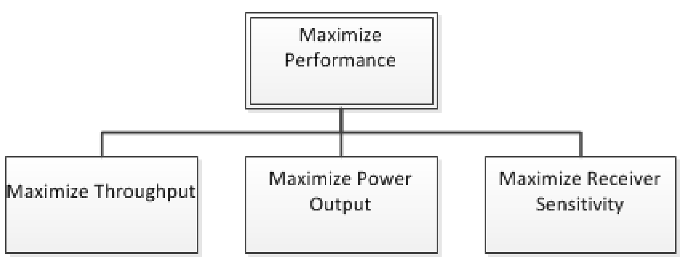

Figure 53. Communication Payload Performance Hierarchy

Performance is a measure of the ability of the communication payload to provide network and connectivity during optimum conditions. Performance is divided into throughput, power output, and receiver sensitivity. Each communication payload's raw data for the attributes included in the performance hierarchy are listed in Table 21. The following describes how each objective is measured across all scenarios.

(1) Throughput. For the purposes of this study, throughput is a measure of the connection speed between the communication payload and a single user, as reported by the vendor in raw number of bits per second. Unless the vendor specifies separate uplink and downlink rates it is assumed that all users share the capacity for both the uplink and downlink. The media access control impacts how the bandwidth (in bps) is shared among users. In some cases, additional radio channels may be implemented to allow for full duplex communications where the system would otherwise be half duplex. Among the radios considered in this study, only the Oceus Xiphos 1RU and 6RU list both uplink and downlink speeds, therefore their speeds will be added together for throughput. All other radios considered are only capable of communication in one direction at a time. Therefore, those radios' throughput is their highest communication speed. In all scenarios, the objective is to maximize throughput.

(2) Power Output. Power output is measured in watts. The objective in all scenarios is to maximize power output.

(3) Receiver Sensitivity. Receiver sensitivity is measured in decibels. The objective in all scenarios is to maximize receiver sensitivity.

Communication System	Throughput (Mbps)	Power Output (Watts)	Receiver Sensitivity (dBm)
Digital Data Link (DDL)	4.5	1.5	-90
Falcon III 7800W OU440	90	.316	-88
Falcon III AN/PRC-117G	.016	20	-118
Ocelot	8	2	-104
Wave Relay	37	2	-92 est.
Wave Relay Quad	4x37=148	2	-92 est.
WildCat II	40	8	-100
Xiphos 1RU	200	80	-119.5
Xiphos 6RU	458	480	-119.5

Table 21. Communication Payload Performance[5]

[5] Table compiled (after AeroVironment, 2012a; Harris, 2012a; Harris, 2012c; Persistent Systems, 2012; Persistent Systems, 2014; TrellisWare, 2014a; Oceus Networks, 2014)

b. Flexibility

The flexibility hierarchy for communication payloads is depicted in Figure 54.

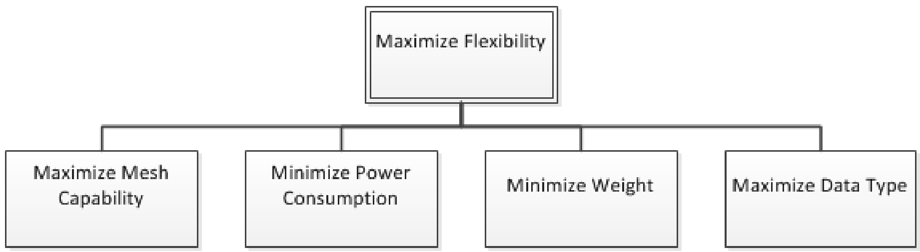

Figure 54. Communication Payload Flexibility Hierarchy

Flexibility describes the ability of the communication payload to operate in varying conditions and fulfill different mission requirements. Flexibility is divided into mesh capability, power consumption, weight, and traffic type. Each communication payload's raw data for the attributes included in the flexibility hierarchy are listed in Table 22. The following describes how each objective is measured across all scenarios.

(1) Mesh Capability. Mesh Capability is yes or no measurement. If the radio can execute a mesh topology, then it is scored as a yes. In all scenarios, the objective is to maximize mesh capability.

(2) Power Consumption. Power consumption describes the required power for normal operations. It is measured in watts. The objective across all scenarios is to minimize power consumption.

(3) Weight. Weight is measured in pounds (lbs) and accounts for the weight of all airborne radio gear required for operation. The objective across all scenarios is to minimize weight.

(4) Traffic Type. Traffic type is listed as voice or data or a combination of the two. For the purposes of this study, voice means VHF and UHF transmission capability. Data refers to any type of data transmissions including video, imagery, voice over Internet Protocol (VoIP) and basic data. Traffic type preference will be determined in each scenario.

Communication System	Mesh Capable	Power Consumption (watts)	Weight (lbs)	Voice or Data
Digital Data Link (DDL)	N	9	.2	Data
Falcon III 7800W OU440	Y	22	5.5	Data
Falcon III AN/PRC-117G	Y	55	12	Voice/Data
Ocelot	Y	4.3	0.19	Data
Wave Relay	Y	16.5	0.2	Data
Wave Relay Quad	Y	55	3.2	Data
WildCat II	Y	21	3.4	Voice/Data
Xiphos 1RU	Y	855	78	Data
Xiphos 6RU	Y	3275	276	Data

Table 22. Communication Payload Flexibility[6]

c. *Readiness*

The readiness hierarchy for communication payloads is depicted in Figure 55.

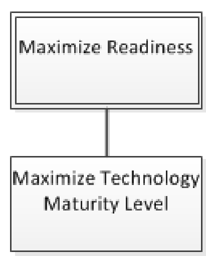

Figure 55. Communication Payload Readiness Hierarchy

Readiness determines how prepared a communications payload is to perform the mission. Readiness is only represented by technology maturity level. The authors originally included availability in the Readiness Hierarchy for communication payloads. However, data for availability was not available and it was removed from the hierarchy as a result. Technology maturity level serves as the closest proxy measure for readiness for communication payloads.

[6] Table compiled (after AeroVironment, 2012a; Harris, 2012a; Harris, 2012c; Persistent Systems, 2012; Persistent Systems, 2014; TrellisWare, 2014a; Oceus Networks, 2014)

(1) Technology Maturity Level. Technology maturity level is measured by the number of years in service for the communication payload. If a communication payload has not entered service yet, it is given a negative score based on the estimated number of years before it will enter service. In all scenarios, the objective is to maximize technology maturity level. The number of years in service for each communication payload is shown in Table 23.

Communication System	IOC	Years in Service
Digital Data Link (DDL)	2009	5
Falcon III 7800W OU440	2010	4
Falcon III AN/PRC-117G	2011	3
Ocelot	2014	0
Wave Relay	2012	2
Wave Relay Quad	2012	2
WildCat II	2010	4
Xiphos 1RU	2011	3
Xiphos 6RU	2011	3

Table 23. Communication Payload Readiness[7]

C. COSTS

In this section, the authors present the cost data for each aerial platform and each communication payload.

1. Aerial Platform Costs

Aerial platform costs are listed in Table 24. Each cost is listed in base year (BY) 2013 U.S. dollars. Costs are based on a single vehicle, tower or aerostat. Unfortunately, due to lack of specificity in available cost data, the authors were not able to differentiate the cost of the individual aerial platform from the launch and recovery equipment, ground control stations, payloads and other support equipment.

[7] Table compiled (after AeroVironment, 2012a; Harris, 2012a; Harris, 2012c; Persistent Systems, 2012; Persistent Systems, 2014; TrellisWare, 2014a; Oceus Networks, 2014)

Aerial Platform	PAUC	Annual O&S	Planned Service Life (Yrs)	Total LCC	Annual LCC
	BY 2013 $M			BY 2013 $M	
Blackjack	5.61	0.57*	15*	14.1	0.94
Cerberus Tower	0.19	0.02*	25*	0.68	0.03
Fire Scout	15.97	2.58	20	67.67	3.38
Global Hawk	227.6	24.01	22	755.88	34.36
Gray Eagle	39.48	2.83	20	96.18	4.81
Hummingbird	17.59	1.78*	20*	53.13	2.66
Predator	12.25	1.41	20*	40.38	2.02
PTDS-74K Aerostat	18.05	1.82*	25*	63.63	2.55
RAID Tower	0.68	0.07*	25*	2.39	0.1
Raven	0.05	0.01*	5*	0.07	0.01
Reaper	30.79	2.92	43	156.41	3.64
Shadow	5.11	0.52*	15*	12.84	0.86
TIF-25K Aerostat	0.24	0.02*	25*	0.86	0.03
Triton	189.4	18.54	24	634.31	26.43
Wasp III	0.06	0.01*	5*	0.09	0.02

*Estimated

Table 24. Aerial Platform Costs[8]

For the purposes of this study, LCC include program acquisition unit costs (PAUC) as well as O&S for the planned service life of the system. The total LCC divided by the planned service life results in annual LCC, which is the final column in Table 24. This method is used to compare platforms with different planned service lives. Disposal costs, which are normally included in LCC, are assumed to be negligible and will not be included in order to simplify the research. Costs are displayed in base year (BY) 2013 millions of dollars.

Annual O&S costs were estimated as indicated in Table 24 as a percentage of PAUC. The percentage was derived using linear analysis of known data points. See Figure 56.

[8] Table compiled (after Nicholas & Rossi, 2011; DoD, 2012a; DoD, 2012b; DoD, 2012c; DoD, 2012d; DoD, 2012e; Valerdi, 2005; Defense Industry Daily, 2010; Defense Industry Daily, 2011a; Defense Industry Daily, 2011b; FBO.gov, 2011)

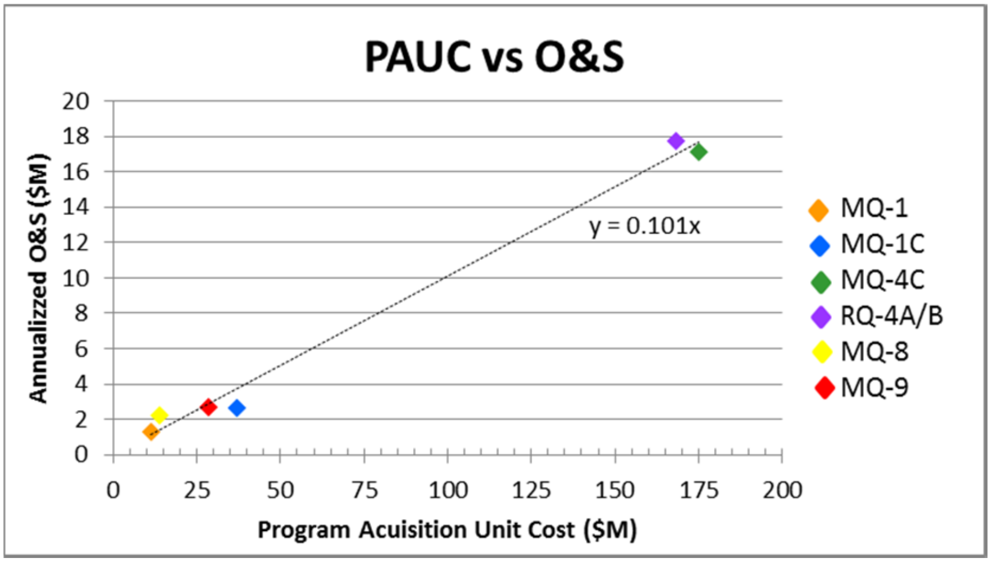

Figure 56. Calculating Annualized O&S from PAUC

2. Communication Payload Costs

LCC for the communication payloads was not available for this study; therefore the authors used acquisition costs only. Costs are listed in BY 2013 dollars. Costs are based on a single, airborne radio only and do not include any user radios or other equipment. See Table 25.

Communication Payload	BY 2013 $
Digital Data Link (DDL)	5,000
Falcon III 7800W OU440	25,000 est.
Falcon III AN/PRC-117G	25,000 est.
Ocelot	10,000 est.
Wave Relay	3,640
Wave Relay Quad	7,142
WildCat II	50,000 est.
Xiphos 1RU	681,333
Xiphos 6RU	1,378,914

Table 25. Communication Payload Costs[9]

[9] Table (after J. Gibson, personal communication, March 4, 2014; AeroVironment, 2012a; NASA SEWP, 2014)

D. SUMMARY

This chapter described the process of setting up and executing a generic CEA; and it detailed the objective hierarchy for aerial platforms and communication payloads. The UAV and communication payload hierarchies involve several attributes, and data for each of these attributes was presented for each potential system. The chapter finished by detailing the LCC of each alternative.

In Chapter IV, the authors will utilize three different scenarios to evaluate the cost-effectiveness of each alternative within the three scenarios. Within each scenario, the authors will answer the questions of how much is enough and assign importance weights to each attribute. Utilizing the authors' best judgment, the answers to these questions will change as conditions and mission requirements change from scenario to scenario. A graphical comparison of the cost-effectiveness of all the alternatives for each of the three scenarios will be offered.

IV. ANALYSIS

This chapter uses realistic scenarios to evaluate aerial platforms and their communication payloads under different conditions. The scenarios provide unique challenges that necessarily drive attribute preferences. Each scenario starts with a description of the mission requirements and pertinent conditions. For ease of presentation, the authors discuss the importance weights before the value functions in this chapter. However, as discussed in Chapter III, importance weights are not determined without considering the value functions and the range of alternatives available. Normally, in a multi-objective analysis and in this study, value functions are determined first, and importance weights are determined second. Once value functions and importance weights are finalized, the MOE and cost of each alternative is graphically depicted and evaluated for cost effectiveness. The analysis of the aerial platforms is presented first, followed by the analysis of communication payloads. At the end of each scenario, the authors discuss the compatibility of one or more of the most cost-effective aerial platforms and communication payloads.

A. HUMANITARIAN AID/DISASTER RELIEF (HADR) SCENARIO

In this scenario, the authors envision a situation similar to Hurricane Katrina in which the U.S. military leads a large relief effort. The following section explains the mission conditions and requirements.

1. HADR Scenario: Mission and Environmental Conditions

A large hurricane has just passed through the area and has left the communication and cellular infrastructure useless. The U.S. military has been ordered to provide aid and coordinate relief efforts in the area. Communications links for rescue teams are needed to affect a fast and successful response. The disaster area is a circular area with a 100 nautical mile (nm) diameter. Taskforce headquarters is stationary and located at an airfield on the immediate perimeter of the disaster area. There are no adversaries. Throughput demand is expected to be more than 200 Mbps at various times and the number of concurrent users could be in the 50-100 range. UHF, VHF, and data relay support is needed. The altitude of all user antennas connecting with the relay are assumed to be zero to simplify calculations. Mission conditions are summarized in Table 26.

Conditions	
Communication Relay Range	50 nm radius or 100 nm diameter
Enemy resistance	None
Terrain	Flat
Weather	Clear Air, Unrestricted Visibility
Duration of communication relay mission	504 hours (21 days)
Type of communication required	Voice/Data

Table 26. HADR Scenario Conditions

2. HADR Scenario: Aerial Platform Importance Weights

Based upon the scenario conditions, the authors' importance weights for the aerial platforms are listed in the hierarchy in Figure 57.

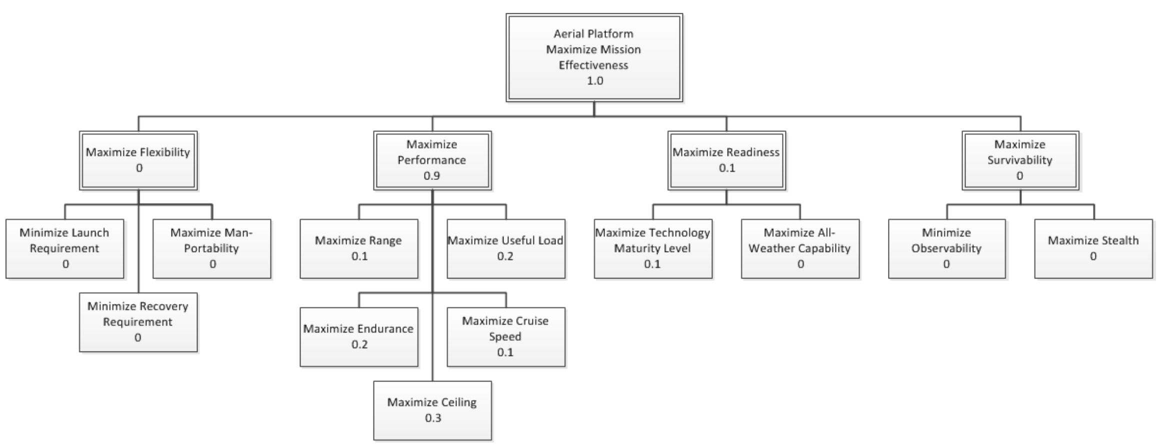

Figure 57. HADR Aerial Platform Hierarchy with Importance Weights

It is the authors' judgment that the following attributes are important for this scenario: range, endurance, ceiling, cruise speed, useful load, and technology maturity level. Ceiling is ranked most important because a sufficient ceiling is needed to ensure coverage of the entire disaster area. Endurance and useful load are considered the next most important attributes for this scenario. Endurance is important because there is a relatively long communication requirement, and useful load is important because of the large number of first responders who need connectivity. Range, cruise speed, and technology maturity level are considered the next most important attributes. Range and cruise speed are important because they allow maneuverability, and technology maturity level represents readiness of the aerial platform.

The authors believe that the following attributes do not affect aerial platform effectiveness for this scenario: launch requirement, recovery requirement, man-portability, all-weather capability, observability and stealth. Man-portability, launch and recovery requirement are not considered important because headquarters is at an operational airfield. All-weather capability is not deemed important because the ceiling and season are such that icing would not be a factor. Observability and stealth are not important because there is no enemy resistance in the scenario. However, these attributes are important for other scenarios and remain in the objectives hierarchy.

Importance weights are broken down by relative sizes in Figure 58.

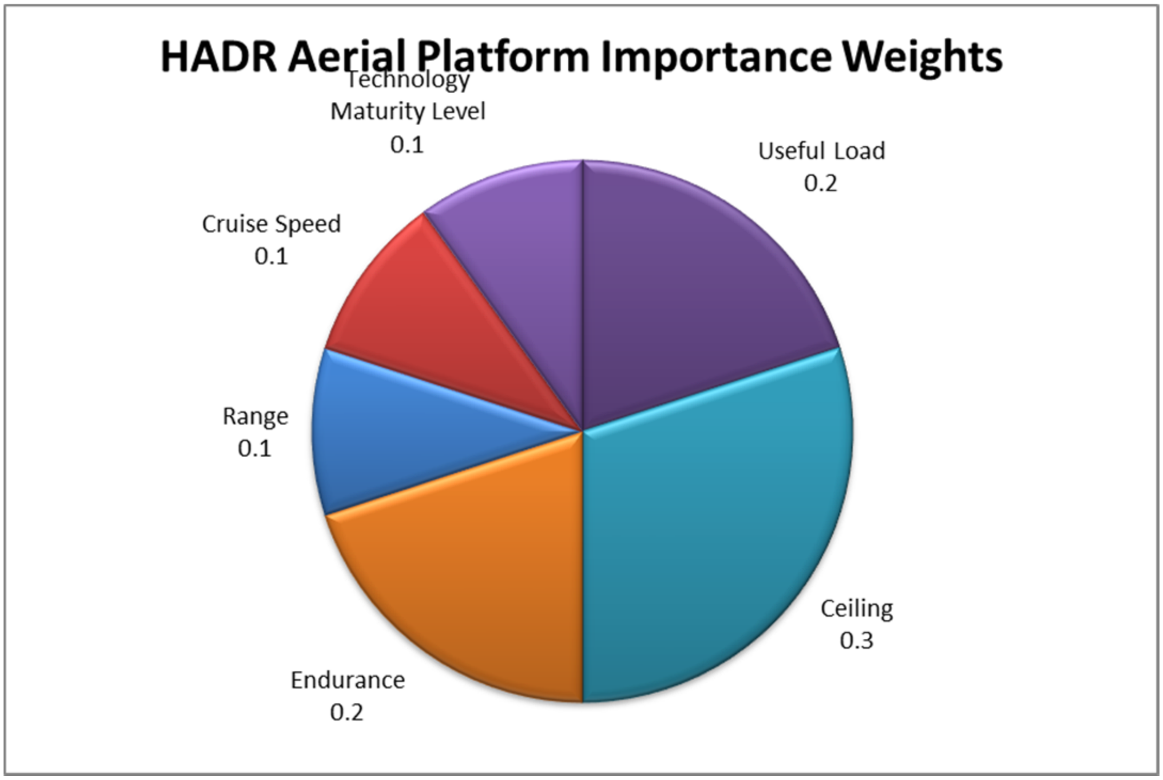

Figure 58. HADR Aerial Platform Importance Weights Pie Chart

3. HADR Scenario: Aerial Platform Value Functions

The following sections describe the aerial platform value functions used in the HADR scenario. Value functions are listed according to their respective hierarchies. Value functions assigned zero importance weights are not discussed. As a reminder, these value functions are derived from the authors' best judgment. Future decision makers will need to design value functions to best match the specific conditions of the mission and their preferences.

a. Flexibility

The aerial platform flexibility hierarchy receives zero importance weight in this scenario as shown in Figure 59. The flexibility hierarchy is shown for purposes of continuity only.

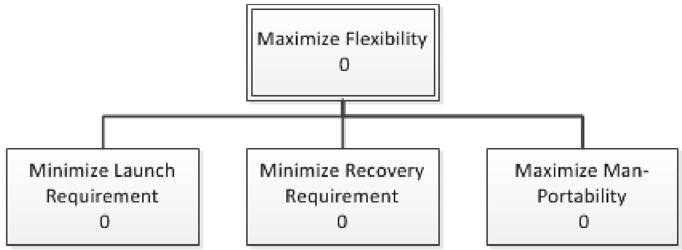

Figure 59. Aerial Platform Flexibility Hierarchy with Importance Weights

b. Performance

The aerial platform performance hierarchy with importance weights is listed in Figure 60.

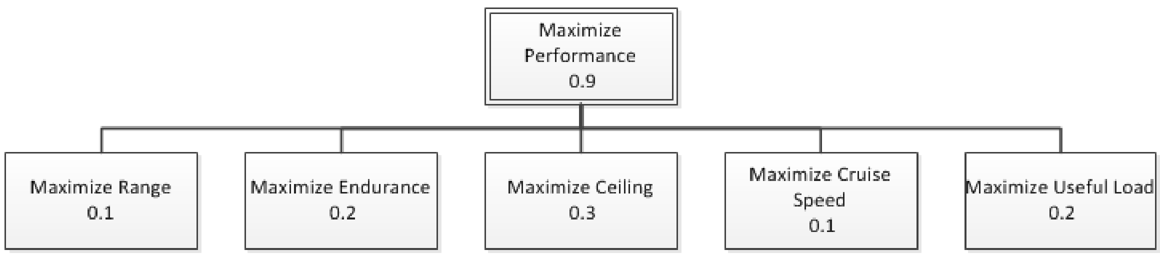

Figure 60. Aerial Platform Performance Hierarchy with Importance Weights

(1) Range. The range value function considers the transit distance to the edges of the operating area for this scenario. The authors use a linear function from 0 to 100 nm as depicted in Figure 61.

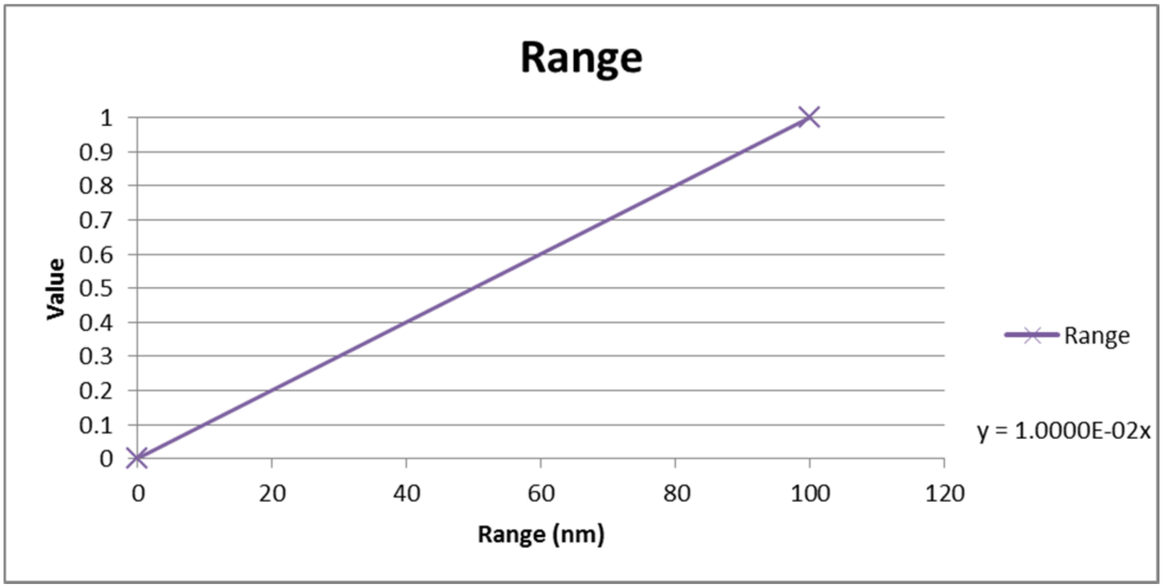

Figure 61. Range Value Function

(2) Endurance. The endurance value function is primarily determined by the duration of the communication relay mission. The authors assigned values for this value function based on the available aerial platforms as depicted in Table 27.

Endurance (hrs)	12	24	48	168	504
Assigned Value	0.2	0.4	0.6	0.8	1.0

Table 27. Endurance Value Function

A 6^{th} order polynomial equation produces a trend line that meets the authors' expectations for the original endurance value function, as depicted in Figure 62. The purple line shows the original points for the value function and the red polynomial line shows the line generated by the 6^{th} order equation.

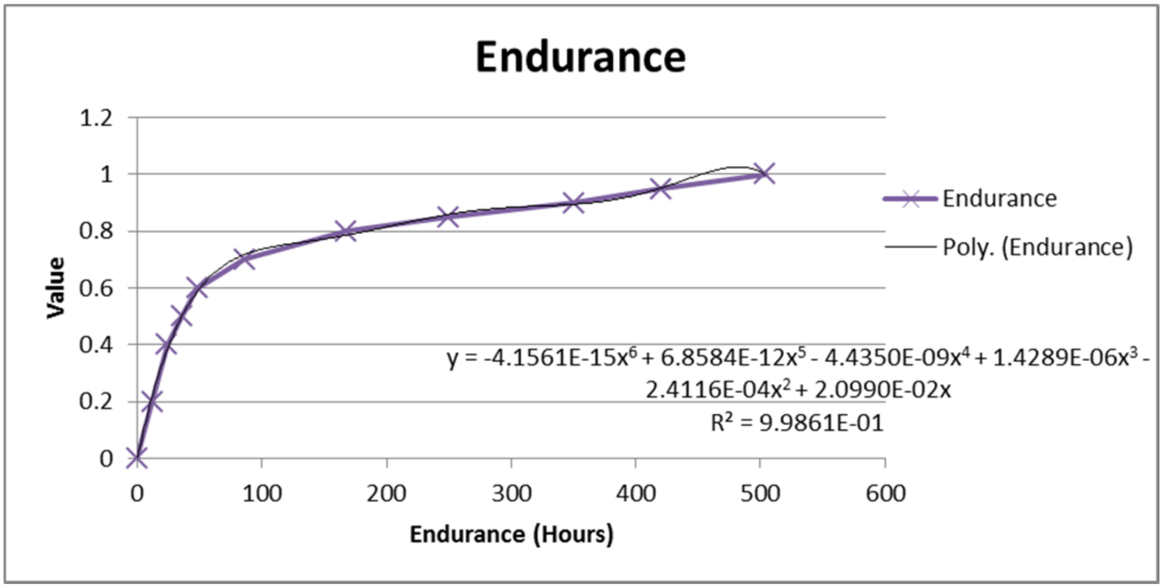

Figure 62. Endurance Value Function Approximation

(3) Ceiling. In this scenario, the ceiling value function is driven primarily by the area of coverage required. A circular area with a radius of 50 nm is the required coverage area. A minimum operating altitude for this mission is calculated using the equation for radio horizon (Herbert, 2013) with the radius of 50 nm as the (d) distance as shown:

$$h = \left(\frac{d}{1.23}\right)^2 \rightarrow h = \left(\frac{50}{1.23}\right)^2 = 1{,}652\,feet$$

However, this altitude only provides 100% coverage for an aerial platform positioned exactly in the center of the area. More flexibility is added if the aerial platform is at a high enough altitude to maneuver to the edges of the area and still provide coverage to the entire operating area.

$$h = \left(\frac{100}{1.23}\right)^2 = 6{,}610\,feet$$

After the previous calculations, the authors create the simple value function for ceiling in Table 28.

Ceiling (feet)	1652	6,610
Assigned Value	0.6	1.0

Table 28. Ceiling Value Function

A 3rd order polynomial equation used to approximate the ceiling's value function is shown in Figure 63.

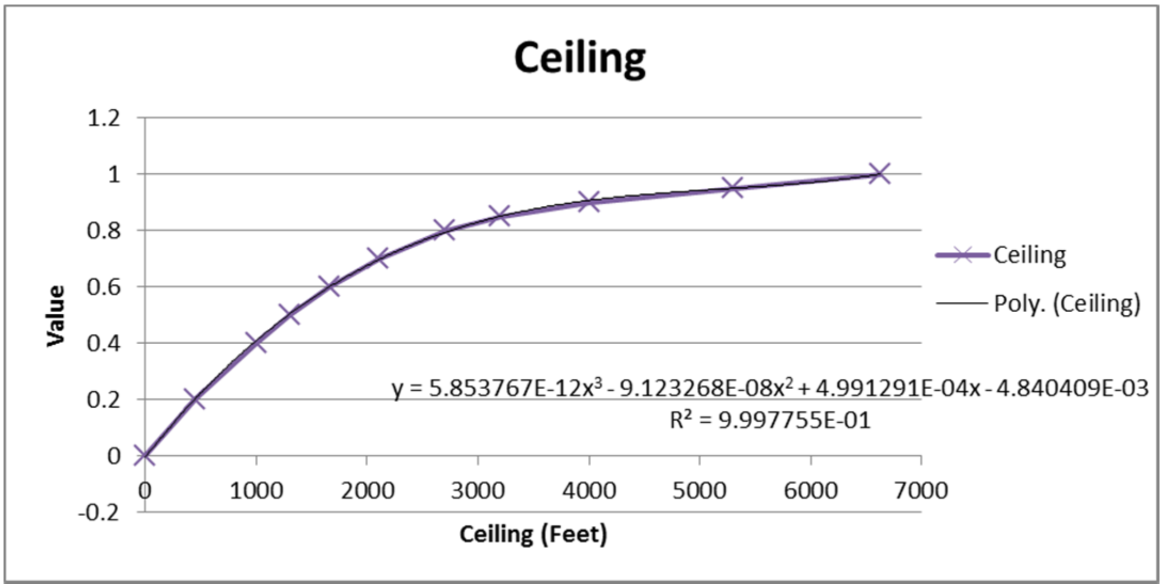

Figure 63. Ceiling Value Function Approximation

(4) Cruise Speed. The cruise speed value function helps reduce gaps in coverage by reducing the aerial platforms transit times. The authors use a linear function from 40 to 200 knots as depicted in Figure 64.

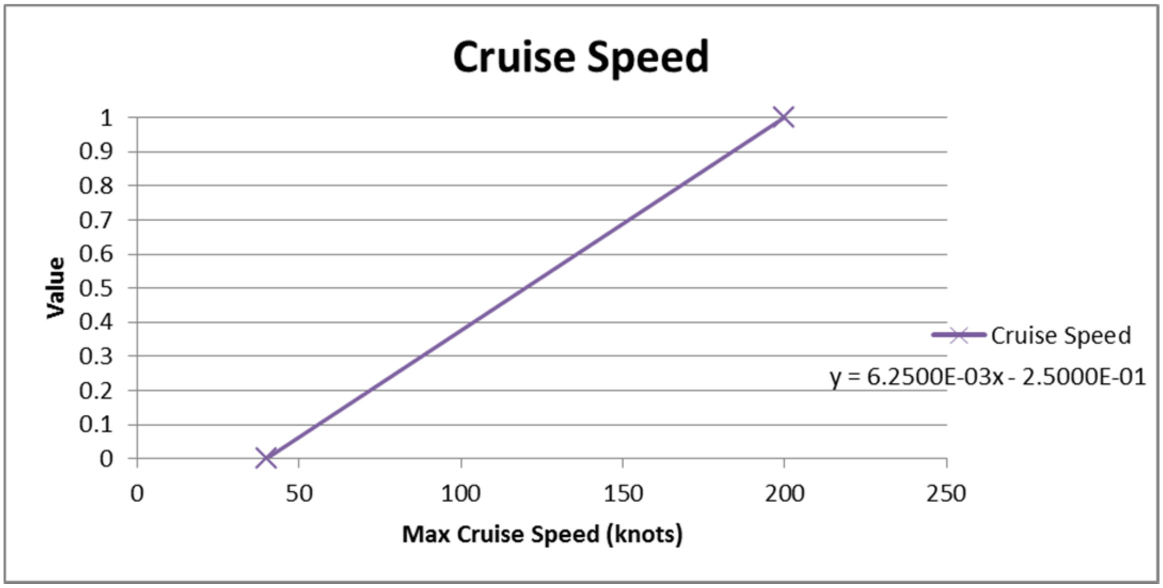

Figure 64. Cruise Speed Value Function

(5) Useful Load. In this scenario, the useful load value function allows an added degree of flexibility in the range of communication payloads the aerial platform can carry. The authors' value function for useful load is listed in Table 29.

Useful load (lbs)	3	10	25	35	50	70	100	150	220	300	350
Assigned Value	0	0.20	0.40	0.50	0.60	0.70	0.80	0.85	0.90	0.95	1.00

Table 29. Useful Load Value Function

The approximation of the useful load value function using a 5th order polynomial equation is shown in Figure 65.

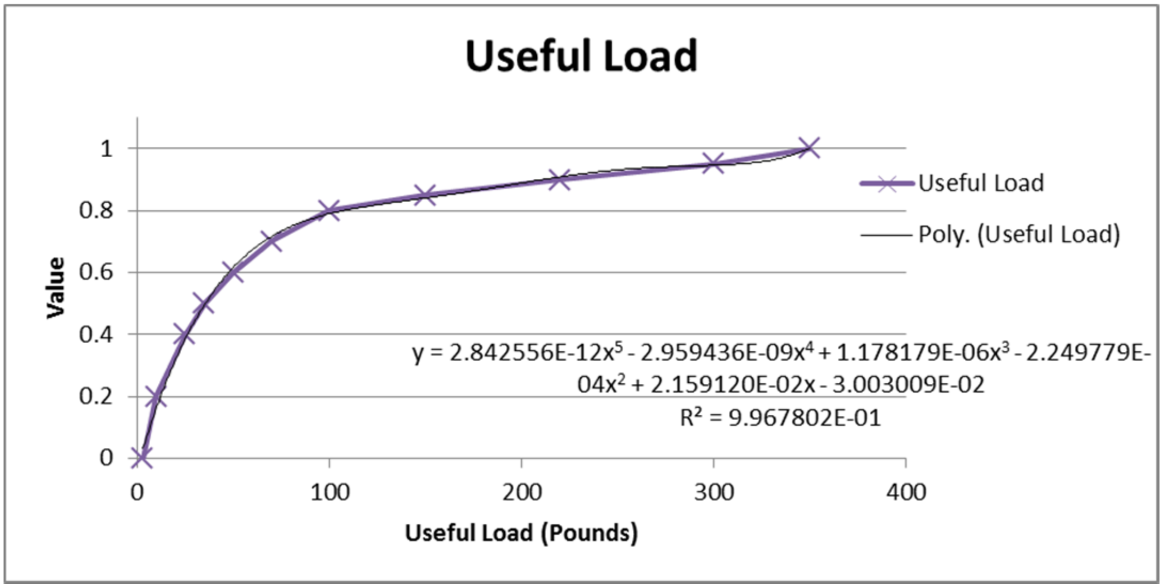

Figure 65. Useful Load Value Function Approximation

c. Readiness

The aerial platform readiness hierarchy with importance weights is listed in Figure 66.

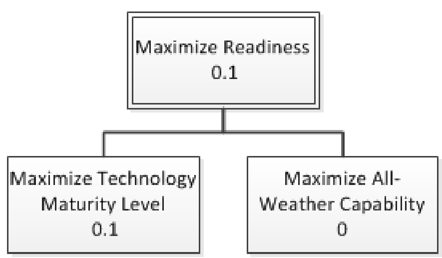

Figure 66. Aerial Platform Readiness Hierarchy with Importance Weights

(1) Technology Maturity Level. The technology maturity level value function starts at 3 years before IOC and receives a maximum score 7 years after IOC. The two points are connected with a linear function as displayed in Figure 67. As stated in Chapter III, a negative technology maturity level indicates the number of years until the aerial platform is expected to enter into service.

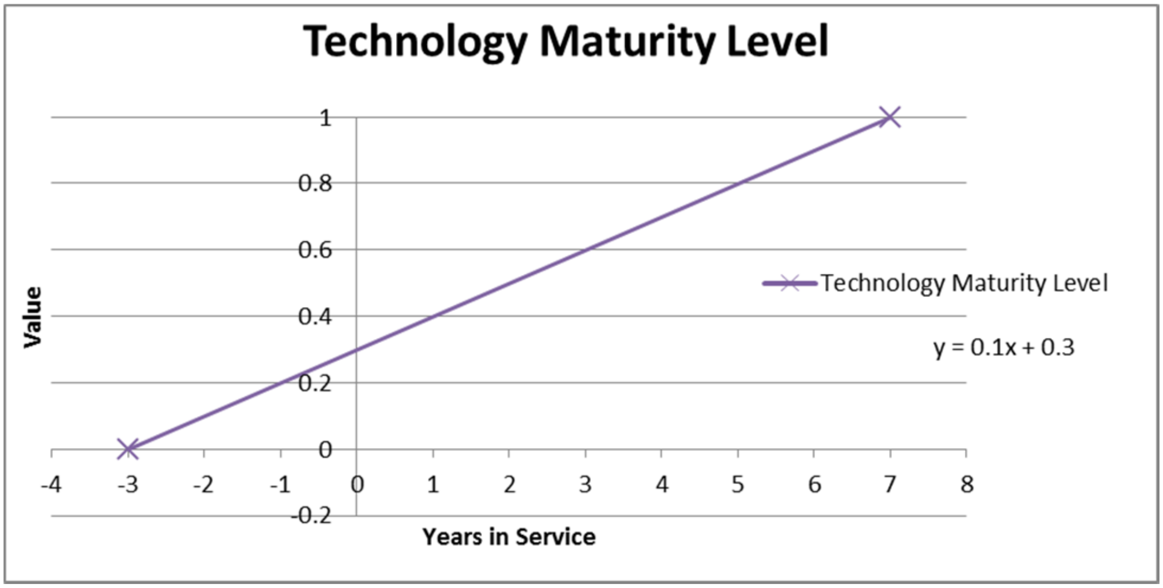

Figure 67. Technology Maturity Level Value Function

d. Survivability

The aerial platform survivability hierarchy receives zero importance weight in this scenario as shown in Figure 68. This hierarchy is presented for purposes of continuity only.

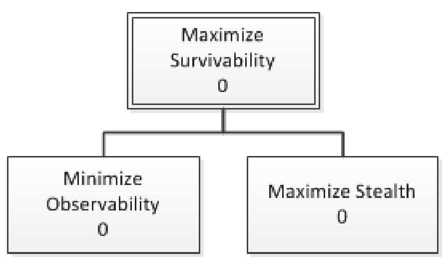

Figure 68. Aerial Platform Survivability Hierarchy with Importance Weights

4. HADR Scenario: Aerial Platform Cost-Effective Solutions

The graph depicting MOE vs annualized LCC is displayed in Figure 69.

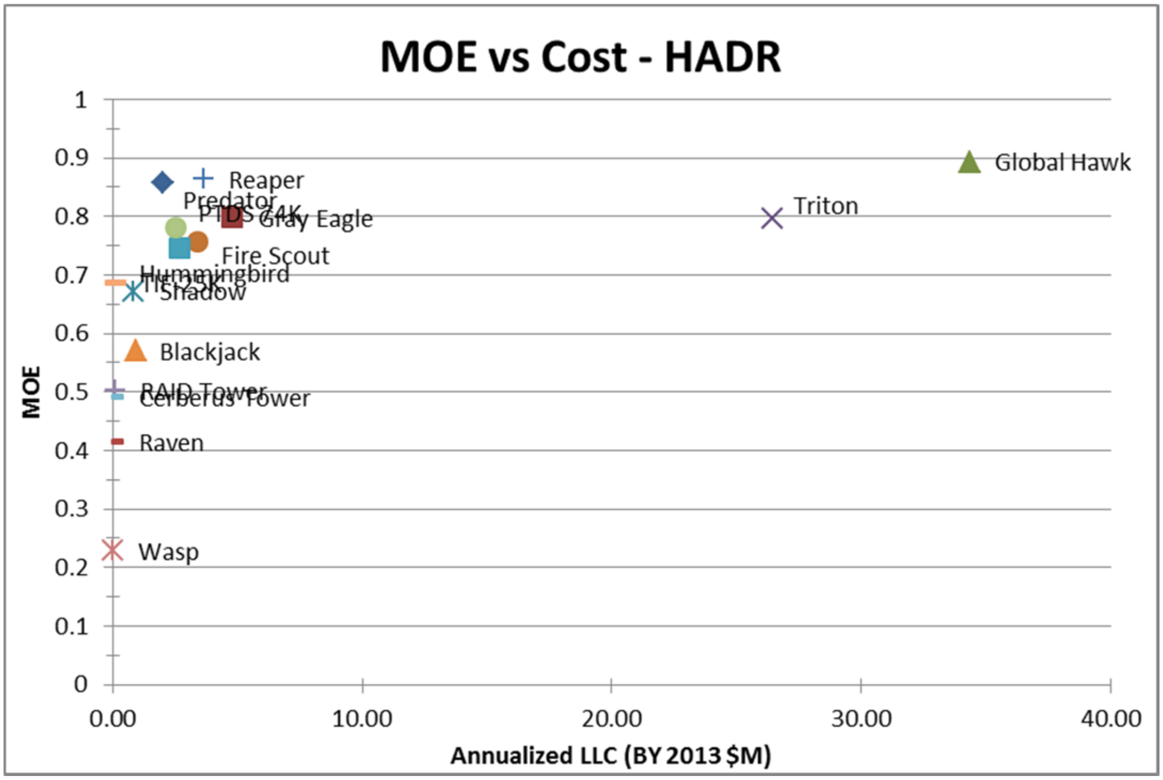

Figure 69. Aerial Platform Cost Effectiveness–HADR–Linear Scale

The graph above uses a linear scale for costs on the x-axis. At this scale, the graph is not user friendly because most of the aerial platforms are stacked up on the left side of the graph. However, because of the linear scale used in this graph, it does give the reader a good representation of the relative cost distribution of each aerial platform.

The authors use a logarithmic scale in the graph to make it more user-friendly, as shown in Figure 70.

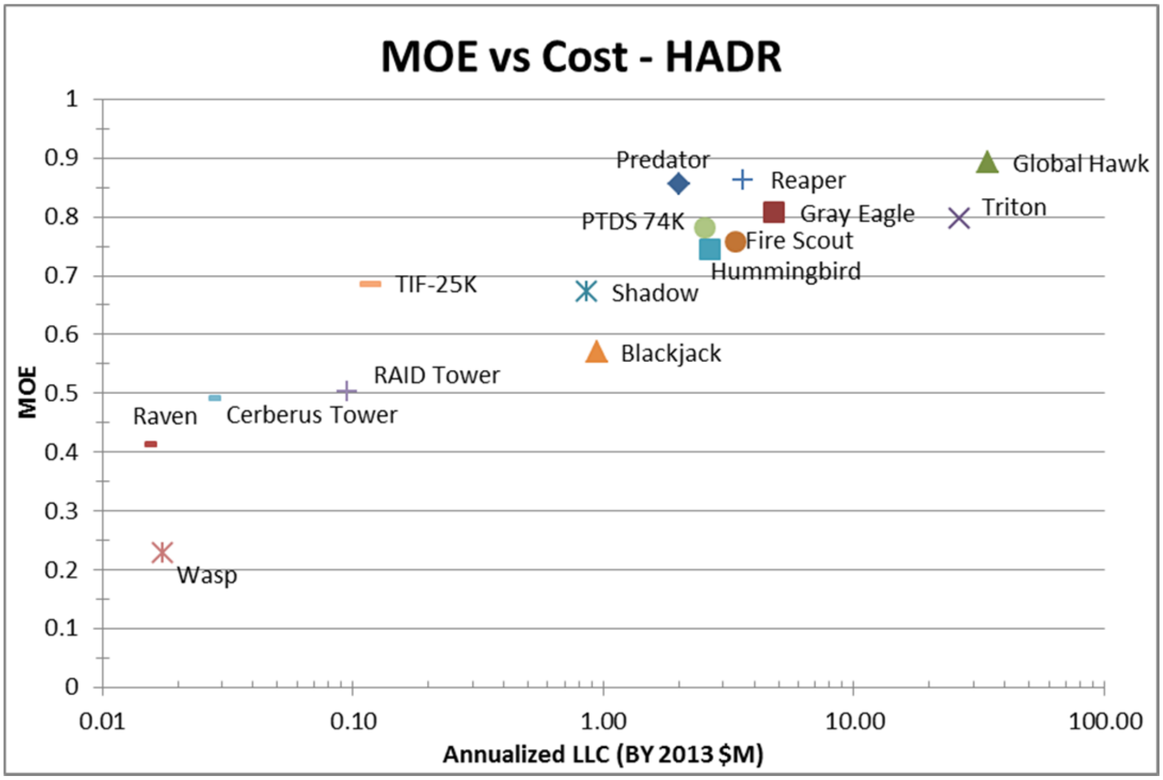

Figure 70. Aerial Platform Cost Effectiveness–HADR–Logarithmic Scale

Next, the aerial platforms are reduced to the efficient solution set, as shown in Figure 71. As a reminder, the efficient set eliminates any alternative that is both less effective and more costly than another alternative.

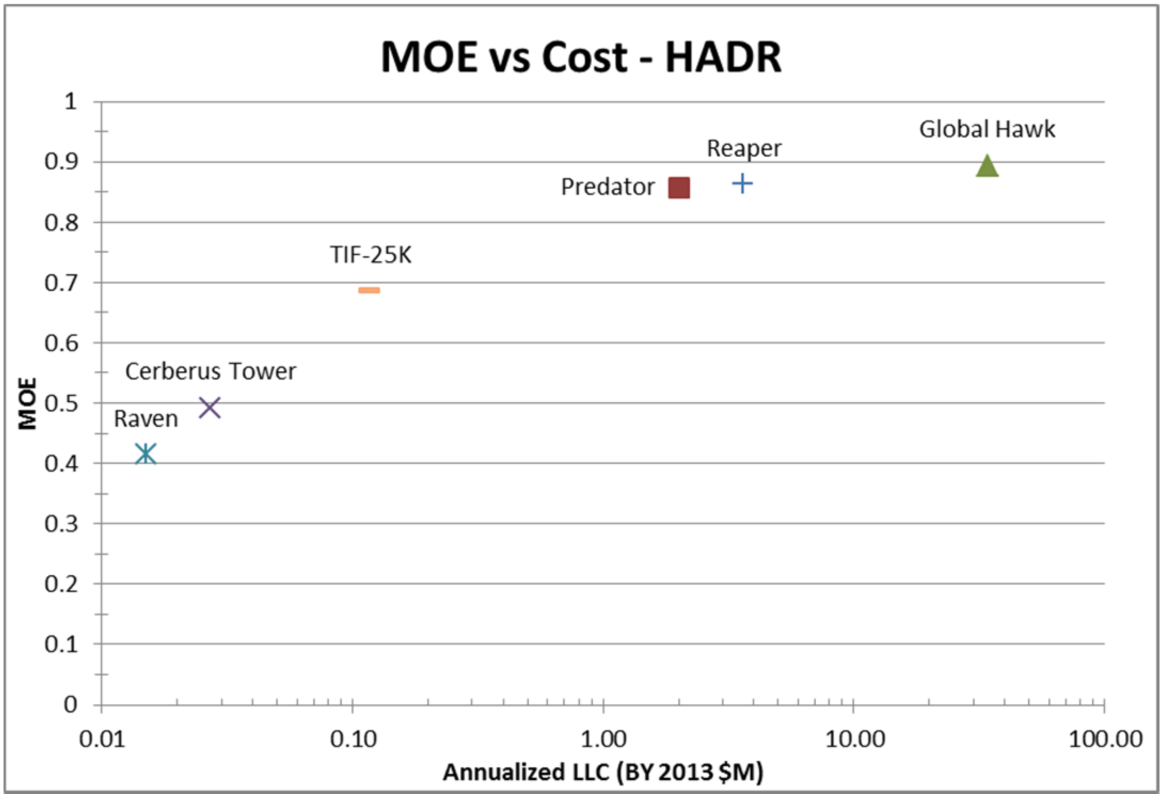

Figure 71. Aerial Platform Efficient Solution–HADR–Logarithmic Scale

The efficient solution set includes the Raven, Cerberus Tower, TIF-25K Tower, Predator, Reaper and Global Hawk. Two low-cost aerial platforms are in the efficient solution set, but are not realistic options in this scenario. First, the Raven's endurance of only 1.5 hours and its payload of about 6.5 ounces eliminate it as an effective solution considering the long duration of the mission and the high demands on the network. Second, while the Cerberus Tower offers nearly limitless endurance and high useful load, its height of only 30 feet allows for an approximately 7 nm radio horizon. The coverage provided by the Cerberus Tower is inadequate to be considered as an effective aerial platform in this scenario. The remaining aerial platforms are shown in Figure 72.

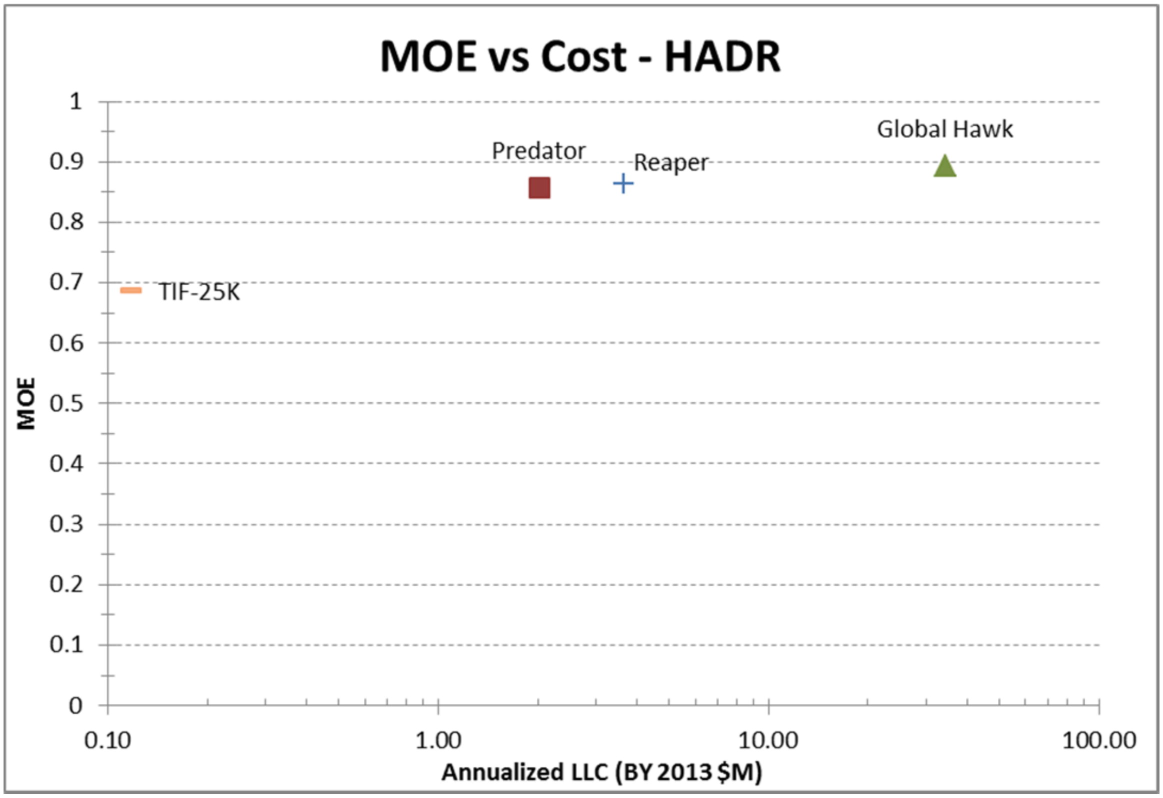

Figure 72. Aerial Platform Remaining Platforms–HADR–Logarithmic Scale

The remaining solutions are the TIF-25K aerostat, Predator, Reaper, and Global Hawk. In this scenario, useful load and ceiling account for half of the total importance weight. All four efficient solutions scored near maximums in the two aforementioned categories.

One UAV that has maximum scores in useful load and ceiling, but is not a part of the remaining four options is the Navy's variant of the Global Hawk, the Triton. Both the Reaper and the Predator produced a higher MOE and cost less than the Triton. Additionally, the Global Hawk had a higher MOE while being more expensive than the Triton. The Triton's lower MOE when compared to the Global Hawk can be attributed almost solely to technology maturity level, the proxy used for readiness. Since the Triton is a relative newcomer to the UAV world, it did not receive the boost from technology maturity level that the other three UAVs in the efficient solution set did.

Analyzing the difference in cost between the alternatives can be deceiving when using a logarithmic scale, as in Figure 72. A linear scale gives a clearer presentation of the relative costs of the remaining aerial platforms as depicted in Figure 73.

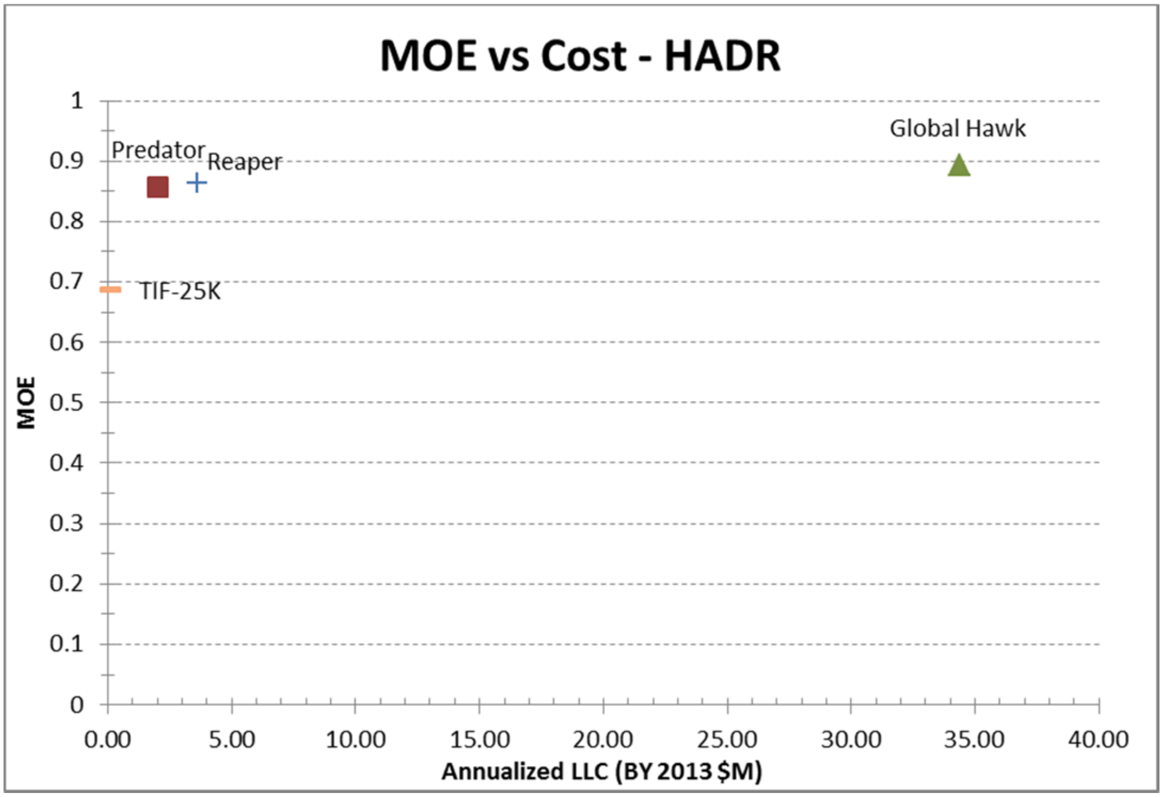

Figure 73. Aerial Platform Tradeoffs–HADR–Linear Scale

While the linear scale does make comparing costs easier, it is hard to see the difference in costs between the TIF-25K, Predator and Reaper because the Global Hawk is so much more expensive. The authors decide to eliminate the Global Hawk from consideration since the Reaper is nearly as effective as the Global Hawk and costs about $30 million less annually. With the Global Hawk out of the picture, the tradeoffs between the four remaining aerial platforms become readily apparent, as shown in Figure 74.

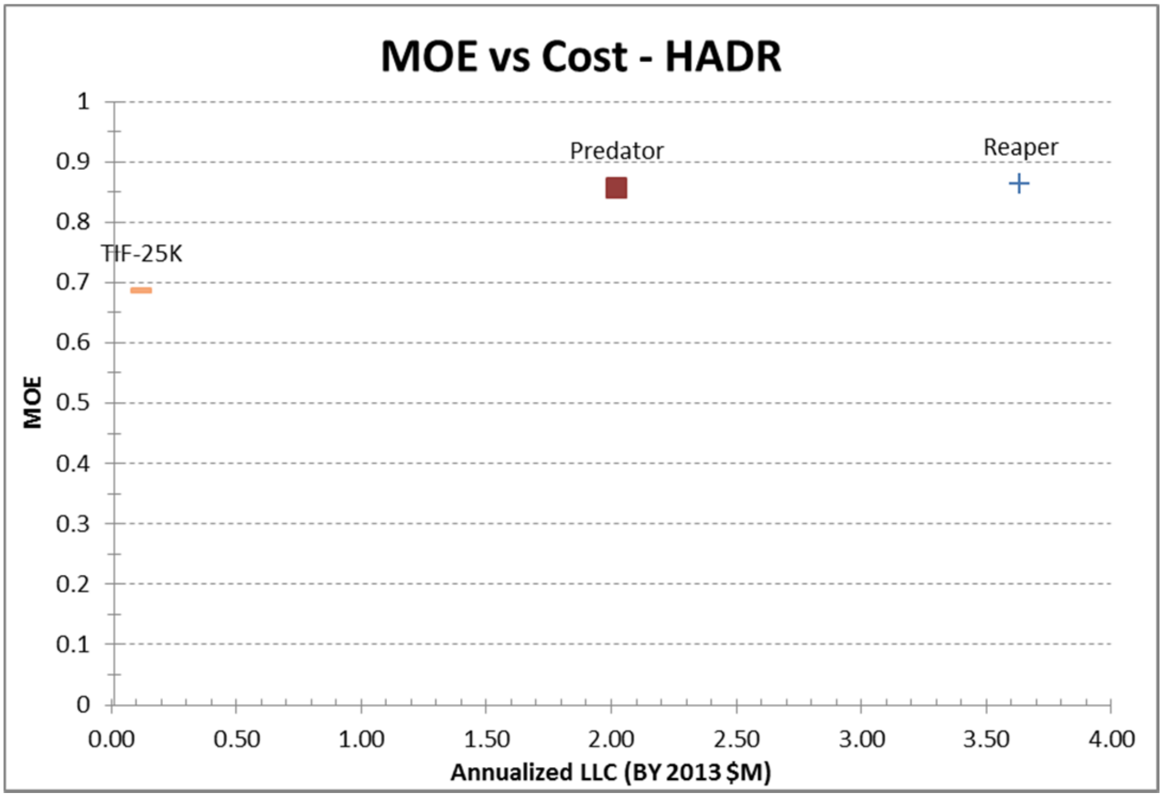

Figure 74. Aerial Platform Tradeoffs–HADR–Linear Scale without Global Hawk

From the graph, the reader can see the relative tradeoffs between the three remaining alternatives. Focusing on the two higher cost options, is the added capability of the Reaper (.863 MOE) worth an extra $1.62M every year above the Predator (.857 MOE)? The authors decide the minimal increase in MOE does not warrant the extra expense and choose the Predator over the more expensive Reaper. Now, the authors are left with the TIF-25K and the Predator. While the Predator is .168 MOE better than the TIF-25K (.689 MOE), it also costs an additional $1.9M per year. Furthermore, despite its higher MOE, the Predator is not better than the TIF-25K for all the attributes. The TIF-25K's endurance of 14 days is much longer than the Predator's endurance of 40 hours. The authors decide that both aerial platforms offer unique capabilities. The TIF-25K offers a low cost aerial platform with long endurance and adequate payload and ceiling, while the Predator offers more maneuverability and a bigger coverage area, albeit at the expense of endurance and more money.

Now that the most cost-effective aerial platforms are decided, the most cost-effective communication payload must be determined.

5. HADR Scenario: Communication Payload Importance Weights

Based upon the scenario conditions, the authors' importance weights for the communication payloads are listed in the hierarchy in Figure 75.

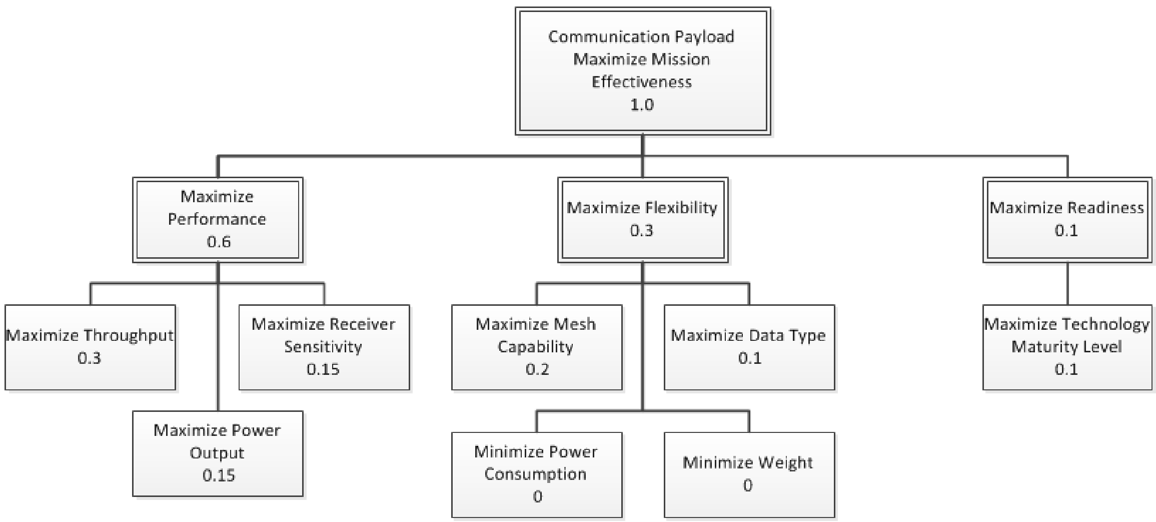

Figure 75. HADR Communication Payload Hierarchy with Importance Weights

In this scenario, the authors consider throughput and mesh capability the first and second most important attributes respectively. Throughput is needed to adequately support multiple users. Mesh capability allows the network to route traffic as nodes enter and leave the network. Power output and receiver sensitivity represent the third and fourth most important attributes in this scenario because both help determine range. The authors consider traffic type and technology maturity level the next most important attributes. Traffic type enables service for multiple waveforms. Since technology maturity level is a proxy measure for readiness, it is important for overall effectiveness. Weight and power consumption is not considered important for this scenario. Each communication payload possesses weight and power attribute values within an acceptable range, so these two attributes do not really distinguish among alternatives; consequently, weight and power each receive an importance weight of 0. Importance weights for communication payload are broken down by relative sizes in Figure 76.

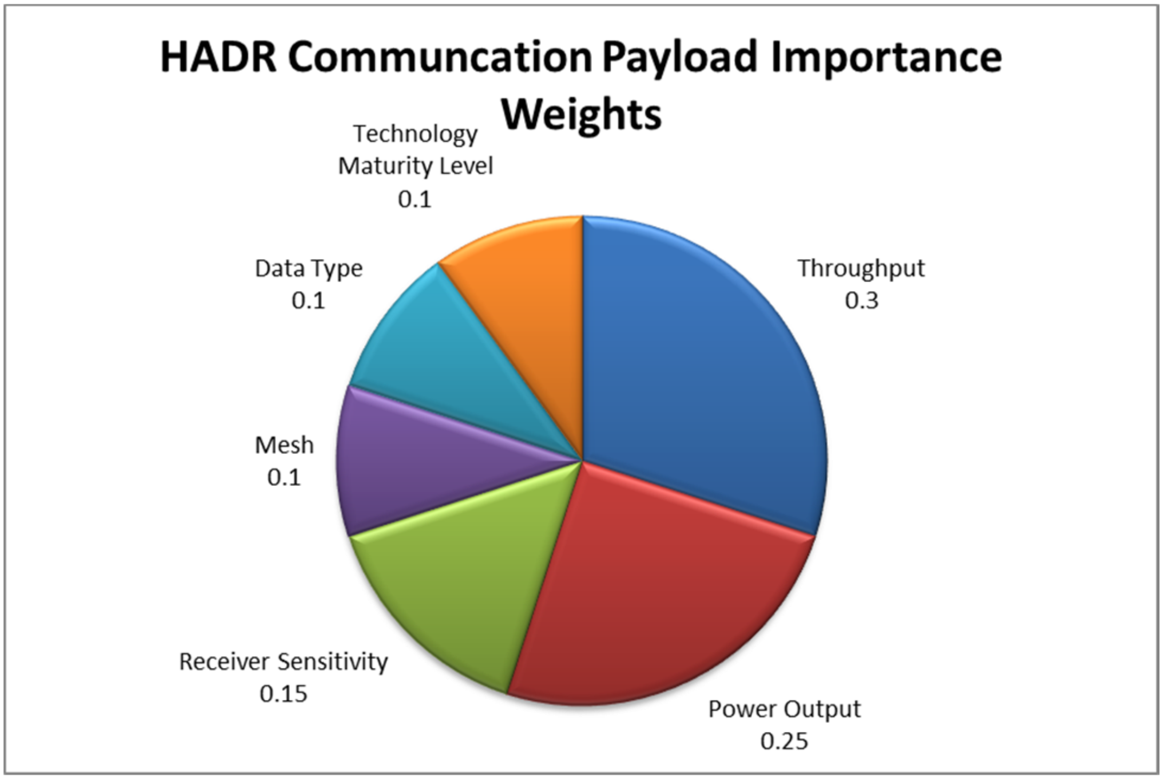

Figure 76. HADR Communication Payload Importance Weights Pie Chart

6. HADR Scenario: Communication Payload Value Functions

The following sections describe the communication value functions used in the HADR scenario. Value functions are listed according to their respective hierarchies. Value functions assigned zero importance weights are not discussed. As a reminder, these value functions are derived from the authors' best judgment. Future decision makers will need to design value functions to best match the specific conditions of the mission and their preferences.

a. Performance

The communication payload performance hierarchy with importance weights is listed in Figure 77.

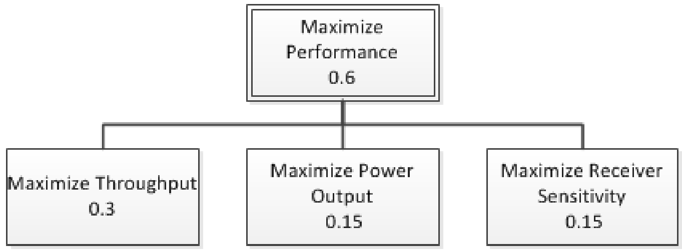

Figure 77. Communication Payload Performance Hierarchy with Importance Weights

(1) Throughput. The throughput value function is represented by a curve starting at 50 Mbps and maxing out at 250 Mbps as depicted in Figure 78.

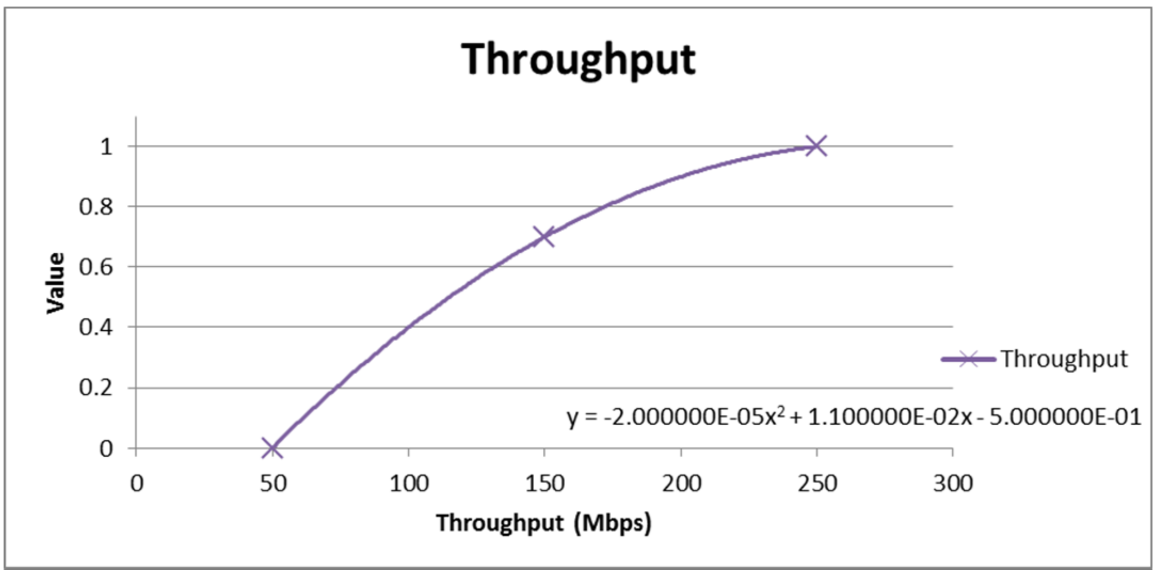

Figure 78. Throughput Value Function

(2) Power Output. The power output's value function is a curve starting at 0 and ending at 500 watts, as depicted in Figure 79.

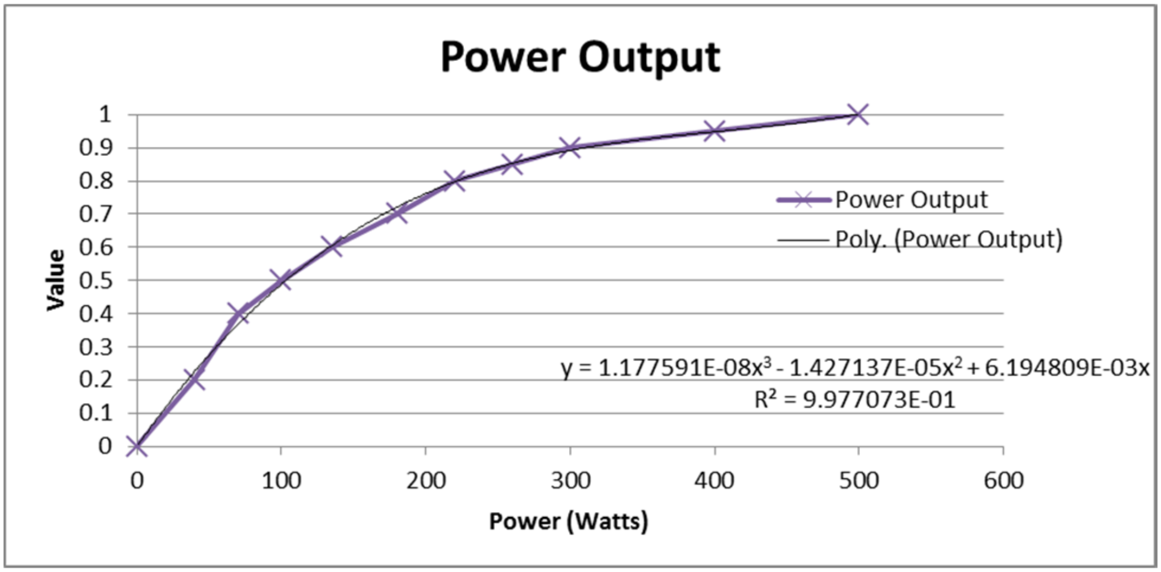

Figure 79. Power Output Value Function

(3) Receiver Sensitivity. Receiver sensitivity uses a value function from -80 to -120 dBm, as depicted in Figure 80.

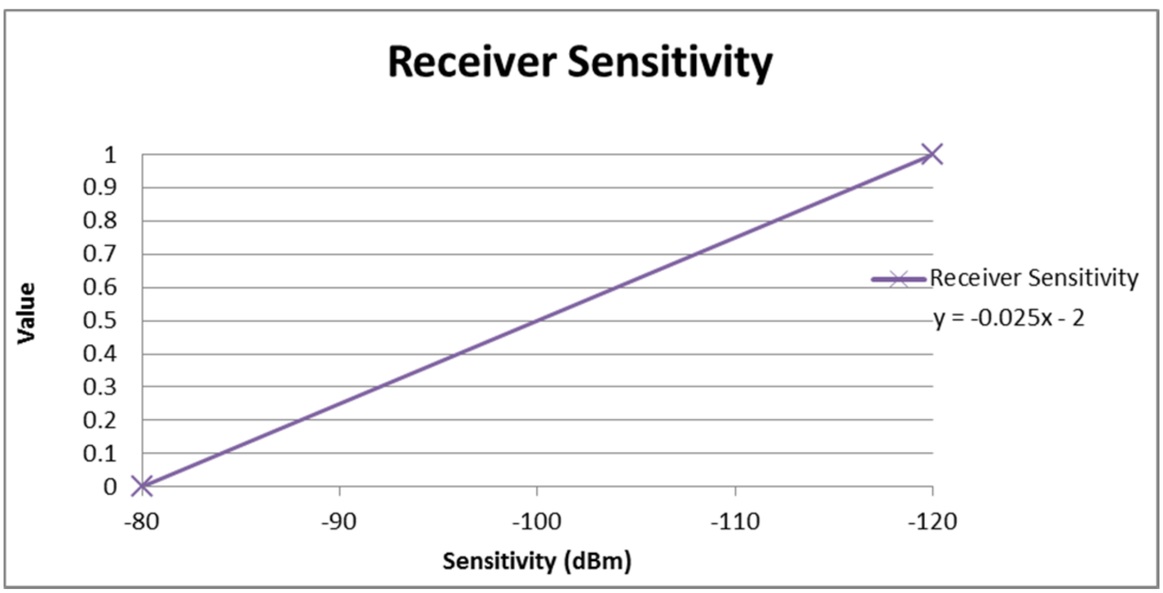

Figure 80. Receiver Sensitivity Value Function

b. *Flexibility*

The communication payload flexibility hierarchy with importance weights is listed in Figure 81.

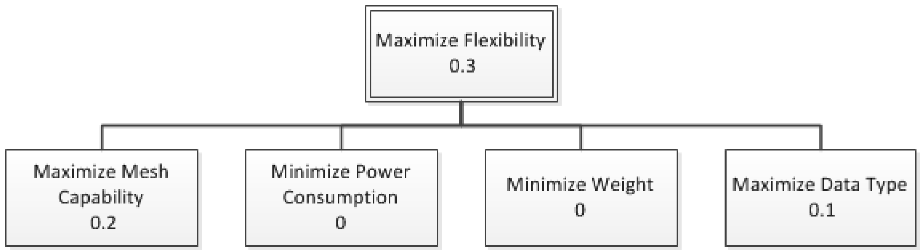

Figure 81. Communication Payload Flexibility Hierarchy with Importance Weights

(1) Mesh Capability. The mesh capability value function is shown in Table 30.

Mesh	No	Yes
Assigned Value	0	1

Table 30. Mesh Capability Value Function

(2) Traffic Type. The traffic type value function is listed in Table 31.

Traffic type	Voice	Data Only	Voice/Data
Assigned Value	0	0.8	1

Table 31. Traffic type Value Function

c. *Readiness*

The communication payload readiness hierarchy with importance weights is listed in Figure 82.

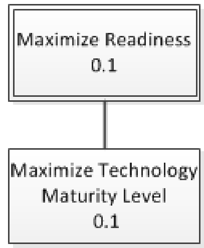

Figure 82. Communication Payload Readiness Hierarchy with Importance Weights

(1) Technology Maturity Level. Technology maturity level for communication payloads is modeled after the technology maturity level value function used for the aerial payloads. Technology maturity level receives a maximum score of 1.0 for 5 years after IOC. 2 years before IOC earns a 0 score. The function is mapped as a linear equation as displayed in Figure 83.

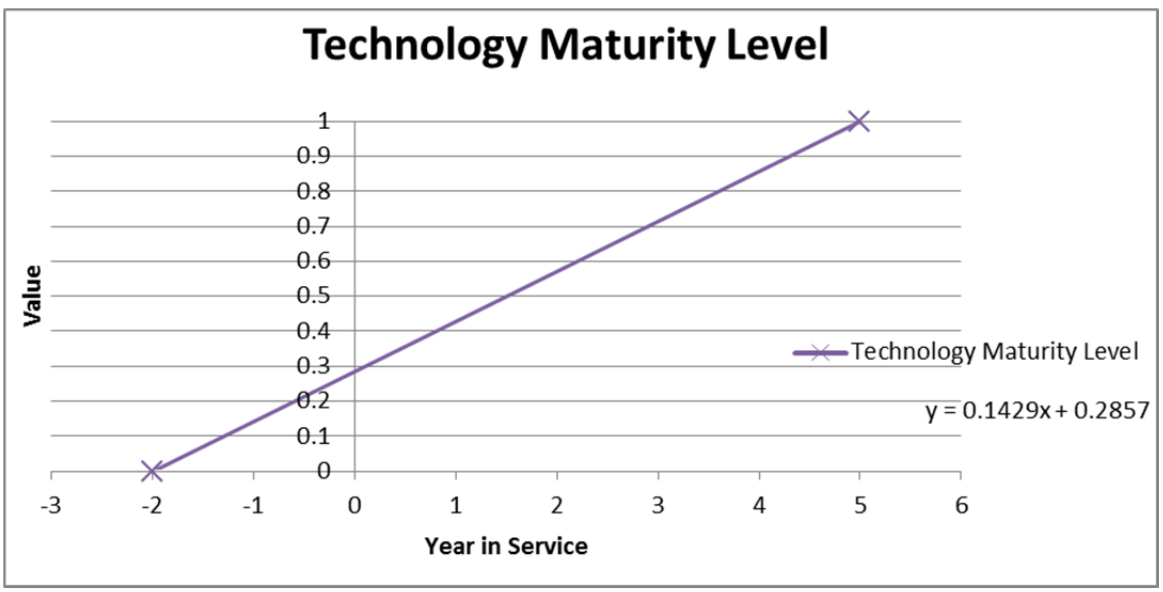

Figure 83. Technology Maturity Level Value Function

7. HADR Scenario: Communication Payload Cost-Effective Solutions

MOE vs annualized LCC is depicted, using a logarithmic scale, in Figure 84.

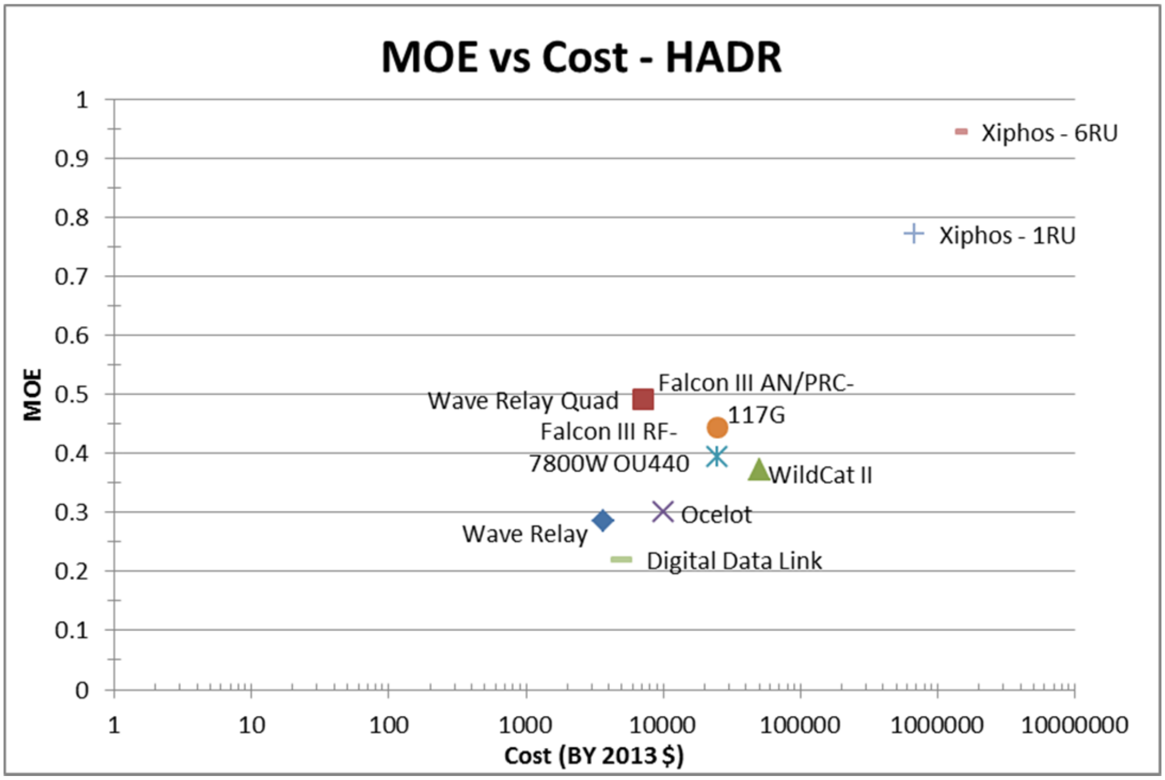

Figure 84. Communications Payload Cost Effectiveness–HADR–Logarithmic Scale

Some communication payloads are dominated by cheaper alternatives. Reducing the communication payloads down to the efficient solution set results in Figure 85.

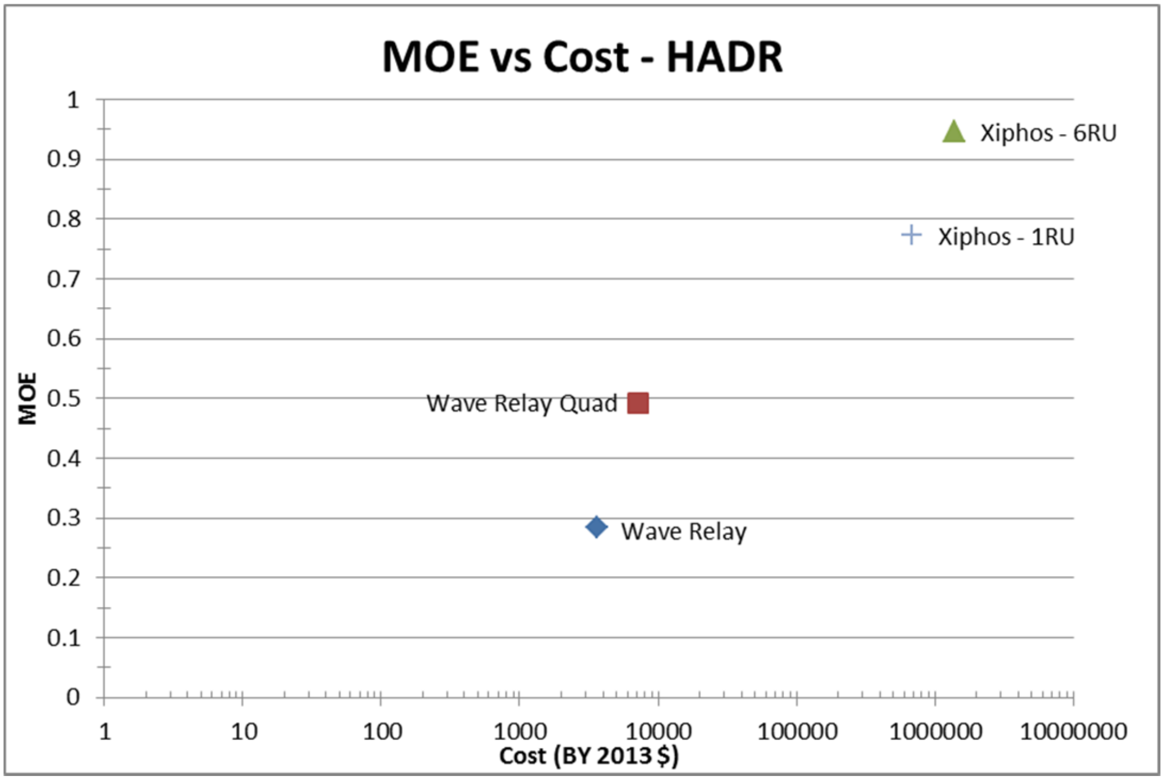

Figure 85. Communications Payload Efficient Solutions–HADR–Logarithmic Scale

Both Wave Relay payloads and both Oceus Networks Xiphos radios are included in the efficient solution set. The Xiphos 1RU and 6RU possess the highest MOE in the group at .772 and .946 respectively. Both radios offer high power output, high throughput and excellent scalability for multiple users. Additionally, both radio units are based on LTE cellular base stations, which means that users can use their LTE enabled devices to access the network directly. Allowing users to bring their own personal LTE enabled cell phones and mobile devices during a HADR situation would help offset the added cost of the Xiphos radio units, while also increasing user familiarity and adoption rates and reduce the administrative burden on the military leading the relief effort. Conversely, both Wave Relay radio units require either each individual user to carry a user radio or multiple radios would have to be interspersed throughout the disaster area and then broadcast a wireless signal for user access. For these reasons, the Xiphos 1RU and 6RU are considered the only effective communication payloads for this scenario. Next, the authors examine the tradeoffs between the Xiphos 1RU and 6RU in Figure 86.

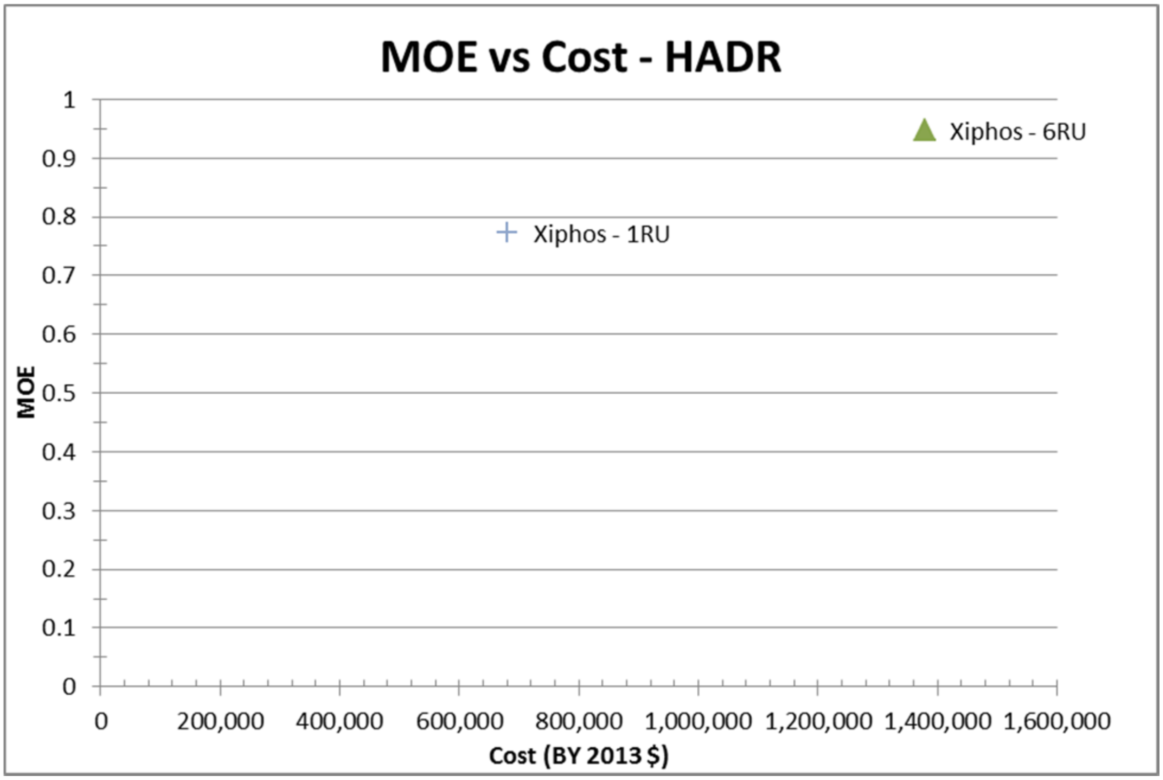

Figure 86. Communications Payload Tradeoffs–HADR–Linear Scale

Is the additional .174 MOE of the Xiphos 6RU (.946 MOE) worth the extra $698K when compared to the Xiphos 1RU (.772 MOE)? The answer to that question depends on the aerial platform the radio units are being installed in, which is discussed next.

8. HADR Scenario: Solution Compatibility

Both the TIF-25K and the Predator have enough useful load to carry either Xiphos radio units. However, available power for the radio units is a differentiator. The Predator has 1,800 watts available for payloads. The Xiphos 6RU's power consumption is over 3,000 watts. The Predator could not support the Xiphos 6RU normally. The TIF-25K Aerostat is capable of sending power to its payload from a ground based source up the tether. The TIF-25K Aerostat should be able to power the Xiphos 6RU radio unit. This may require high voltage power sent from the ground up to the Aerostat to avoid high power losses over the long transmission line of the tether, but it is feasible. Compatibility of the solutions is listed in Table 32.

	Xiphos 1RU	Xiphos 6RU
TIF-25K	Y	Y
Predator	Y	N

Table 32. HADR Compatibility

B. LONG-RANGE SCENARIO

The long-range scenario depicts a situation where headquarters is trying to establish communications with a warship at sea that does not have satellite communication capability.

1. Long-Range Scenario: Mission and Environmental Conditions

Leadership at headquarters needs to establish UHF communications with a ship 340 nm away. The ship has lost its satellite communication capability. Headquarters is based at a large airfield near the coast. The altitude of the headquarters antenna and the ship antenna are assumed to be zero to simplify calculations. See a summary of the conditions in Table 33.

Conditions	
Communication Relay Range	340 nm
Enemy Resistance	None
Terrain	Flat/ocean
Weather	Clouds with possibility of icing conditions at higher altitudes
Duration of communication relay mission	4 hours
Type of communication required	Voice (UHF)

Table 33. Long-Range Scenario Conditions

2. Long-Range Scenario: Aerial Platform Importance Weights

Based upon the scenario conditions, the authors' importance weights for the aerial platforms are listed in the hierarchy in Figure 87.

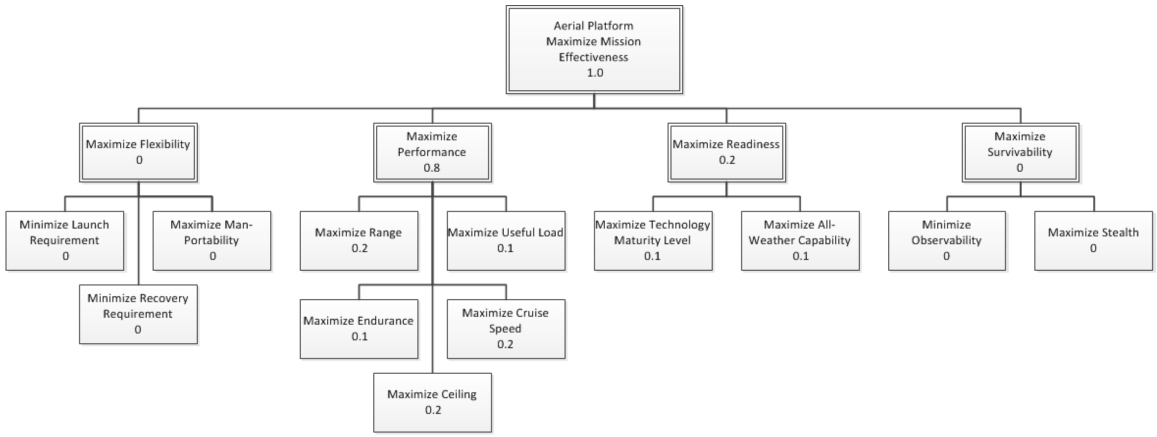

Figure 87. Long-Range Aerial Platform Hierarchy with Importance Weights

The authors rank range, ceiling and cruise speed the three most important attributes in this scenario. Endurance, useful load, technology maturity level and all weather capability are the remaining important attributes. Range, cruise speed and endurance help enable the aerial platform to get in position to execute the mission. A sufficient ceiling is needed to help ensure that sufficient radio horizon is attained to relay communications between the two nodes at long range. Useful load is important because the communication payload needs to be robust enough to transmit and receive long-range signals. Icing conditions are expected, therefore, all-weather capability is needed for this scenario. Finally, technology maturity level is important because it represents overall readiness.

As in the previous scenario, the authors did not give importance weights to launch requirement, recovery requirement, man-portability, observability and stealth for similar reasons. For the graphical depiction of the breakdown of importance weights, see Figure 88.

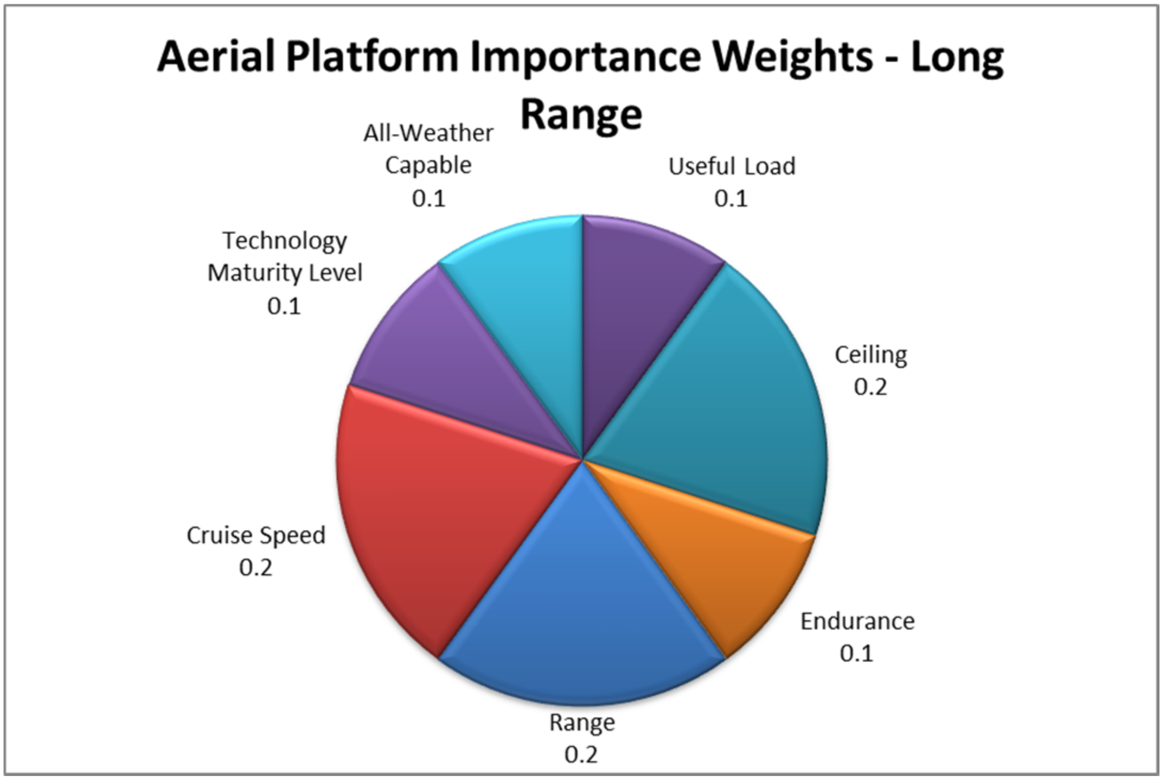

Figure 88. Long-Range Aerial Platform Importance Weights Pie Chart

3. Long-Range Scenario: Aerial Platform Value Functions

The following sections describe the aerial platform value functions used in the long-range scenario. Value functions are listed according to their respective hierarchies. Unless otherwise noted, value functions for this scenario are derived using similar methods as the previous scenario. Value functions assigned zero importance weights are not discussed. As a reminder, these value functions are derived from the authors' best judgment. Future decision makers will need to design value functions to best match the specific conditions of the mission and their preferences.

a. Flexibility

The aerial platform flexibility hierarchy with importance weights is listed in Figure 89. The flexibility hierarchy is shown for purposes of continuity only.

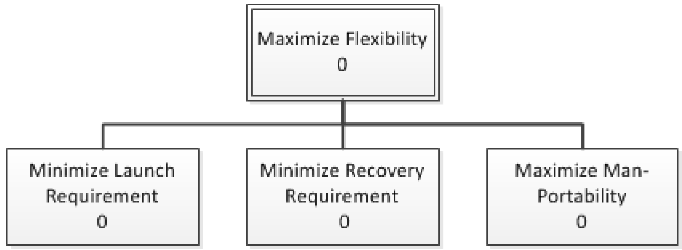

Figure 89. Aerial Platform Flexibility Hierarchy with Importance Weights

b. Performance

The aerial platform performance hierarchy with importance weights is listed in Figure 90.

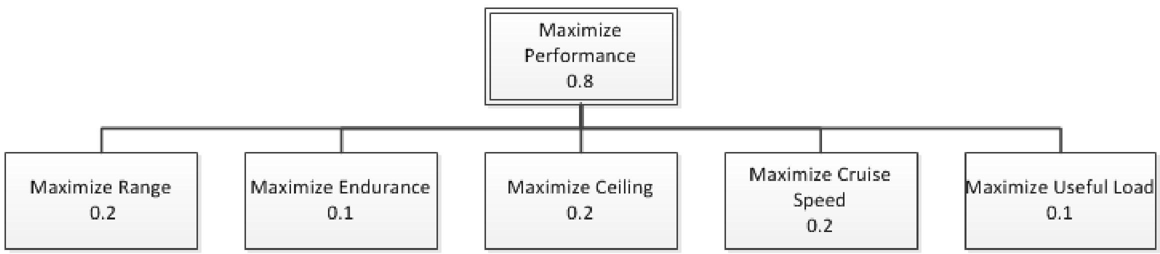

Figure 90. Aerial Platform Performance Hierarchy with Importance Weights

(1) Range. Communication relay range is the primary driver of the range value function for this scenario. The authors use a curve starting at 150 nm and ending at 340 nm as shown in Figure 91.

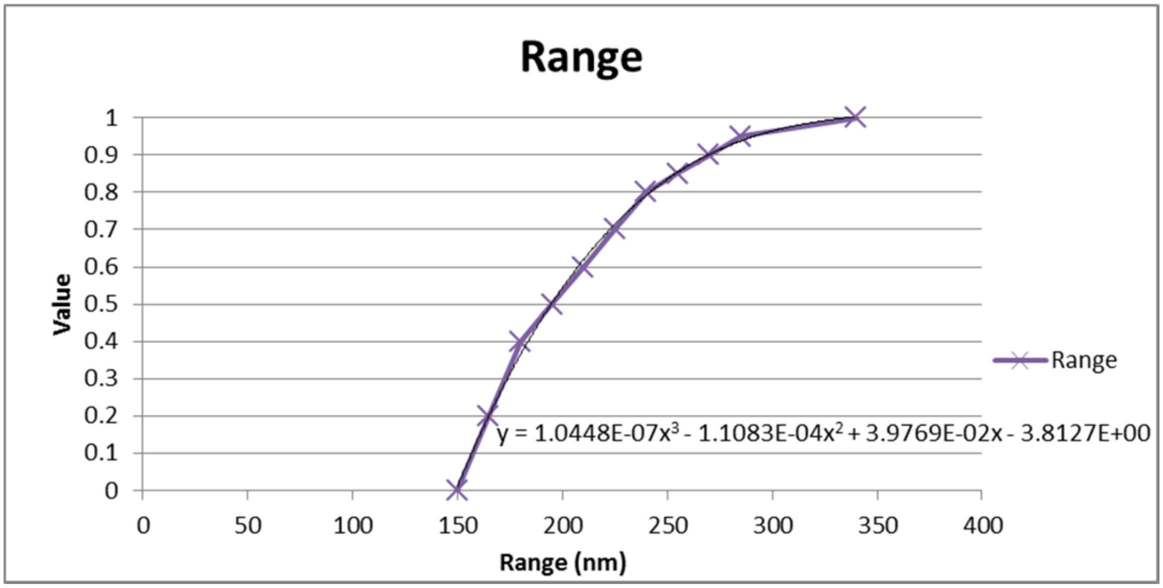

Figure 91. Range Value Function

(2) Endurance. The endurance value function is primarily determined by the duration of the communication relay mission and transit times. The authors' value function for endurance is shown in Figure 92.

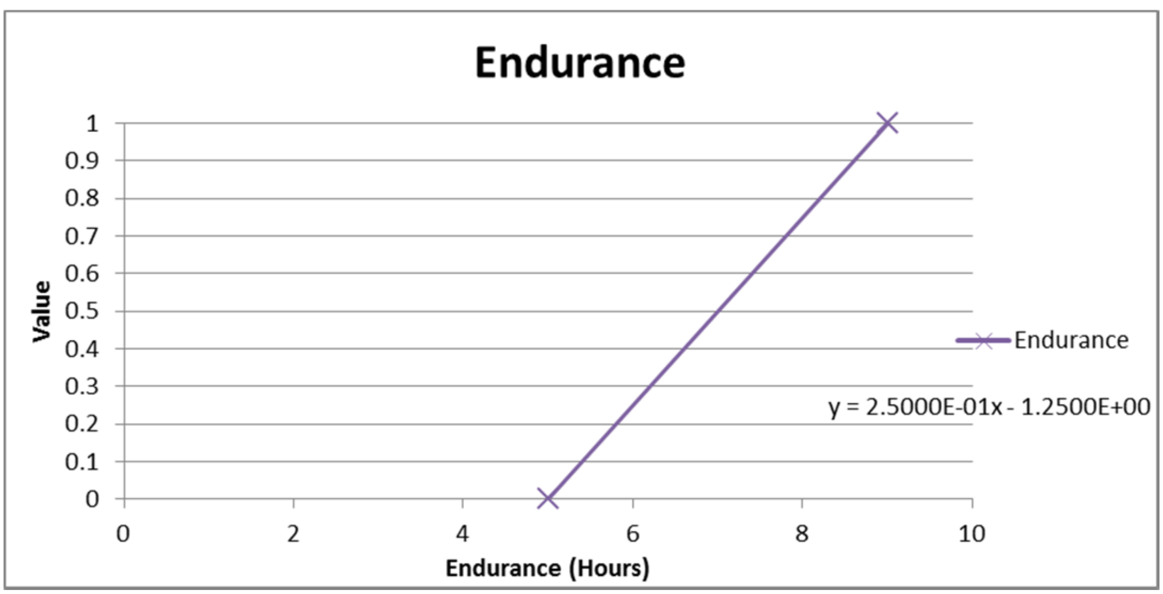

Figure 92. Endurance Value Function

(3) Ceiling. The minimum required ceiling for this mission is calculated using the equation for height from Chapter II:

$$h = \left(\frac{R}{1.23}\right)^2$$

$$R = \frac{340nm}{2} = 170nm$$

$$\rightarrow h = \left(\frac{170}{1.23}\right)^2 = 19{,}102\,feet$$

Consequently, the value function uses a curve starting at the minimum altitude for this mission. Higher ceilings allow the aerial platform to operate closer to its base and therefore it is rewarded with a higher effectiveness score, as depicted in Figure 93.

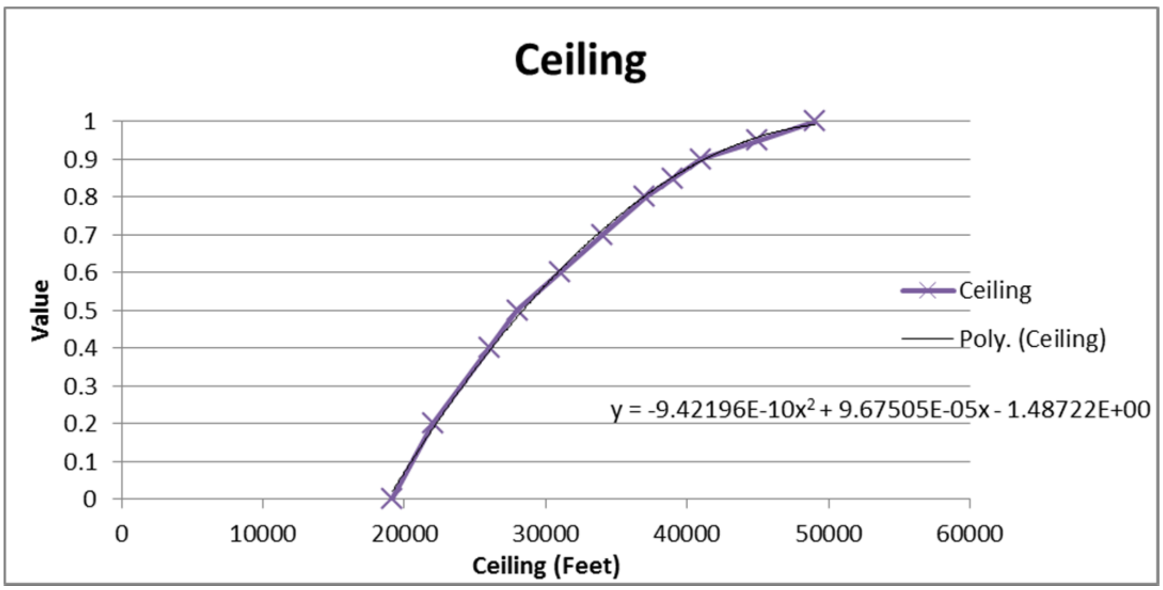

Figure 93. Ceiling Value Function

(4) Cruise Speed. Cruise speed increases efficiency by reducing transit times. Cruise speed's value function is shown in Figure 94.

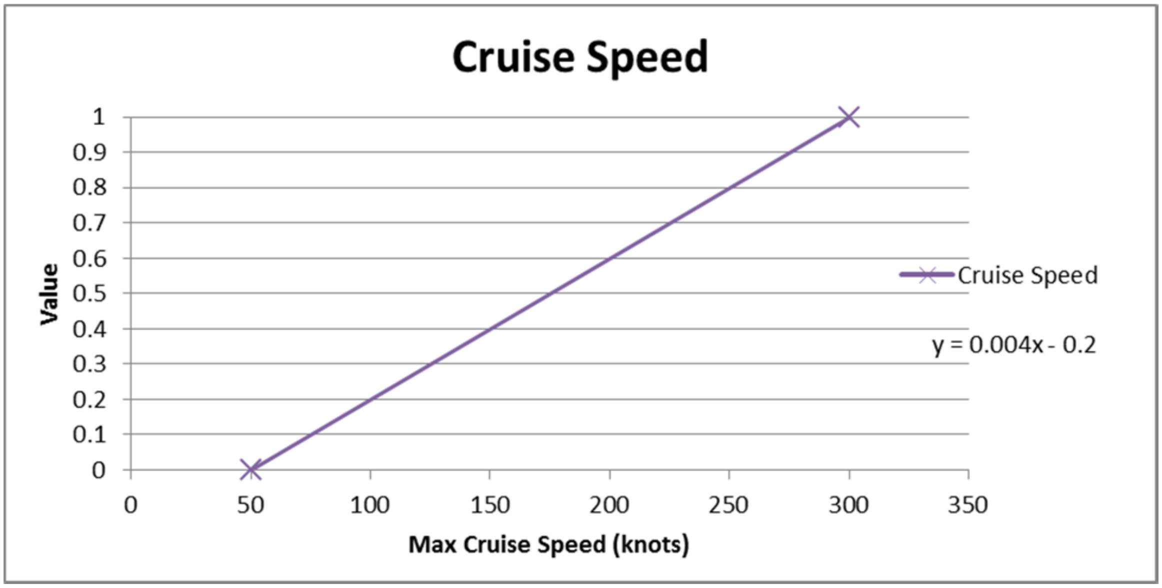

Figure 94. Cruise Speed Value Function

(5) Useful Load. The useful load value function is shown in Figure 95.

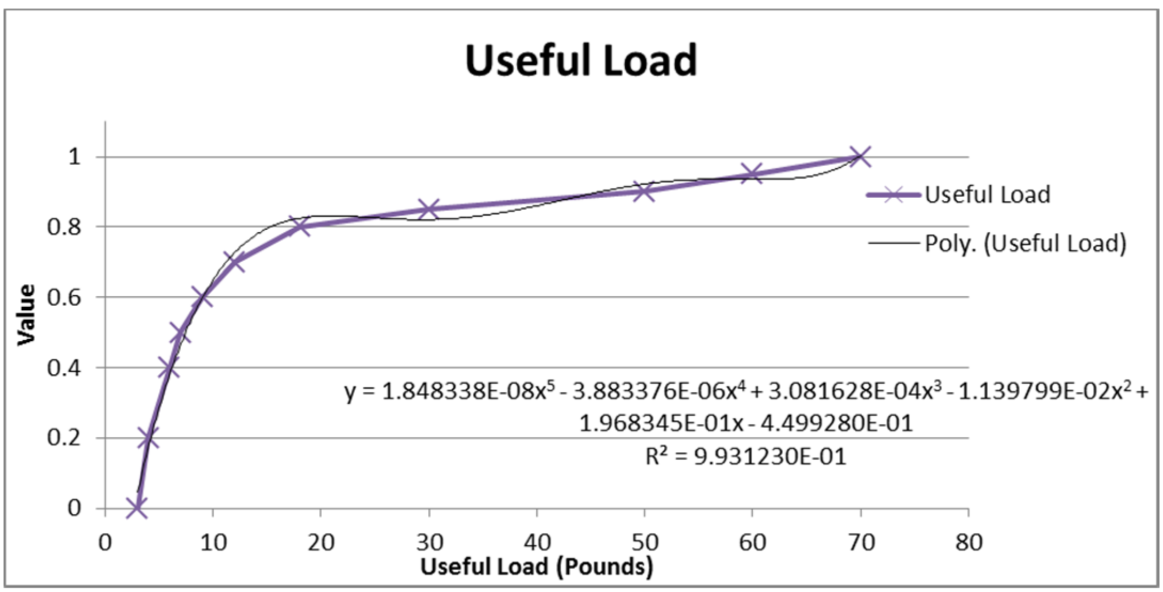

Figure 95. Useful Load Value Function

c. Readiness

The aerial platform readiness hierarchy with importance weights is listed in Figure 96.

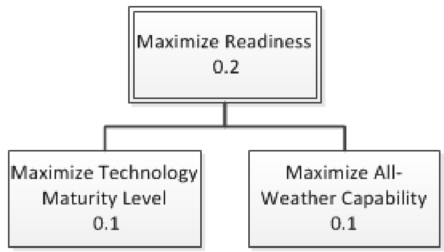

Figure 96. Aerial Platform Readiness Hierarchy with Importance Weights

(1) Technology Maturity Level. Technology maturity level remains the same from the HADR scenario and is not discussed here. For more information, refer to Figure 67.

(2) All-Weather Capability. The all-weather capability value function of aerial platforms is a simple binary function. Aerial platforms that possess deicing capability or are impervious to it (towers), receive a 1.0 score. All other platforms receive a score of 0. See Table 34.

De-icing	1
None	0

Table 34. All-Weather Capable Value Function

d. Survivability

Aerial platform survivability hierarchy with importance weights is listed in Figure 97. For this scenario, survivability is given zero weight. Consequently, the value functions for the individual attributes that makeup survivability is not discussed in this scenario.

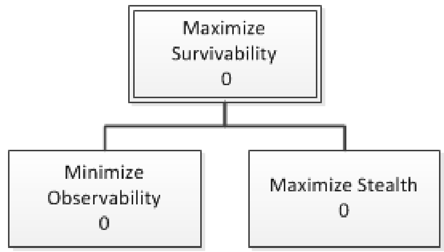

Figure 97. Aerial Platform Survivability Hierarchy

4. Long-Range Scenario: Aerial Platform Cost-Effective Solutions

MOE vs annualized LCC for each aerial platform is shown in Figure 98.

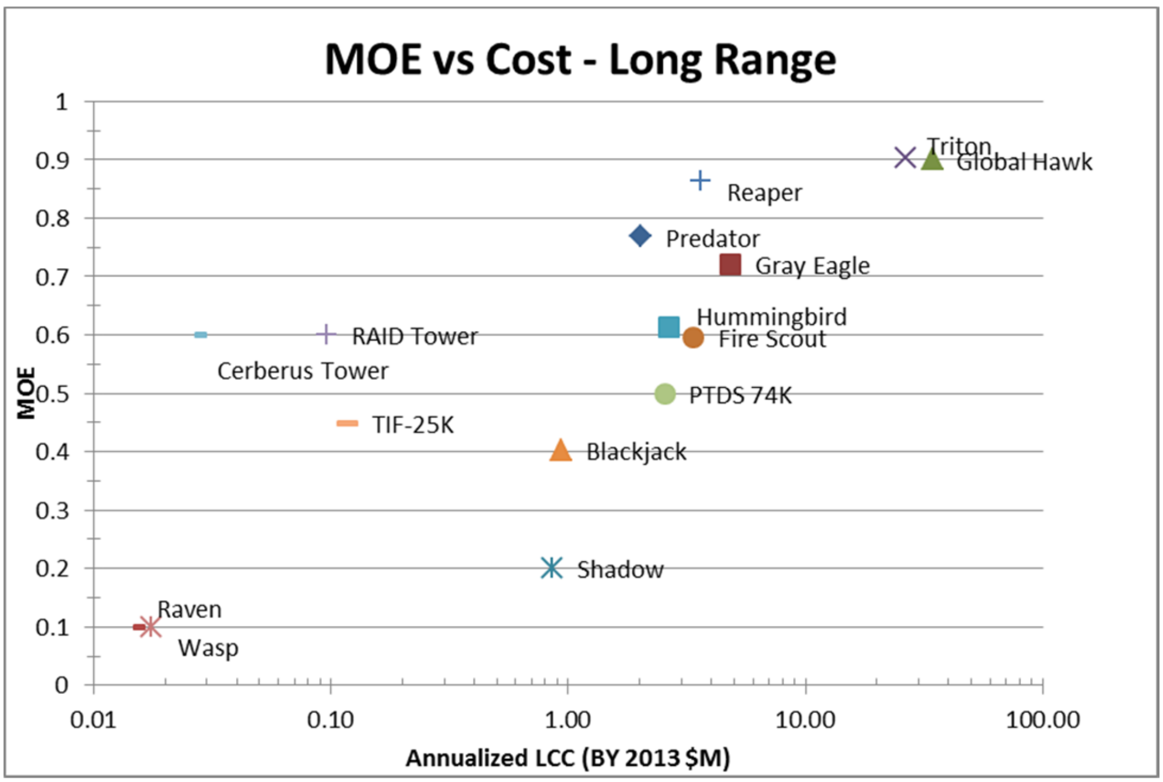

Figure 98. Aerial Platform Cost Effectiveness–Long-Range–Logarithmic Scale

Although each tower has a 0.6 MOE, neither tower is a feasible solution to this scenario because their ceilings are significantly lower the minimum required ceiling for this mission. The minimum ceiling can be determined using the radio horizon equation to calculate the minimum altitude necessary to communicate between two locations at sea level (Herbert, 2013), 40 nm apart, as depicted in Figure 99.

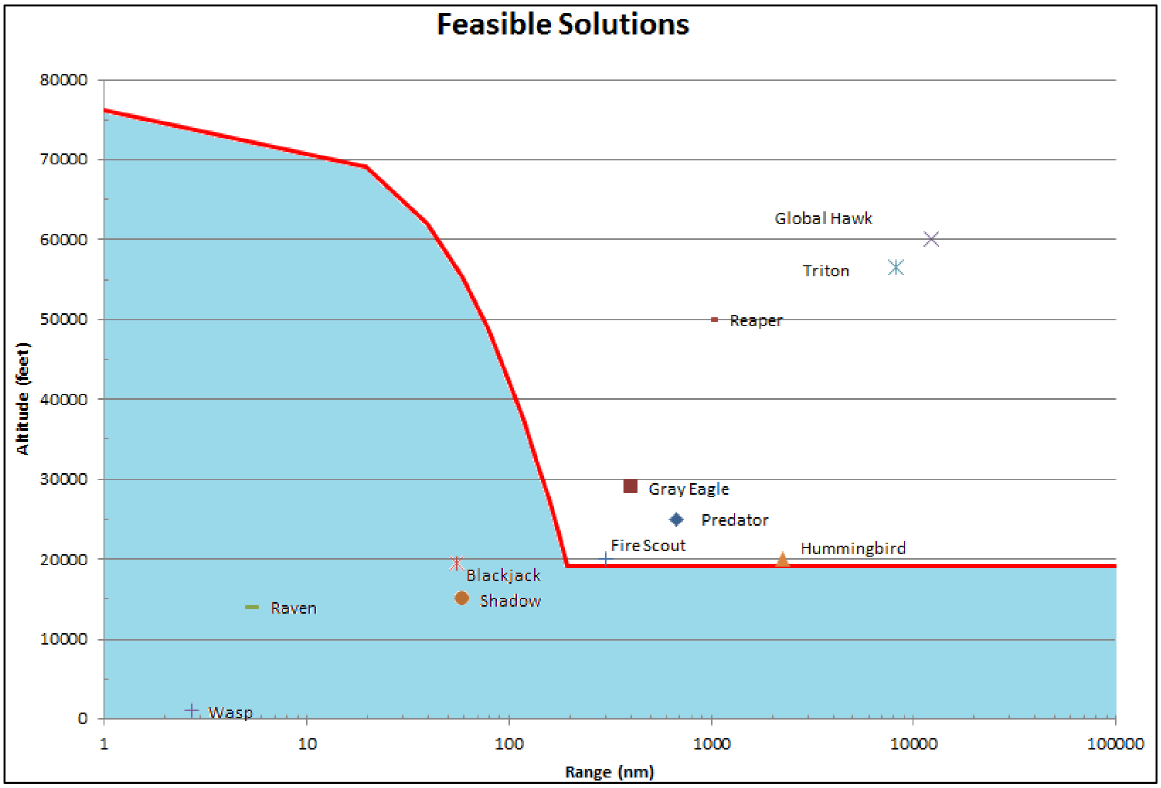

Figure 99. Aerial Platforms Feasible Solutions–Logarithmic Scale

The red line indicates the necessary altitude for an aerial platform for each range value. Any platform depicted below the red lines is not a feasible solution. If an aerial platform's range is exactly half the communication relay range (170 nm), an aerial platform must have a ceiling above 19,102 feet to maintain a radio horizon with both headquarters and the ship simultaneously. Any aerial platform with a ceiling lower than this altitude is not feasible because the aerial platform could not serve as the communication link between headquarters and the warship at sea, regardless of its range. If an aerial platform's range is shorter than 170 nm, it will need a ceiling greater than 19,102 feet. For example, the Shadow's has a range of 68 nm, which leaves a range of 272 nm to the ship. The Shadow would need a ceiling of at least 48,902 feet for its radio horizon to include the ship. The Shadow's ceiling is much lower than 48,902 feet and it is not included in the feasible solutions.

The cost-effectiveness of the remaining feasible aerial platforms are plotted in Figure 100.

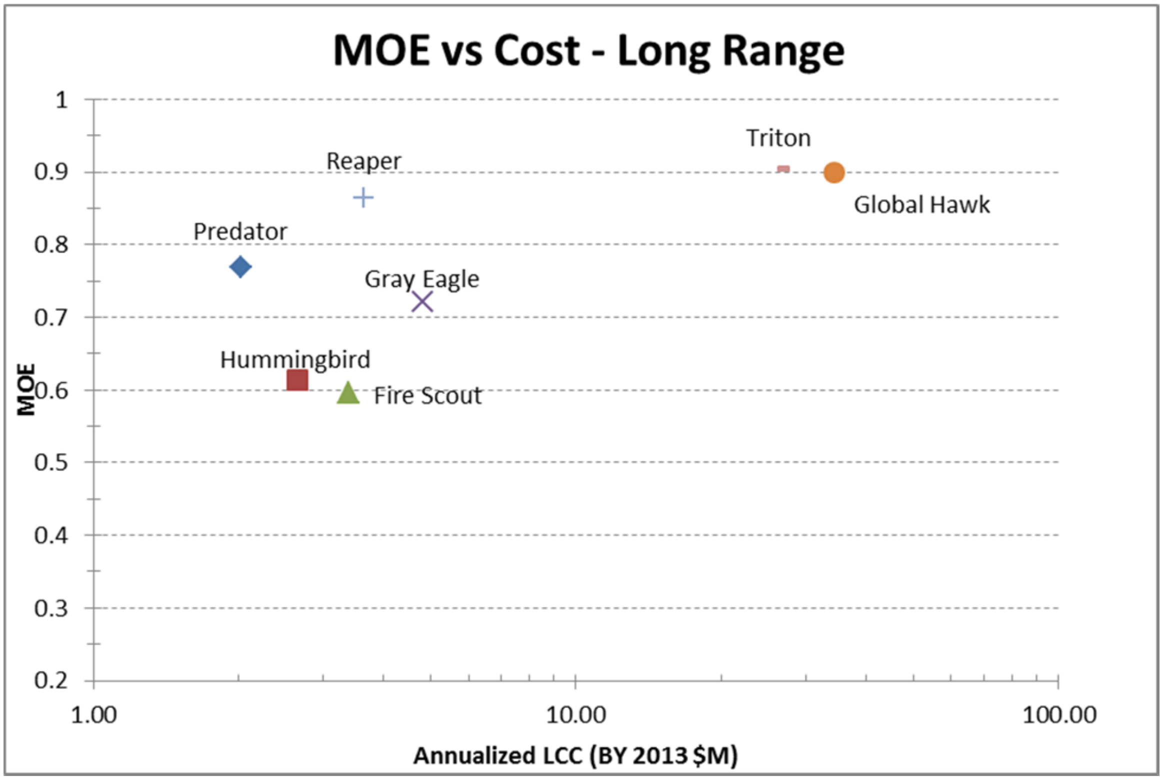

Figure 100. Remaining Aerial Platforms Cost Effectiveness–Long-Range–Logarithmic Scale

Next, the authors identify the efficient solutions and switch to a linear scale in Figure 101.

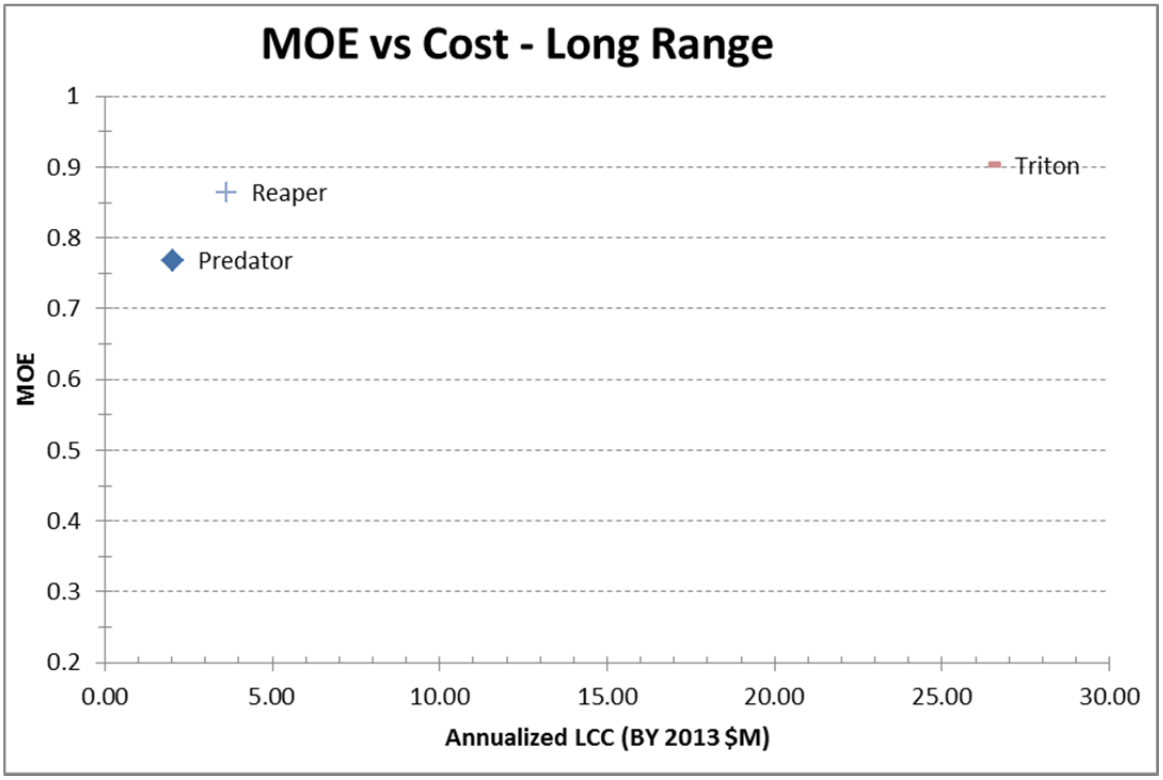

Figure 101. Remaining Aerial Platforms Cost Effectiveness–Long-Range–Linear Scale

The Predator, Reaper and Triton UAVs are identified as the efficient solution set. It is readily apparent that the Triton is several orders of magnitude more expensive than the other two UAVs. Is the .04 MOE increase of the Triton (.904 MOE) above Reaper (.865 MOE) worth the expense? In this scenario, the answer could be yes. The Triton has de-icing capability, while the Reaper does not. Depending on where the icing level is, the Triton may be the only viable option. If the icing conditions are not a factor, the much higher cost of the Triton and minimal increase in MOE above the Reaper all but eliminates it as a cost-effective solution. Comparing the Predator and Reaper, the decision is not clear. While the Reaper costs $1.6M more than the Predator, its MOE is .096 higher than the Predator (.769 MOE). The authors decide not to choose between the three UAVs. All three will be evaluated for compatibility with the most cost-effective communication payloads.

5. Long-Range Scenario: Communication Payload Importance Weights

Based upon the scenario conditions, the authors' importance weights for the communication payloads are listed in the hierarchy in Figure 102.

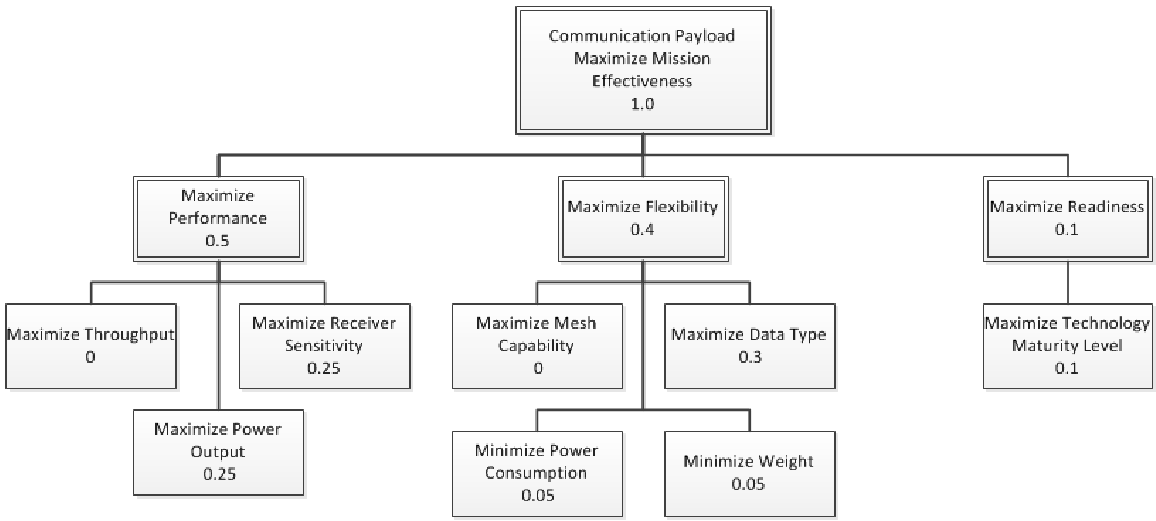

Figure 102. Long-Range Communication Payload Hierarchy with Importance Weights

In this scenario, the authors consider traffic type the most important factor. Traffic type enables the communication payload to interface with the proper waveform. Power output and receiver sensitivity help with long-range communications and are ranked next most important after traffic type. Technology maturity level is ranked less than the aforementioned attributes. Technology maturity level is a proxy for readiness. Weight and power consumption are the last two attributes in this scenario that receive importance weight. Weight and power consumption help ensure compatibility with aerial platforms. Throughput is not considered important for this scenario since it is only relaying voice communications and not data. Mesh capability is also considered unimportant for this scenario. Importance weights are broken down by relative sizes in Figure 103.

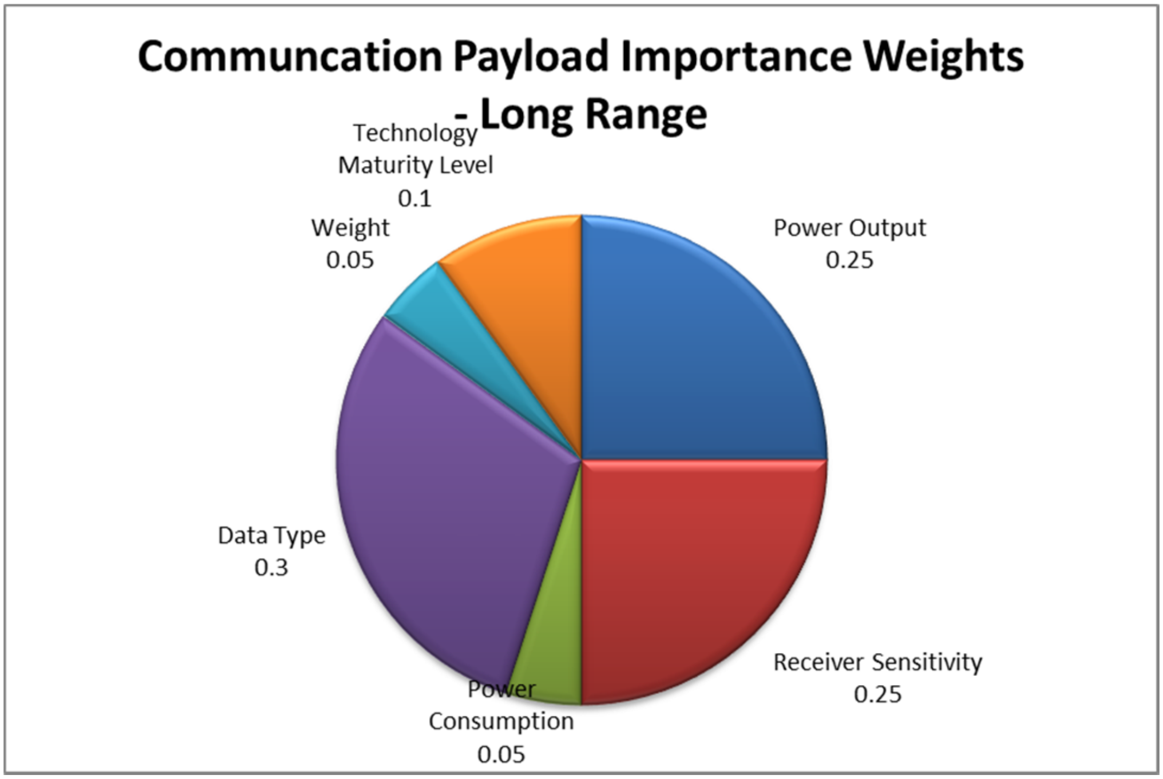

Figure 103. Long-Range Communication Payload Importance Weights Pie Chart

6. Long-Range Scenario: Communication Payload Value Functions

The following sections describe the communication payload value functions used in the long-range scenario. Value functions are listed according to their respective hierarchies. Unless otherwise noted, value functions for this scenario are derived using similar determination methods as the previous scenario. Value functions assigned zero importance weights are not discussed.

a. Performance

The communication payload performance hierarchy with importance weights is listed in Figure 104.

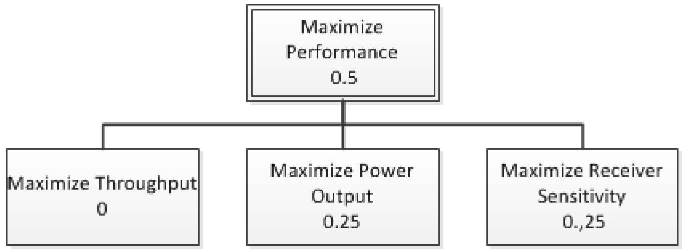

Figure 104. Communication Payload Performance Hierarchy with Importance Weights

(1) Power Output. The power output value function is listed in Figure 105.

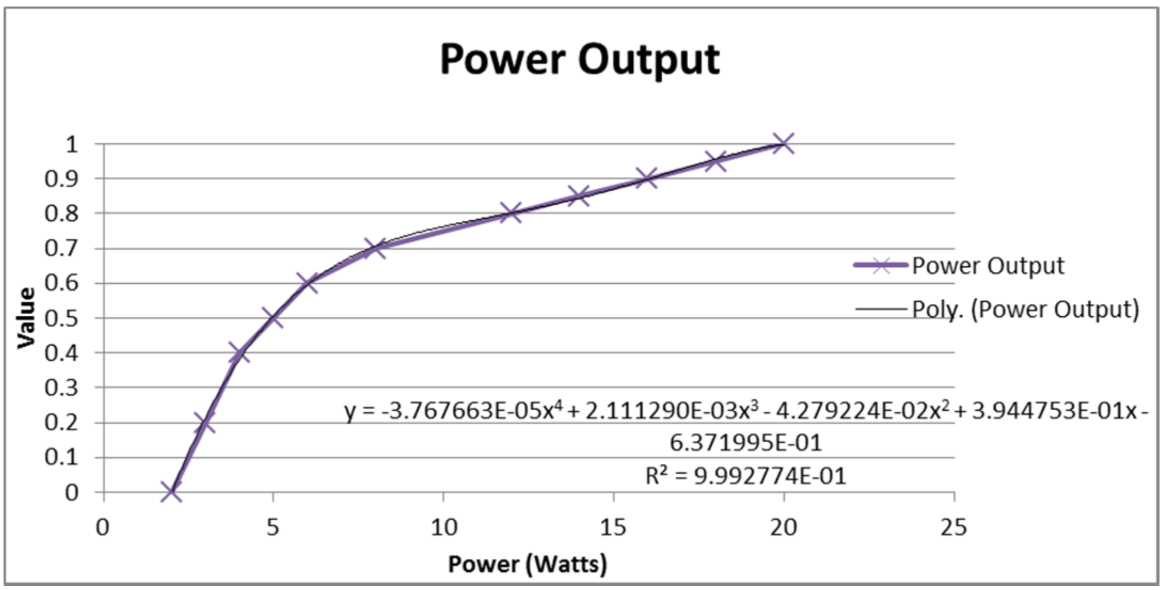

Figure 105. Power Output Value Function

(2) Receiver Sensitivity. The receiver sensitivity value function remains the same from the previous scenario. For more information, refer to Figure 80.

b. Flexibility

The Communication Payload flexibility hierarchy with importance weights is listed in Figure 106.

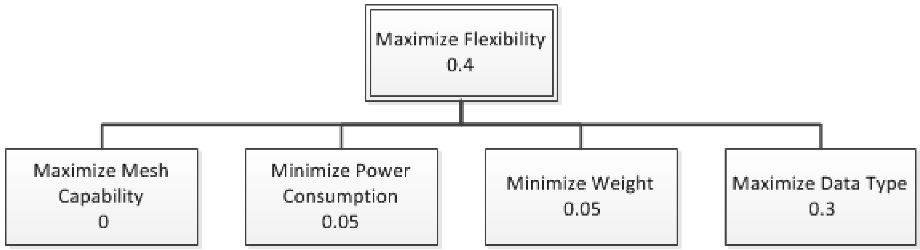

Figure 106. Communication Payload Flexibility Hierarchy with Importance Weights

(1) Power consumption. The power consumption value function is shown in Figure 107.

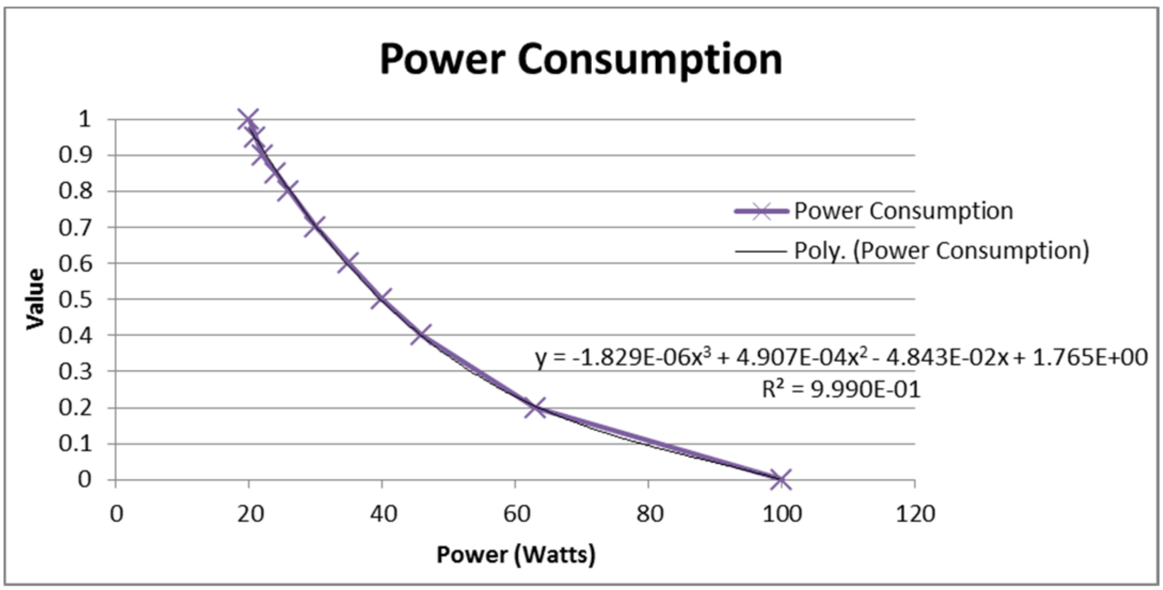

Figure 107. Power Consumption Value Function

(2) Weight. The weight value function is listed in Figure 108.

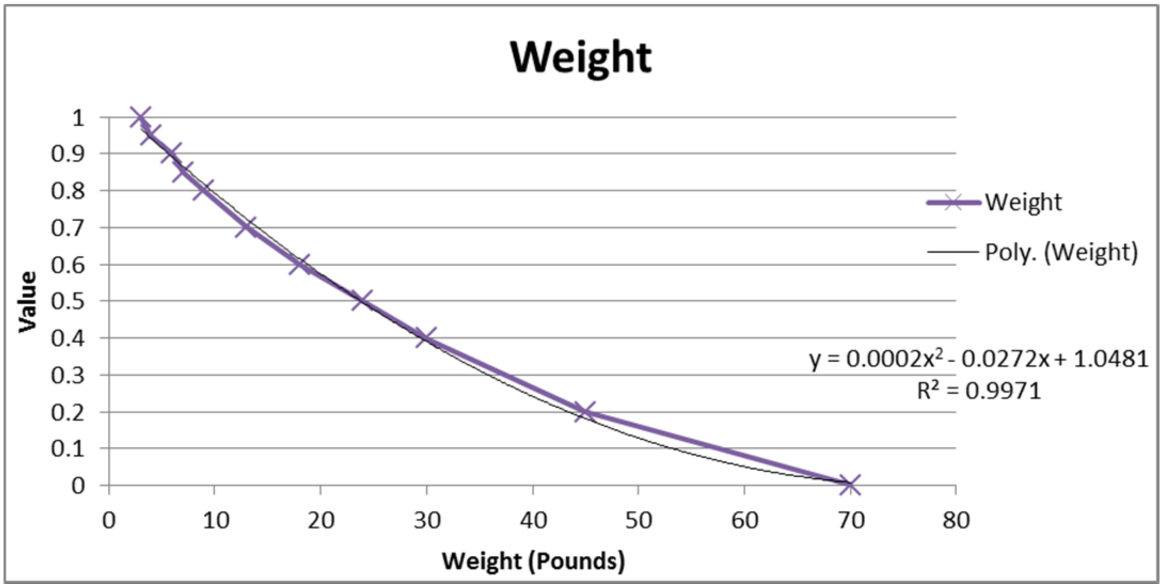

Figure 108. Weight Value Function

(3) Traffic type. Traffic type value function is listed in Table 35.

Traffic type	Voice	Data Only	Voice/Data
Assigned Value	1	0	1

Table 35. Traffic type Value Function

c. Readiness

The Communication Payload readiness hierarchy with importance weights is listed in Figure 109.

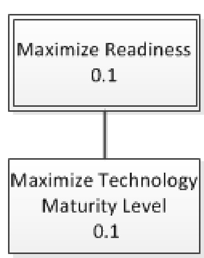

Figure 109. Communication Payload Readiness Hierarchy with Importance Weights

(1) Technology Maturity Level. The technology maturity level value function remains the same from the previous scenario and it is not discussed here. For more information, refer to Figure 83.

7. Long-Range Scenario: Communication Payload Cost-Effective Solutions

MOE vs annualized LCC is listed in Figure 110.

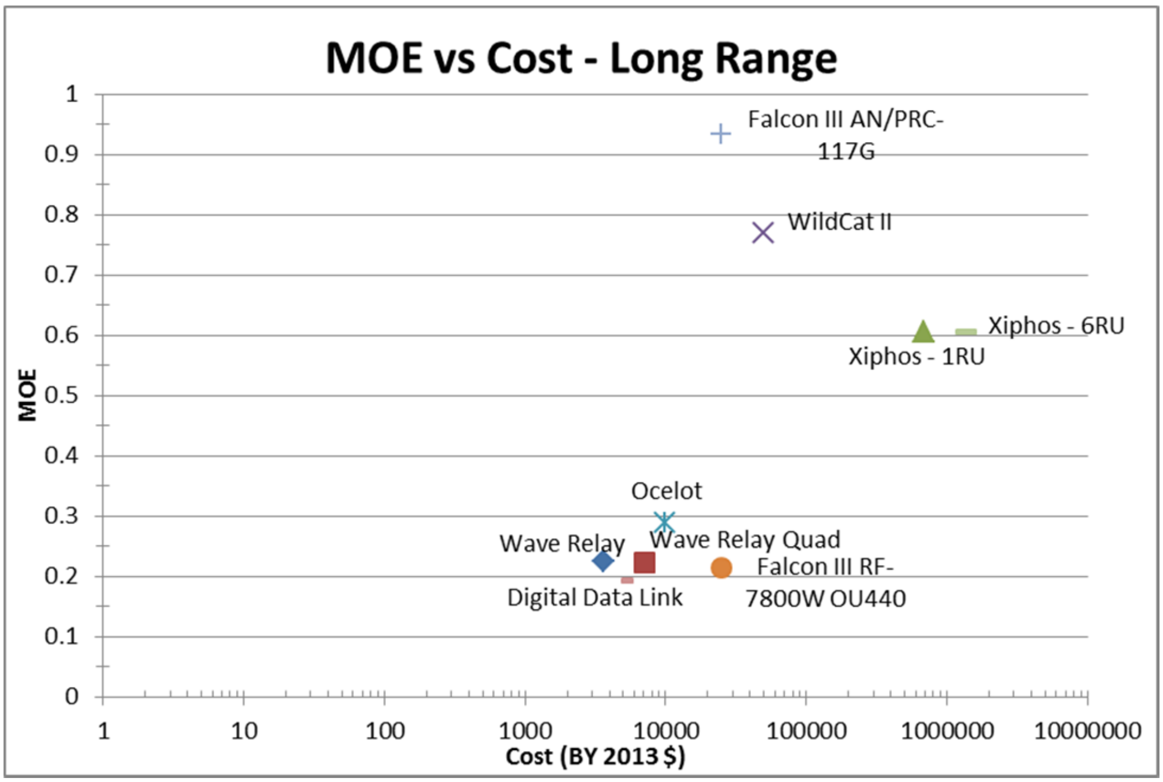

Figure 110. Communication Payload Cost Effectiveness–Long-Range–Logarithmic Scale

The efficient solution set is shown in Figure 111.

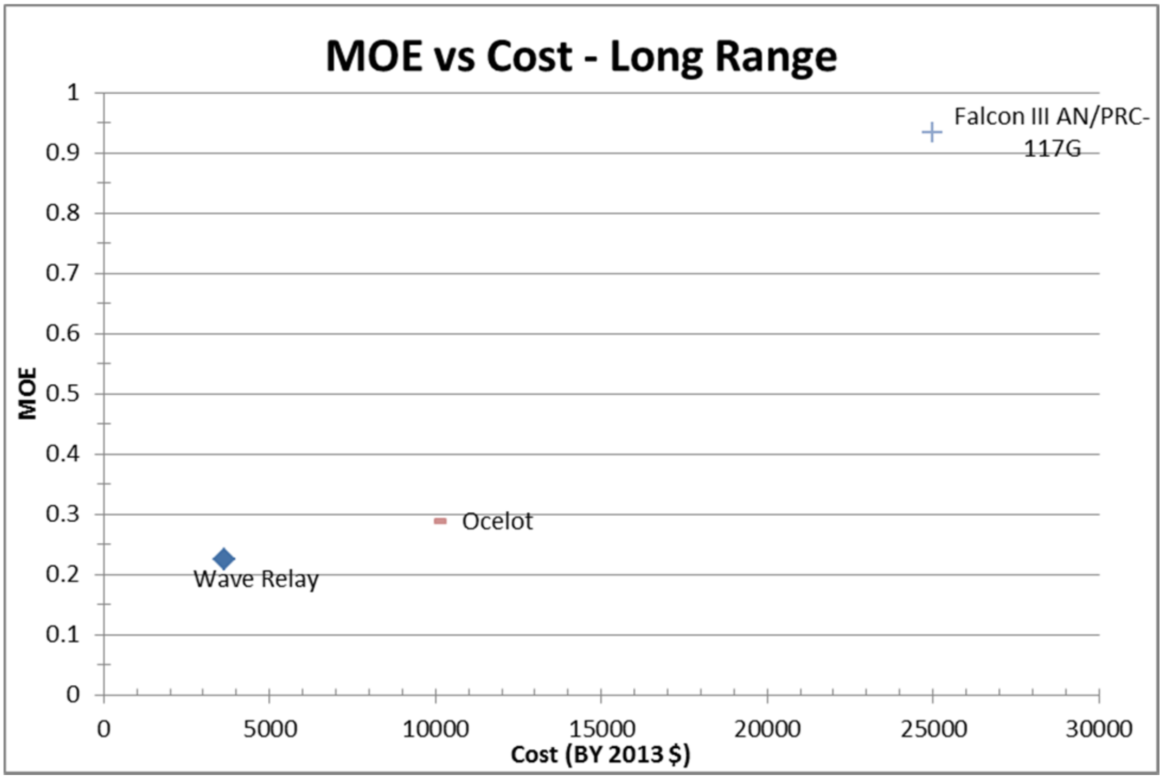

Figure 111. Communication Payload Efficient Solution–Long-Range–Logarithmic Scale

The efficient solution set includes Wave Relay, Ocelot and the Falcon III AN/PRC-117G. However, Wave Relay and Ocelot lack voice capability and both of them have less than a .3 MOE, which leads the authors to conclude that none of them are suitable alternatives for this scenario. Only the Harris Falcon III AN/PRC-117G is left as a viable alternative. For $25K, the AN/PRC-117G provides voice and data capability, 20 watts of power output and an excellent receiver sensitivity of -118 dBm. Considering this, it is no wonder the AN/PRC-117G's MOE is a very high .934 and is considered the most cost-effective communication payload the Long-Range Scenario. Next, the authors explore the compatibility of the AN/PRC-117G with the most cost-effective aerial platforms.

8. Long-Range Scenario: Solution Compatibility

From the aerial platform analysis earlier, the three identified cost-effective aerial platforms were the Predator, Reaper, and the Triton UAVs. The Predator offers an effective low cost option. The Reaper offers twice the ceiling of the Predator and a turbine engine for a reasonable increase in cost over the Predator. The Triton offers unparalleled mission effectiveness while also being the most expensive of the three options by several orders of magnitude. With that, how compatible are three UAVs with the most cost-effective communication payload: the Harris Falcon III AN/PRC-117G? Evaluating them based on power consumption and weight, all three can easily support the 12 pound, 55 watt 117G radio. See Table 36.

	Harris Falcon III AN/PRC-117G
Predator	Y
Reaper	Y
Triton	Y

Table 36. Long-Range Compatibility

C. TACTICAL USER SCENARIO

This scenario describes a tactical user, such as a small seal team or a single soldier, trying to establish communications with higher command to coordinate extract. The local terrain is mountainous and enemy resistance is in the immediate vicinity.

1. Tactical User Scenario: Mission and Environmental Conditions

The tactical user is close to completing his mission and needs to radio back to base to arrange a helicopter extract. Range between the tactical user and headquarters is 10 nautical miles. There is a 500 foot mountain blocking radio signals back to base. Enemy resistance is high locally. The tactical user lacks satellite communication capability. Additionally, the base last had contact with the tactical user 24 hours ago. No extraction plans or time of next contact had been established. The number of end users is small. The primary method of communications is UHF/VHF, but video may also be necessary. The altitude of the tactical user antenna and the base antenna are assumed to be zero to simplify calculations.

This scenario is structured so that it is generally preferable for the tactical user to have possession and control of the aerial platform, and attributes that enable the tactical user to control the aerial platform will be most important in this scenario. This scenario's conditions are summarized in Table 37.

Conditions	
Communication Relay Range	10 nm
Enemy Resistance	High level of resistance, low tech enemy
Type of threat	Small arms/RPGs
Terrain	Mountainous
Weather	High clouds
Length of communication relay mission	1 hour
Type of communication required	Voice /Data

Table 37. Tactical User Scenario Conditions

2. Tactical User Scenario: Importance Weights

Based upon the scenario conditions, the authors' importance weights for the communication payloads are listed in the hierarchy in Figure 112.

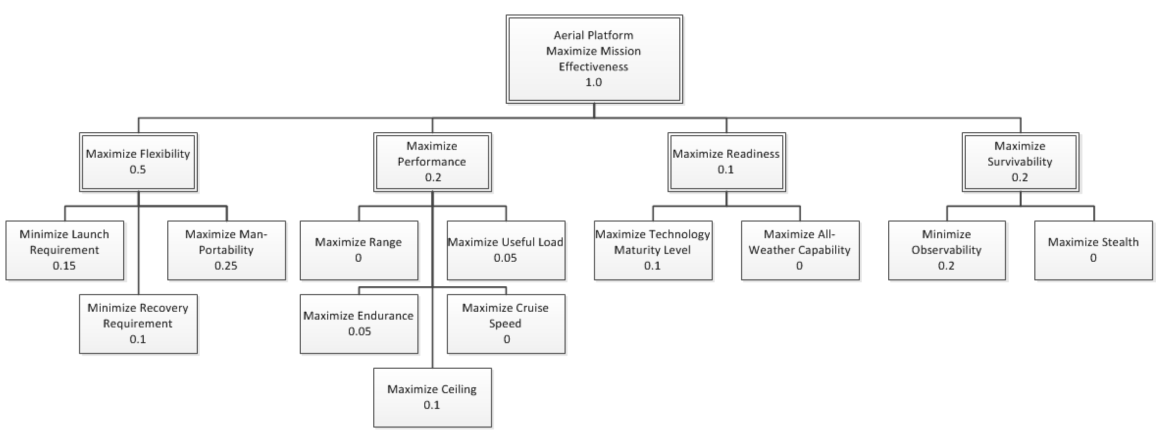

Figure 112. Tactical User Aerial Platform Importance Weights

The authors rank range and man-portability first in importance. The next two attributes in importance are survivability and launch requirement respectively. After the top three, recovery requirement, ceiling, and technology maturity level are ranked next in importance. Finally, endurance and useful load are the last two attributes to receive any importance. Man-portability, observability, launch and recovery requirements all help the tactical user to operate the aerial platform by himself without being spotted by the enemy. The launch requirement is favored over recovery requirement because completing the mission takes precedence over recovering the aerial platform. Technology maturity level is a proxy for readiness. Ceiling enables the aerial platform line of sight over the mountain. Endurance and useful load help ensure basic mission requirements are met. Range is not necessary for this mission if ceiling requirements are met. The authors assume the enemy is low tech, so stealth is not needed. Finally, no icing conditions are expected and all-weather capability is not considered important. For a breakdown of importance weights, see Figure 113.

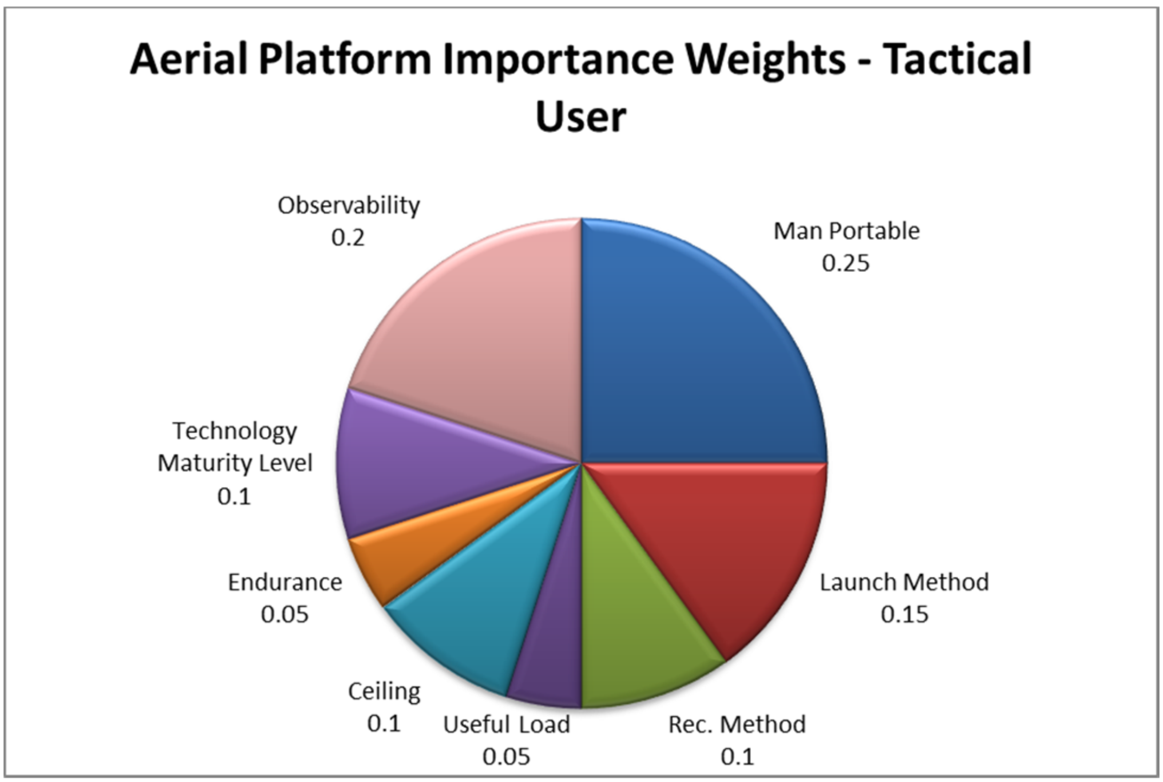

Figure 113. Tactical User Aerial Platform Importance Weights Pie Chart

3. Tactical User Scenario: Aerial Platform Value Functions

The following sections describe the aerial platform value functions used in the tactical user scenario. Value functions are listed according to their respective hierarchies. Unless otherwise noted, value functions for this scenario are derived using similar determination methods as previous scenarios.

a. Flexibility

The aerial platform flexibility hierarchy with importance weights is listed in Figure 114.

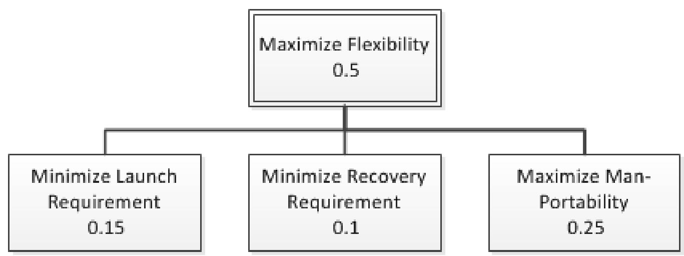

Figure 114. Aerial Platform Flexibility Hierarchy

(1) Launch Requirement. The value function for launch requirement is listed in Table 38. Values above 0.5 are given to launch methods that offer ease of launch and help the tactical user avoid detection by the enemy. Lower value methods help the nearby base launch the aerial platform without a prepared surface or runway.

Launch Requirement	Value
Catapult	0.3
Hand launch	0.8
Runway	0
Vertical	1

Table 38. Launch Requirement Value Function

(2) Recovery Requirement. The value function for recovery requirement is listed in Table 39. Similar to the launch requirement value function, values above 0.5 are given to methods that allow ease of recovery and help the tactical user avoid detection by

the enemy. Lower value methods help the base recover the aerial platform without a prepared surface or runway.

Recovery Requirement	Value
Deep Stall	0.8
Vertical Wire/Arrestment	0.3
Runway	0
Vertical	1

Table 39. Recovery Requirement Value Function

(3) Man-Portability. The value function for man-portability is listed in Table 40.

Man-Portability	Value
Yes	1
No	0

Table 40. Man-Portability Value Function

b. Performance

The aerial platform performance hierarchy with importance weights is listed in Figure 115.

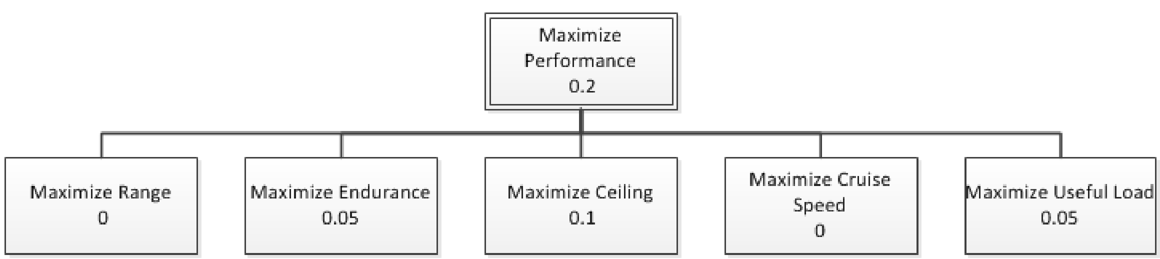

Figure 115. Aerial Platform Performance Hierarchy with Importance Weights

(1) Endurance. The duration of the communication relay mission is used to derive the endurance value function, which is shown in Figure 116.

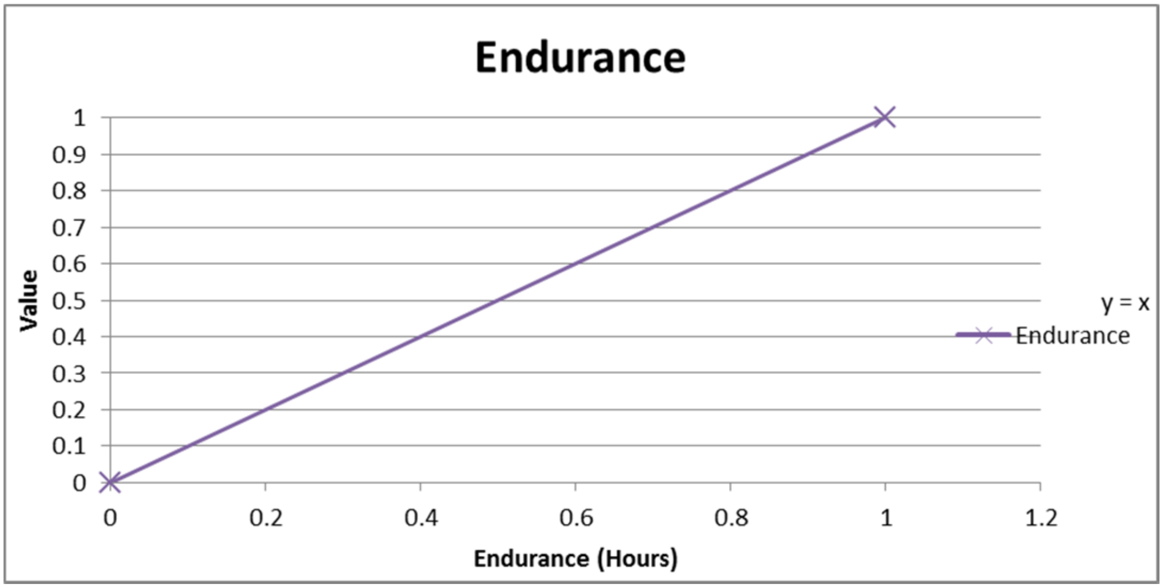

Figure 116. Endurance Value Function

(2) Ceiling. The ceiling value function is designed to help ensure line of sight above the nearby 500 ft mountain. See Table 41.

Ceiling	Value
≥ 1000 ft	1
< 1000 ft	0

Table 41. Ceiling Value Function

(3) Useful Load. The useful load value function is depicted in Figure 117.

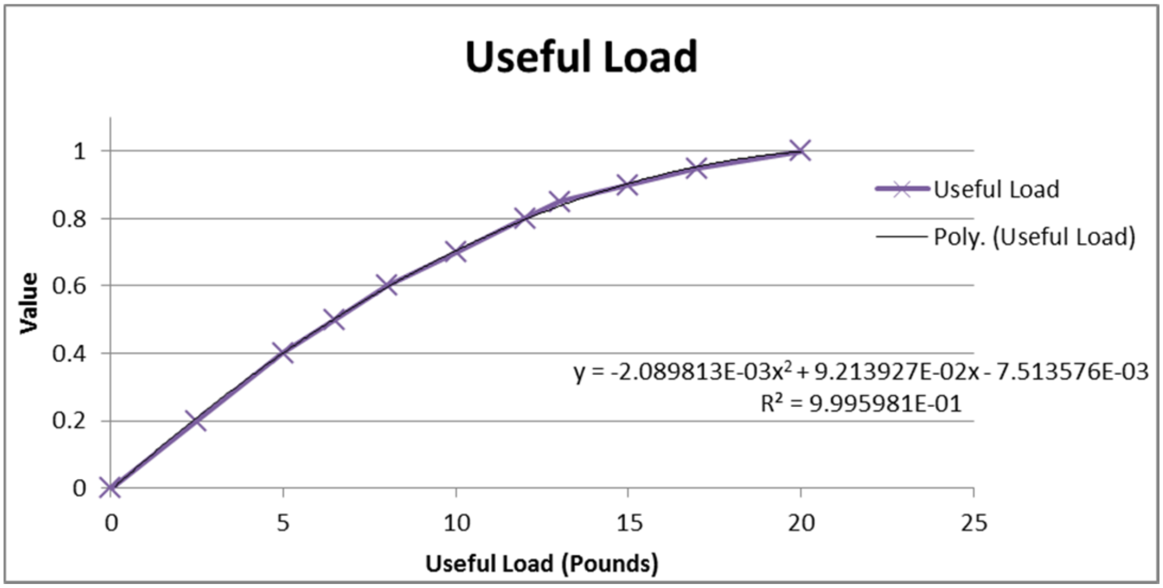

Figure 117. Useful Load Value Function

c. Readiness

The aerial platform readiness hierarchy with importance weights is listed in Figure 118.

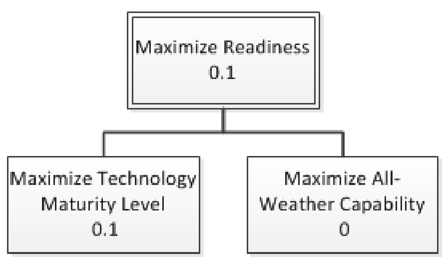

Figure 118. Aerial Platform Readiness Hierarchy with Importance Weights

(1) Technology Maturity Level. Technology maturity level remains the same from the HADR scenario and is not discussed here. For more information, refer to Figure 67.

d. Survivability

The aerial platform survivability hierarchy with importance weights is listed in Figure 119.

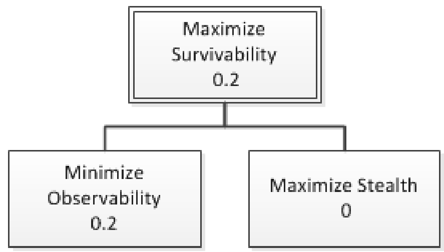

Figure 119. Aerial Platform Survivability Hierarchy

(1) Observability. A linear function is used for observability's value function as depicted in Figure 120.

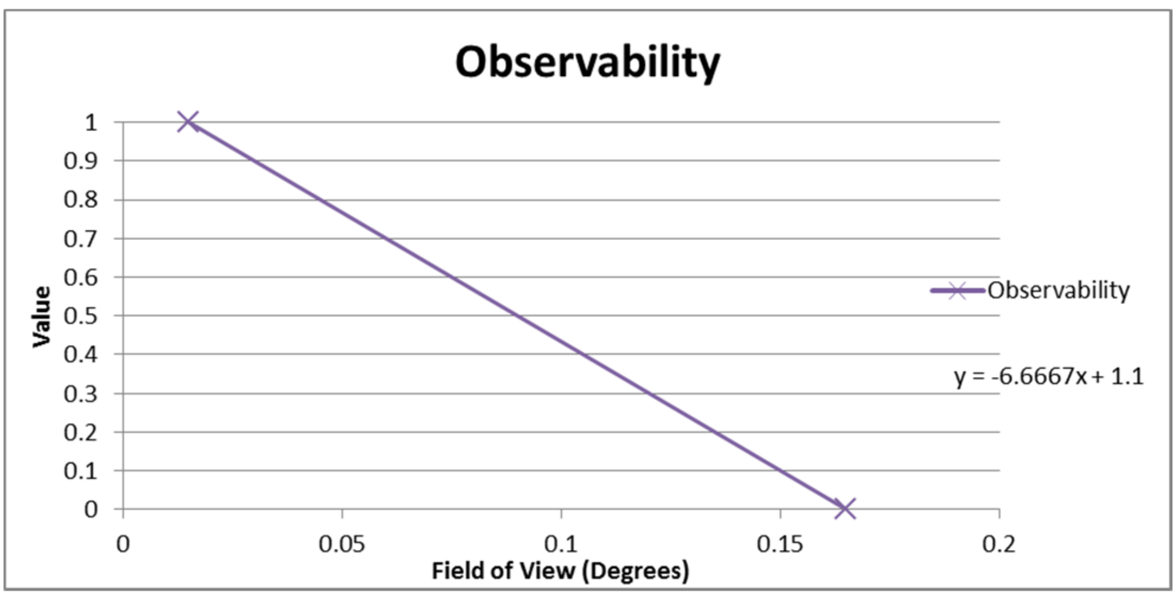

Figure 120. Observability Value Function

4. Tactical User Scenario: Aerial Platform Cost-Effective Solutions

The authors show the cost-effectiveness of each aerial platform in Figure 121.

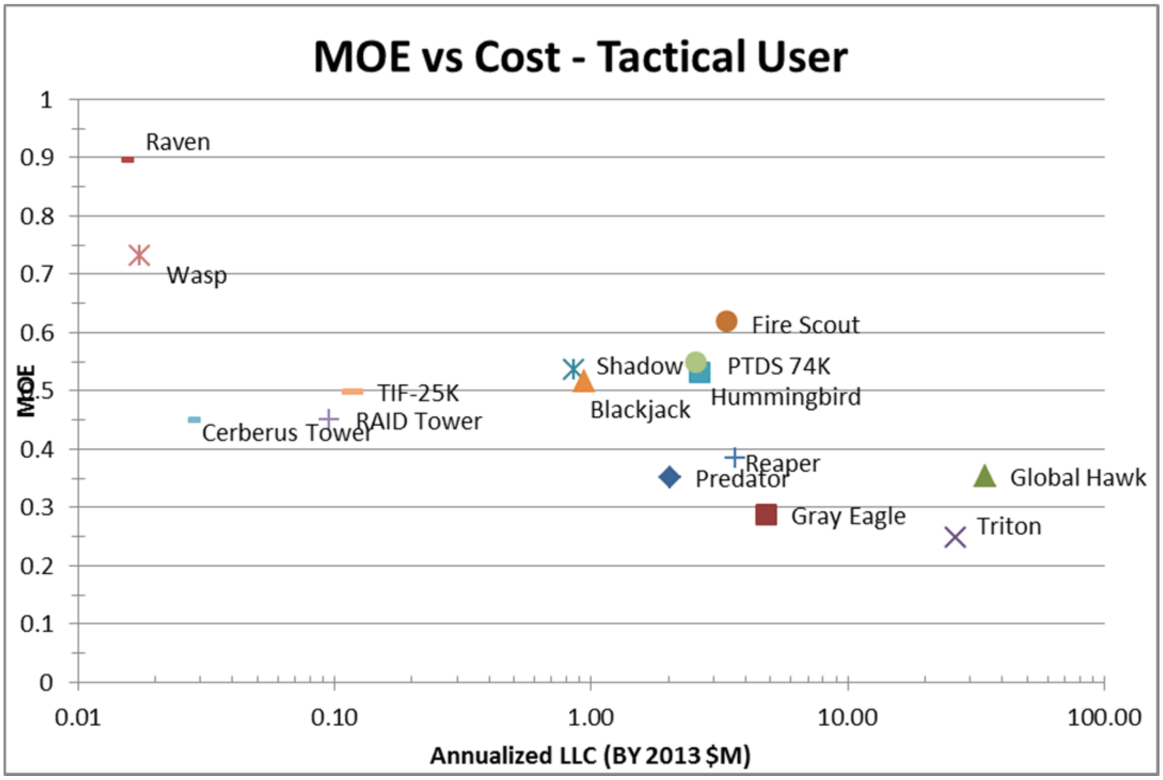

Figure 121. Aerial Platform Cost Effectiveness–Tactical User–Logarithmic Scale

The cost-effectiveness graph shows that the Raven UAV appears to be a superior solution for the tactical user scenario. As discussed in Chapter III, a superior solution is when an alternative has both a higher MOE and a lower cost than any other alternative. The Raven costs less and has a higher MOE than all other alternatives. The only other alternative whose effectiveness and cost are even comparable to the Raven is the Wasp III UAV.

The Wasp III is actually more portable than the Raven due to its smaller size and less weight and is less observable than the Raven. The Raven has more useful load, a better range, and longer endurance than the Wasp III. Based on the authors' value functions and importance weights, the Raven is more effective and less expensive than the Wasp III. Another decision maker may determine observability and portability are more important relative to the other objectives than ascertained in this thesis. In that case, the Wasp III may be judged more effective than the Raven. Next, the authors examine the most cost-effective communication payloads for this scenario.

5. Tactical User Scenario: Communication Payload Importance Weights

Based upon the scenario conditions, the authors' importance weights for the communication payloads are listed in the hierarchy in Figure 122.

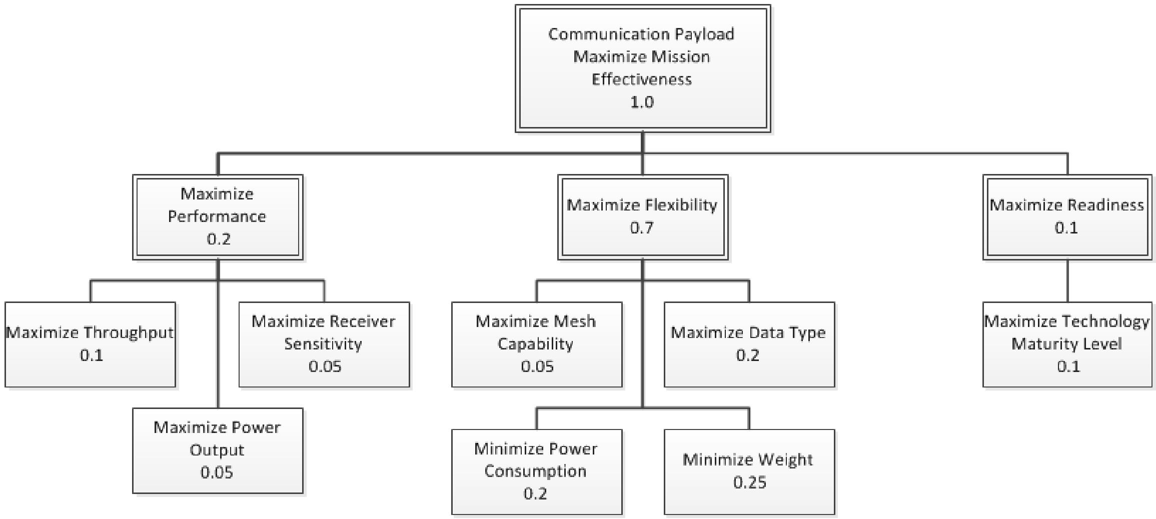

Figure 122. Tactical User Communication Payload Hierarchy with Importance Weights

In this scenario, the authors consider weight the most important attribute of the communication payload. Traffic type and power consumption are next most important. Weight and power consumption help ensure a smaller aerial platform that is more portable can carry the communication payload. Traffic type is necessary to ensure compatibility between the two nodes. Throughput and technology maturity level are ranked next after the top three attributes. Throughput allows the tactical user some ability to transmit or receive video. Technology maturity level represents readiness, which is always important. Power output, receiver sensitivity, and mesh capability are ranked next. Power output and receiver both help determine communication range. Mesh capability allows for some flexibility in the network that could help the tactical user. Importance weights are broken down by relative sizes in Figure 123.

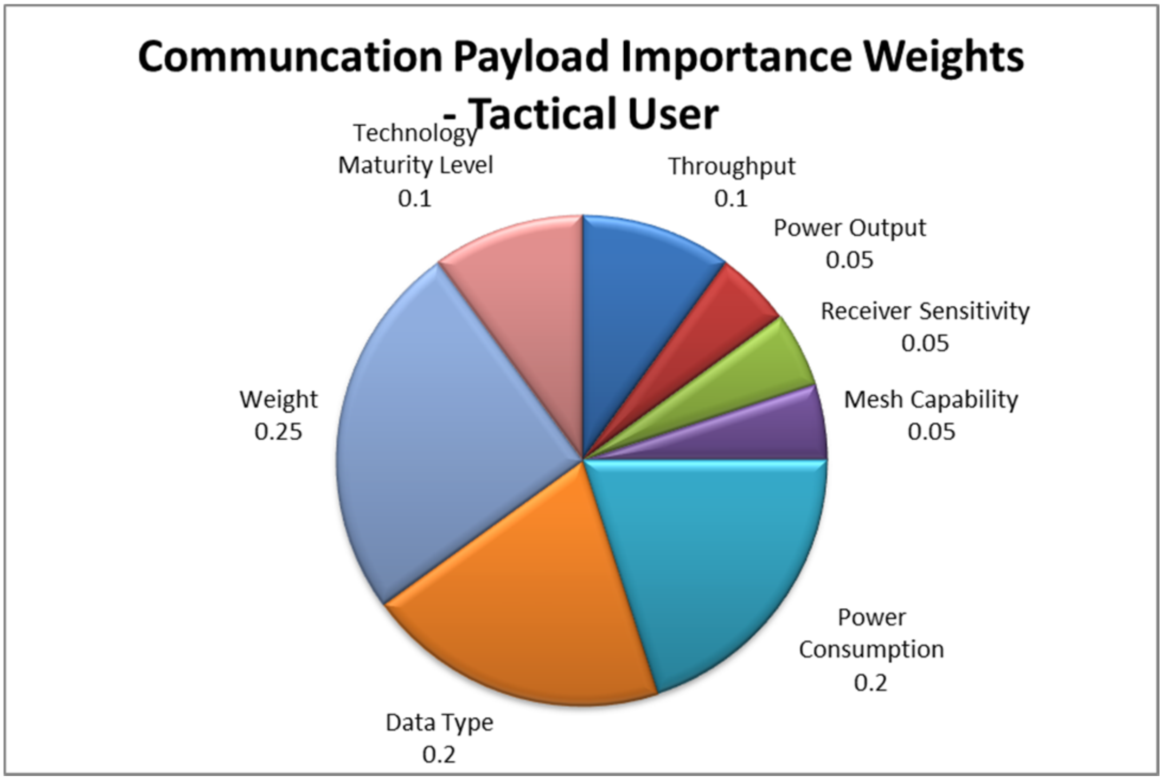

Figure 123. Tactical User Communication Payload Importance Weights Pie Chart

6. Tactical User Scenario: Communication Payload Value Functions

The following sections describe the communication payload value functions used in the tactical user scenario. Value functions are listed according to their respective hierarchies. Unless otherwise noted, value functions for this scenario are derived using similar determination methods as previous scenarios. Value functions assigned zero importance weights are not discussed.

a. Performance

The communication payload performance hierarchy with importance weights is listed in Figure 124.

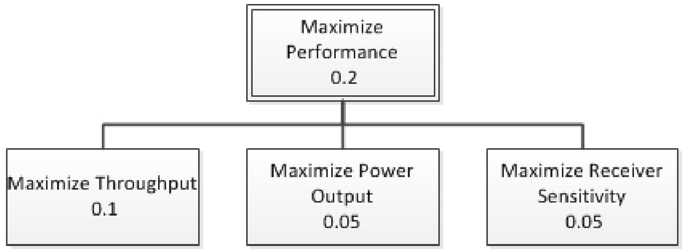

Figure 124. Communication Payload Performance Hierarchy with Importance Weights

(1) Throughput. The throughput value function is depicted in Figure 125.

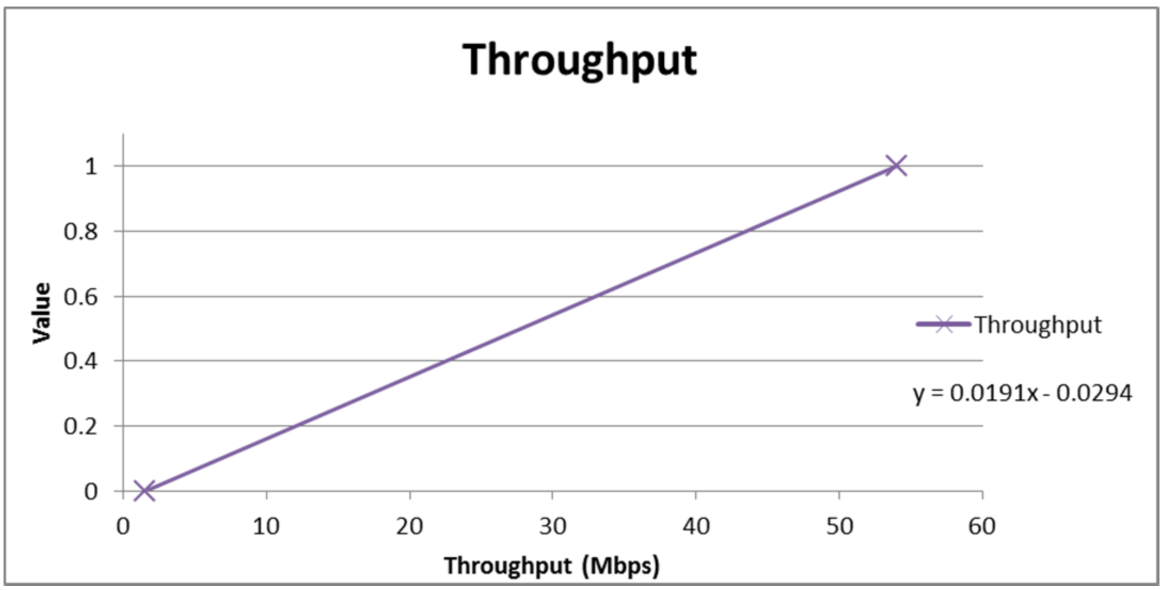

Figure 125. Throughput Value Function

(2) Power Output. The power output value function is shown in Figure 126.

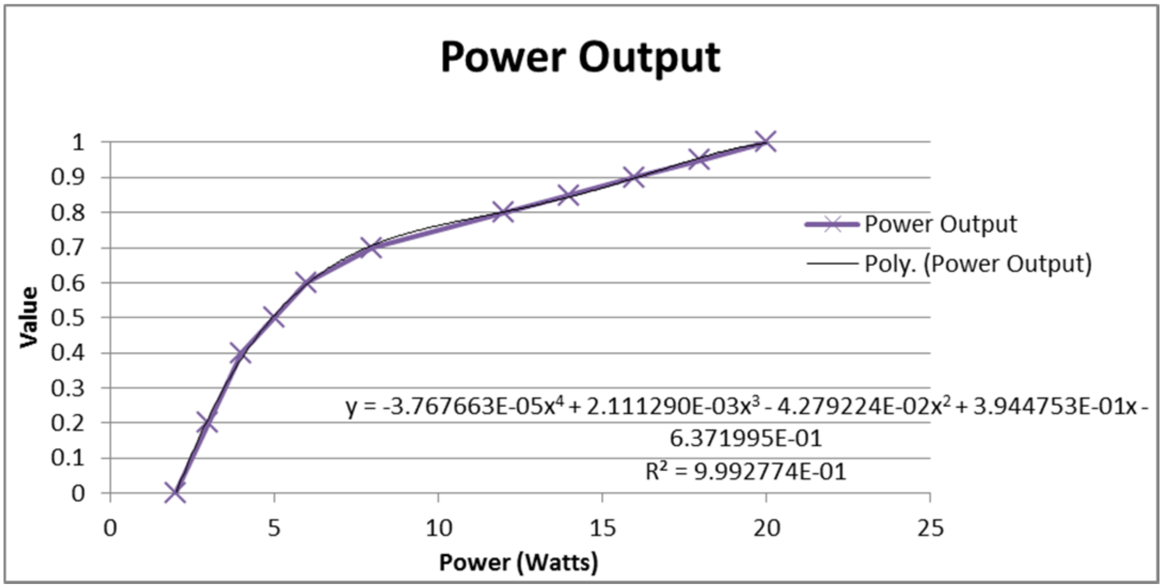

Figure 126. Power Output Value Function

(3) Receiver Sensitivity. The receiver sensitivity value function remains unchanged from previous scenarios and it is not discussed. For more information, refer to Figure 80.

b. Flexibility

The communication payload flexibility hierarchy with importance weights is listed in Figure 127.

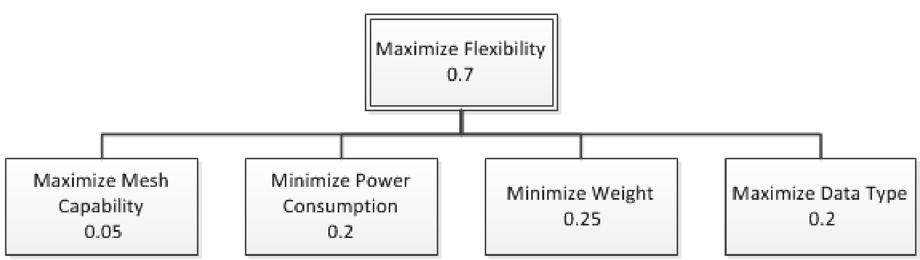

Figure 127. Communication Payload Flexibility Hierarchy with Importance Weights

(1) Mesh Capability. The mesh capability value function is shown in Table 42.

Mesh	No	Yes
Assigned Value	0	1

Table 42. Mesh Capability Value Function

(2) Power Consumption. The power consumption value function is shown in Figure 128.

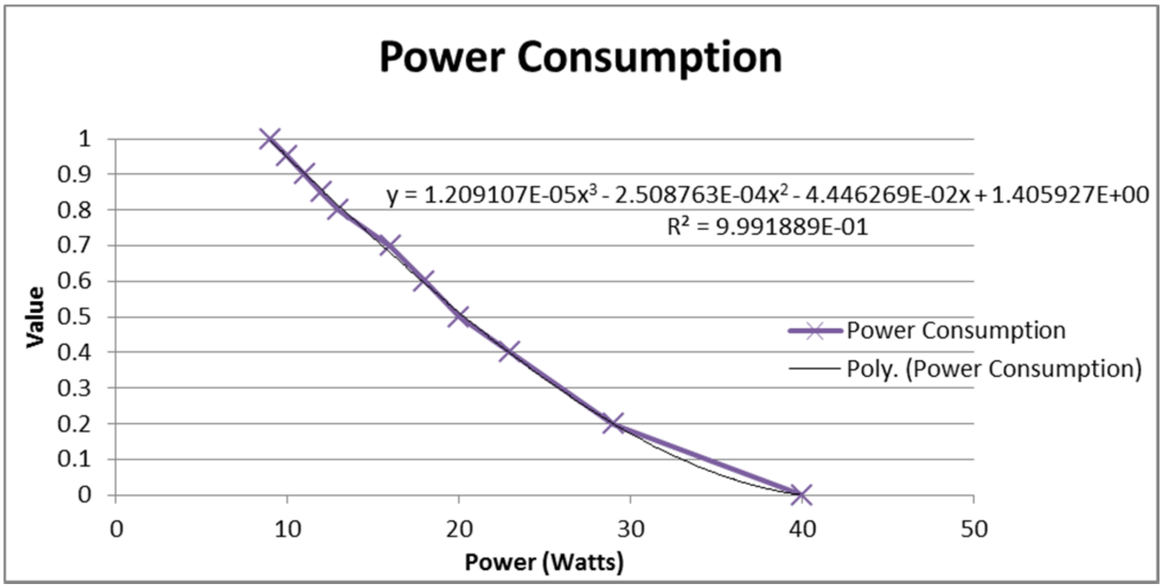

Figure 128. Power Consumption Value Function

(3) Weight. The weight value function is listed below in Figure 129.

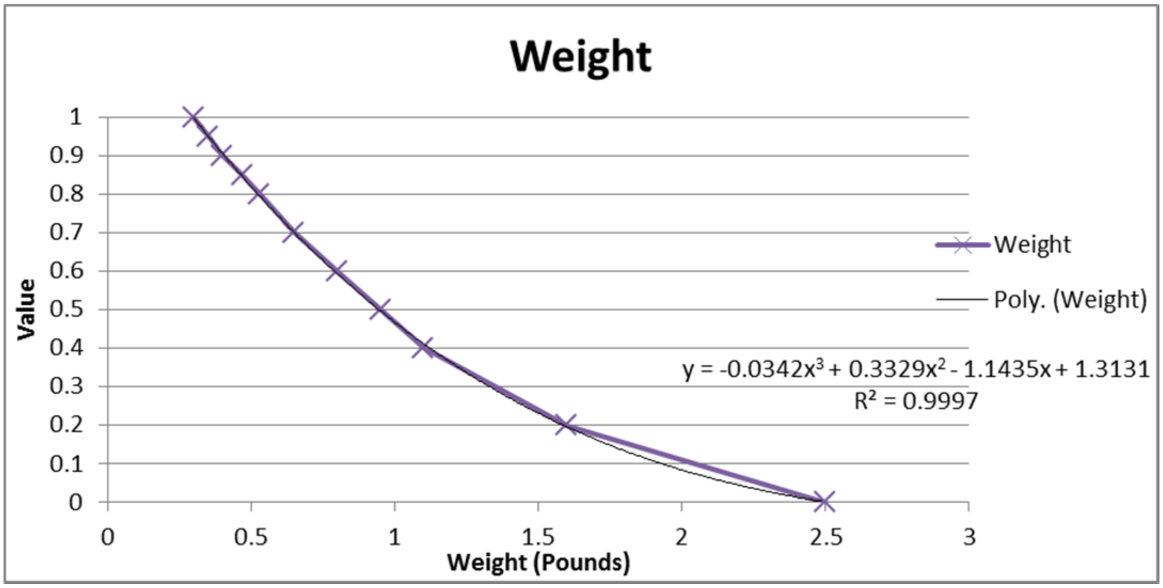

Figure 129. Weight Value Function

(4) Traffic Type. The traffic type value function is shown in Table 43.

Traffic type	Voice	Data Only	Voice/Data
Assigned Value	.5	.7	1

Table 43. Traffic type Value Function

c. Readiness

The Communication Payload readiness hierarchy with importance weights is listed in Figure 130.

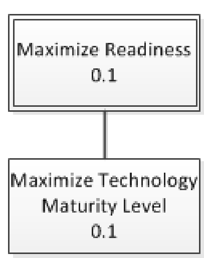

Figure 130. Communication Payload Readiness Hierarchy with Importance Weights

(1) Technology Maturity Level. The technology maturity level value function remains the same from the previous scenario. For more information, refer to Figure 83.

7. Tactical User Scenario: Communication Payload Cost-Effective Solutions

The authors show the cost-effectiveness of the communication payloads for the tactical user scenario in Figure 131.

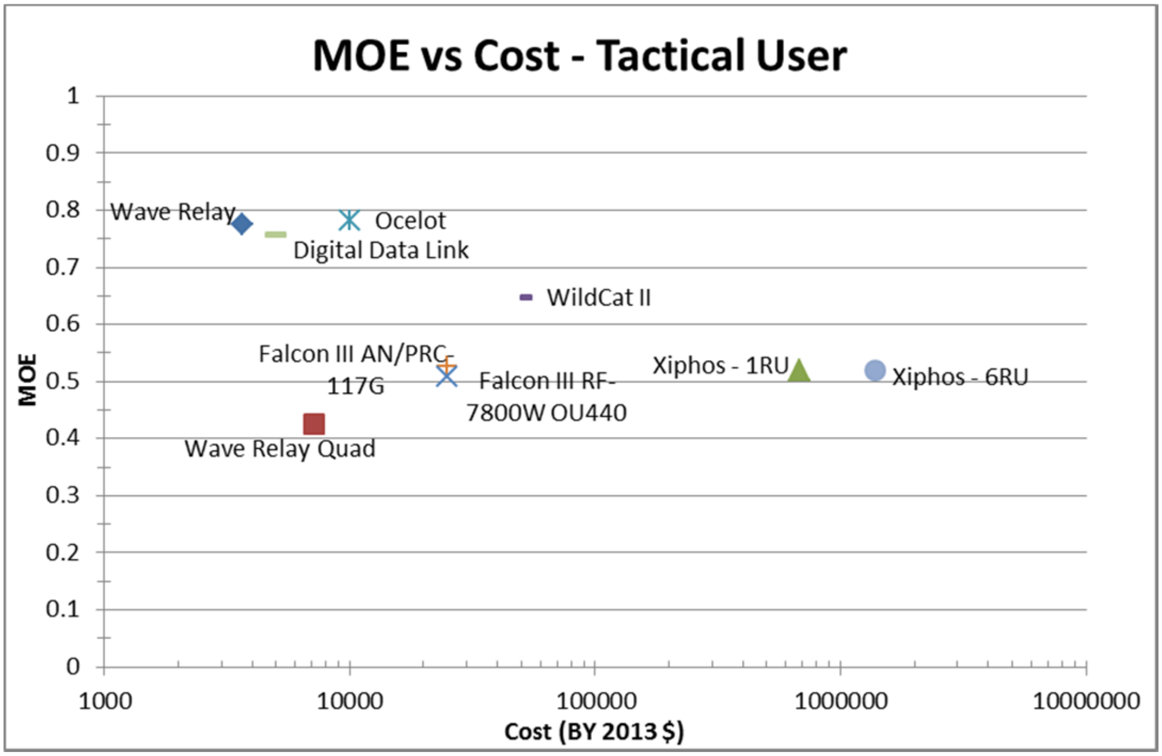

Figure 131. Communication Payload Cost Effectiveness–Tactical User–Logarithmic Scale

The efficient solution using a linear scale is shown in Figure 132.

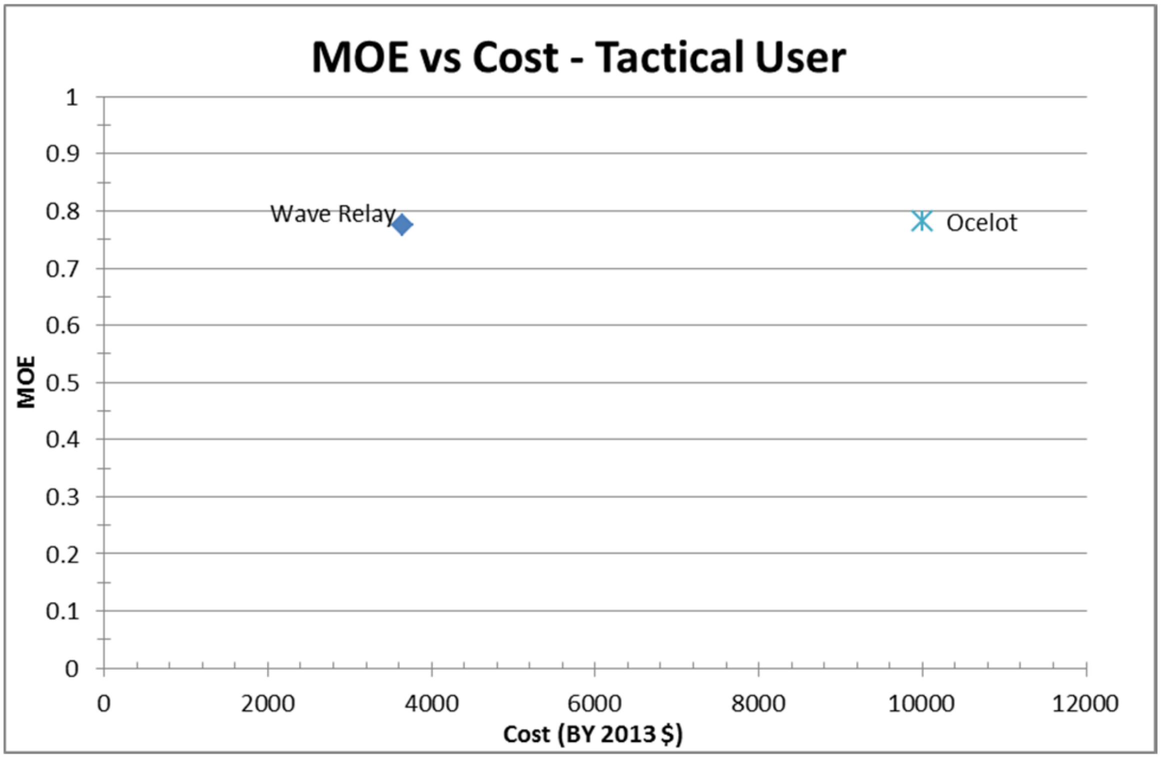

Figure 132. Communication Payload Efficient Solution–Tactical User–Linear Scale

The efficient solution set includes the Wave Relay and the Ocelot. Each radio possesses low weight and mesh capability. The Ocelot scores significantly better than Wave Relay in power consumption and receiver sensitivity. Alternatively, the Wave Relay performs much better than the Ocelot in throughput. Focusing on MOE, the Ocelot scores only .01 higher than the Wave Relay radio, however it costs nearly three times as much. The authors decide that despite the difference in cost, there could be situations where either radio could be advantageous. The authors choose to include both the Ocelot and the Wave Relay as the most cost-effective communication payloads for this scenario. Next, the authors examine the compatibility of the Ocelot and Wave Relay with the Raven UAV.

8. Tactical User Scenario: Solution Compatibility

The Raven has a useful load of 6.5 ounces or 184 grams, which can easily accept the weight of the Ocelot at about 85 grams or the Wave Relay card at 96 grams. However, with additional wiring, dedicated battery and antenna, either the Ocelot or

Wave Relay could exceed the Raven's useful load, which could result in degraded performance of the airframe. Additionally, even though both communication payloads possess a small form factor, the payload compartment of the Raven may not be able to support either radio. In a previous NPS study, a Raven was tested with a Wave Relay payload. However, the Wave Relay radio had to be taped onto the outside of the UAV instead of being secured inside the payload compartment, which is not ideal for performance of the UAV or the communication link (Menjivar, 2012). The authors cannot conclude that the Ocelot or Wave Relay communication payloads are compatible with the Raven.

One communication payload that would work with the Raven is AeroVironment's DDL. AeroVironment offers the DDL with the Raven B UAV from the factory. DDL's price is positioned between the Wave Relay and the Ocelot at $5,000, but it has a slightly lower MOE than either one at .757. However, compatibility between the DDL and the Raven is assured, whereas the Ocelot and the Wave Relay units needs further testing to ensure compatibility. See Table 44.

	Ocelot	Wave Relay	DDL
Raven	Unknown	Unknown	Yes

Table 44. Tactical User Compatibility

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V. CONCLUSION

A. SUMMARY OF FINDINGS

This study utilizes a multi-objective analysis to analyze and compare the cost-effectiveness of 15 aerial platforms and 9 communication payloads. Three scenarios cover a variety of requirements across different mission sets. The steps to a multi-objective analysis are:

1. Create an objectives hierarchy that lists all the desirable goals or attributes
2. Create value functions for each attribute
3. Assign importance weights to each attribute
4. Plot MOE vs cost to help the decision maker identify the most cost-effective solutions using satisficing, efficient, and superior solutions
5. Evaluate the solution for feasibility

In the first scenario, a HADR situation is presented which requires long endurance and high bandwidth capability. The most cost-effective aerial platforms are the TIF-25K aerostat and the Predator UAV. The TIF-25K aerostat combines endurance measured in week and a high useful load with a moderate ceiling. Additionally, the TIF-25K can utilize a tether to power its payloads from the ground. The Predator is a very capable UAV platform with a relatively long endurance, long range, and reasonable cost of ownership. The most cost-effective communication payloads are the two configurations of the Oceus Networks Xiphos (1RU and 6RU), due to their high throughput, power output, and excellent scalability. Additionally, because the two radio units are based on LTE cellular base stations, they allow users to bring their own devices to interface directly. However, the Oceus Networks Xiphos radio can be relatively heavy (78 lbs to 276 lbs depending on configuration) and power hungry (855 to 3275 watts depending on configuration). The chosen solution for this scenario was a TIF-25K aerostat with a Xiphos 6RU connected to ground power or a Predator with a Xiphos 1RU configuration.

In the second scenario, a long-range relay is needed to connect users across a 340 nm range, which required a minimum altitude of 19,102 feet due to radio horizon, and

UHF capability. The most cost-effective aerial platforms are the Predator, Reaper, and Triton. Due to its UHF capability, sensitivity, and power output, the Harris Falcon III AN/PRC-117G is the most cost-effective communication payloads. Each of the three aerial platforms could be the best choice, depending on the decision maker's preference for price (Predator), better altitude and performance (Reaper), or outstanding performance and deicing capability (Triton). The extra performance and capability of the Triton comes with a much higher ownership cost than the Predator or Reaper.

In the final scenario, a covert, tactical situation is presented where portability is preferred. The most cost-effective aerial platform is the Raven, which combined man-portability and adequate range and endurance with the lowest cost of any aerial platform in this study. The Ocelot and the Wave Relay are the most cost-effective communication payloads for this scenario. Ocelot is a small form factor radio unit with a low weight, low power consumption and good receiver sensitivity. Wave Relay possesses low weight and relatively high throughput for its small form factor, and it is the cheapest communication payload considered in this study. However, compatibility between the Raven and Ocelot or Wave Relay cannot be confirmed at this time. However, the slightly less effective and medium priced DDL is definitely compatible with the Raven and can be considered an acceptable solution in the interim until more compatibility testing can be completed between the Raven and the Ocelot and Wave Relay communication payloads.

B. FUTURE RESEARCH

The preceding analysis and conclusions rely on a number of assumptions. Some of the assumptions may not be valid and future research is needed to test the validity of these assumptions. Other areas opportunities for future research are discussed below.

1. Technical and Operational Research

In this study, the authors assess compatibility between the most cost-effective aerial platforms and communication payloads within each scenario based on manufacturer's provided specifications. Actual field testing would provide a proof of concept and help validate the findings of this study. Other technical research of interest includes:

- Analysis of the challenges facing very long endurance UAVs with mission durations ranging from one week to 5 years
- Study of observability for different types of UAVs, aerostats, and untethered balloons, including visible and acoustic signatures
- Antennas for aerial platforms to enhance VHF, UHF and data communications
- Effects of enemy actions on UAV operations including hacking operations and jamming
- Mishap rates for small UAVs and aerostats
- The effectiveness of stealth UAVs and whether nearly continuous radio and connectivity requirement of UAVs render stealth moot against a sophisticated enemy.
- Best practices of UAVs against a sophisticated enemy where air superiority is not assured
- Availability of UAVs and communication radios reliability data, including mean time to repair (MTTR), mean time between failures (MTBF), and average turn–around times
- Feasibility of using free-flight balloons for ISR and communication relay platforms

2. Cost Analysis

Since complete, transparent, and reliable cost data was not always available, further research of the fully captured costs for UAVs, military towers, and aerostats would enable a more accurate and detailed analysis.

The authors received a request from a stakeholder within the U.S. Marine Corps to analyze and determine the individual cost per hour of UHF over-the-horizon communications among a range of alternatives. Additionally, the authors received a request to assess the cost effectiveness of multi-hop aerial relays utilizing multiple, less capable and less expensive, UAVs and communication payloads to achieve similar results to a more expensive UAV and communication payload that requires traditional satellite guidance. These topics were outside the scope of this research; however, they deserve their own dedicated research in the authors' judgment.

3. Multi-Objective Analysis

This study focused on the communications relay mission. Different missions, such as ISR, would present an interesting and useful subject for future research. Additionally, within the communication relay mission, future research could utilize different scenarios to assess different capabilities of each aerial platform and communication payload.

The authors utilized a sample set of aerial platforms and suitable communication platforms for this study. However, many more alternatives were originally considered, but a lack of reliable data forced the authors to exclude these alternatives. Different alternatives, such as foreign-made UAVs, could enhance the analysis and help identify an even more cost-effective solution. In the following sections, the authors list 5 categories of aerial platforms that offer unique capabilities or could provide exceptional value.

a. HALE UAVs

UAVs such as Titan Aerospace's Solara 50 and 60, AeroVironment's Global Explorer and Boeing's Phantom Eye are new UAVs that offer intriguing HALE options for the DoD at potentially reasonable costs. Civilian companies are expressing interest in these UAVs, and social media giant Facebook is rumored to be targeting the company Titan Aerospace for acquisition (Perez & Constine, 2014). Facebook wants to connect rural parts of the world using Solara 50s and 60s as shown in Figure 133. HALE UAVs offer persistent, satellite-like coverage over a geographic area, but unlike satellites, they can be repositioned, repaired, and re-tasked. Compared to currently available HALE UAVs like the Global Hawk and Triton, these new UAVs offer much longer endurance with a potential cost savings.

Figure 133. Solara 50 (from Perez & Constine, 2014)

b. Small UAVs

AeroVironment and other companies are creating more capable small UAVs. The Puma AE and Wasp III's younger sibling, the Wasp AE, offer all -weather capability and increased payloads with similar portability and cost to the smaller Raven and Wasp III. The Puma AE is shown in Figure 134. The Wasp AE, with longer endurance than the original Wasp, is shown in Figure 135. Because these smaller UAVs are much cheaper, more portable, and require less support than larger UAVs, small teams can operate them, thereby delegating control to the lowest levels of command allowing more effective and timely use of their capabilities and force-multiplying effects.

Figure 134. Puma AE (from AeroVironment, 2013)

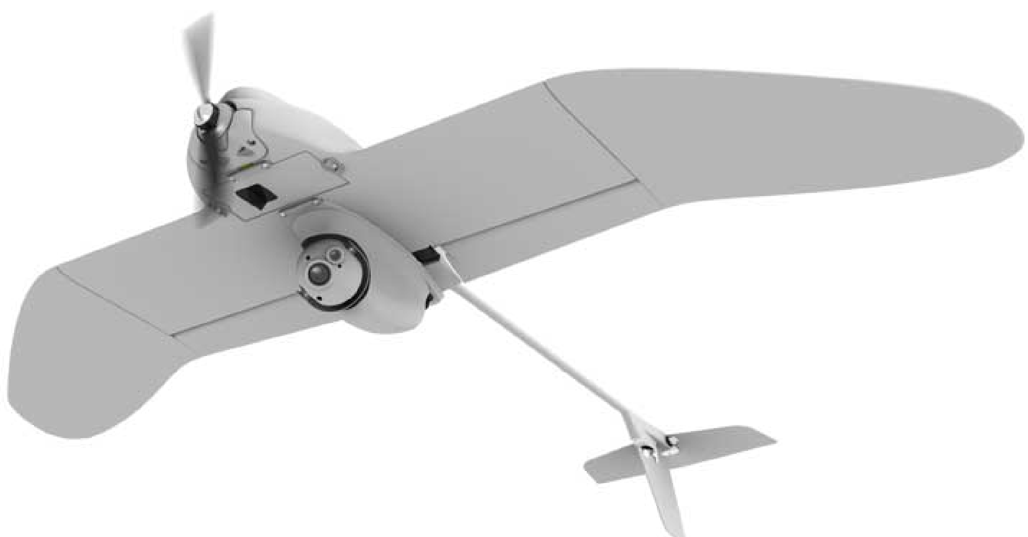

Figure 135. Wasp AE (from AeroVironment, 2013)

c. *Multi-rotor UAVs*

Another growing area is multi-rotor UAVs. The corporate world is starting to see the potential of these aircraft. Amazon recently announced that it plans to implement a delivery system utilizing autonomous multi-rotor vehicles (Amazon.com, 2014) as shown in Figure 136. A multi-rotor craft mounted on a Humvee could be useful, and the multi-rotor UAV could utilize a tether to power and control it, as well as pass data back and forth. A craft such as this could provide ISR as well as a communication relay simultaneously for convoy operations or threat detection. The multi-rotor could stay airborne for long periods of time because it is not utilizing onboard power. Additionally, it may even be able to follow the movement of the Humvee; therefore it would not have to be recovered if the Humvee needed to move.

Figure 136. Amazon Prime Air (from Amazon.com, 2014)

d. Untethered Balloons

Experiments are being conducted with untethered balloons that carry communication payloads to the edges of the atmosphere to provide UHF/VHF and data connectivity to supported units. The commercial sector is utilizing these balloons to provide a source for low cost broadband to rural areas (Google, 2014). While balloons do not have traditional steerage methods, they can be commanded to climb and descend to take advantage of different air streams in the upper atmosphere, thereby allowing them to stay aloft over a position for longer periods of time. Typically, their useful life is limited to the battery powering the communication payload. Based on conversations with experts, untethered balloons can provide satellite-like coverage over a designated area for 8-12 hours for less than $20,000 without steering the balloon. If the balloon and payload can be recovered after the flight, the payload can be reused which reduces costs even more.

e. Taller Towers

The towers included in this study were not tall enough to provide an effective solution for any of the scenarios presented in this study. However, if taller towers were considered, they may have provided a very competitive and cost-effective alternative to the other aerial platforms included in this study.

C. RESEARCH CONTRIBUTIONS

This research offers a framework for comparing the cost-effectiveness of dissimilar aerial platforms and communication payloads across different mission sets. It presents two hierarchies that group attributes important for the communication relay mission. It includes 12 attributes by which to evaluate aerial platforms and 8 attributes by which to evaluate communication payloads.

These individual evaluations are combined to examine feasibility of the different alternatives. This research develops value functions and weighting parameters that change based upon mission requirements and are easily adapted to other mission sets including the traditional ISR mission. This research analyzes the total LCC for aerial platforms in order to compare platforms with varying lifespans.

The authors provide a careful cost-effectiveness of the aerial platforms and communication payloads where the question is answered as to whether it is worth spending more money to achieve more effective solutions. The most cost-effective solutions are identified for three distinct mission environments and instructions are offered for future decision makers to replicate this CEA using their own preferences and mission requirements.

APPENDIX A. DETAILED HIERARCHIES

This appendix offers an enlarged, landscape view of the hierarchies depicted in the main body of this work. Figures 137, 138, and 139 are provided.

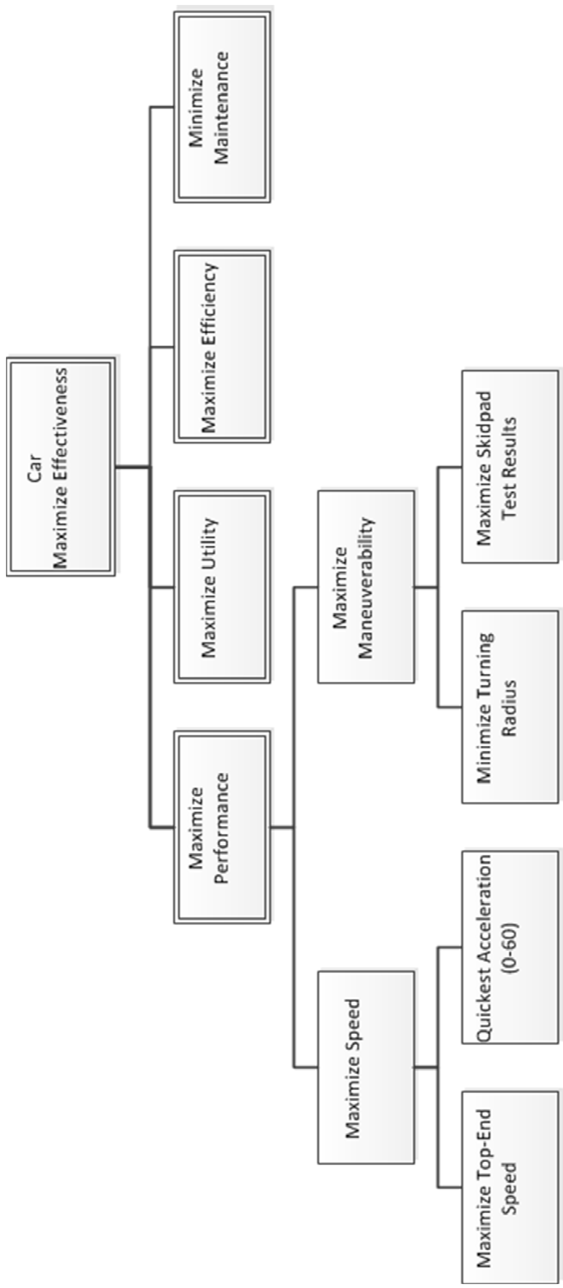

Figure 137. Enlarged Car Effectiveness Hierarchy

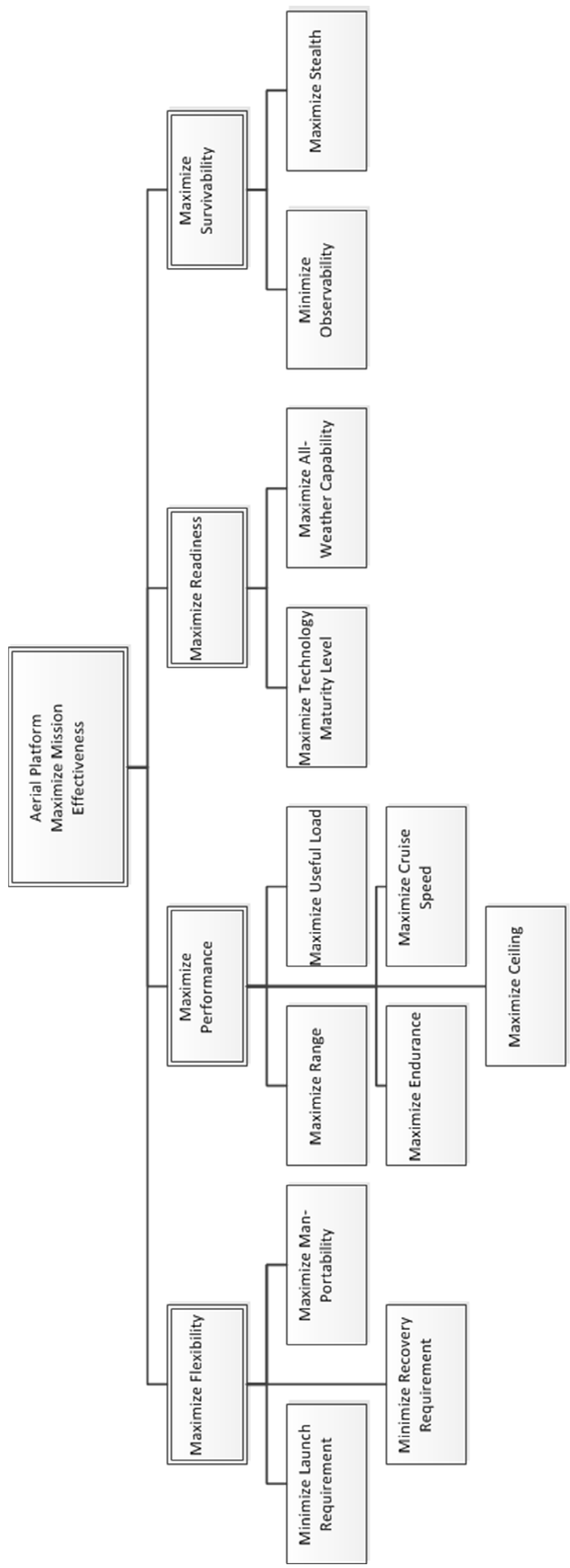

Figure 138. Enlarged Aerial Platform Effectiveness Hierarchy

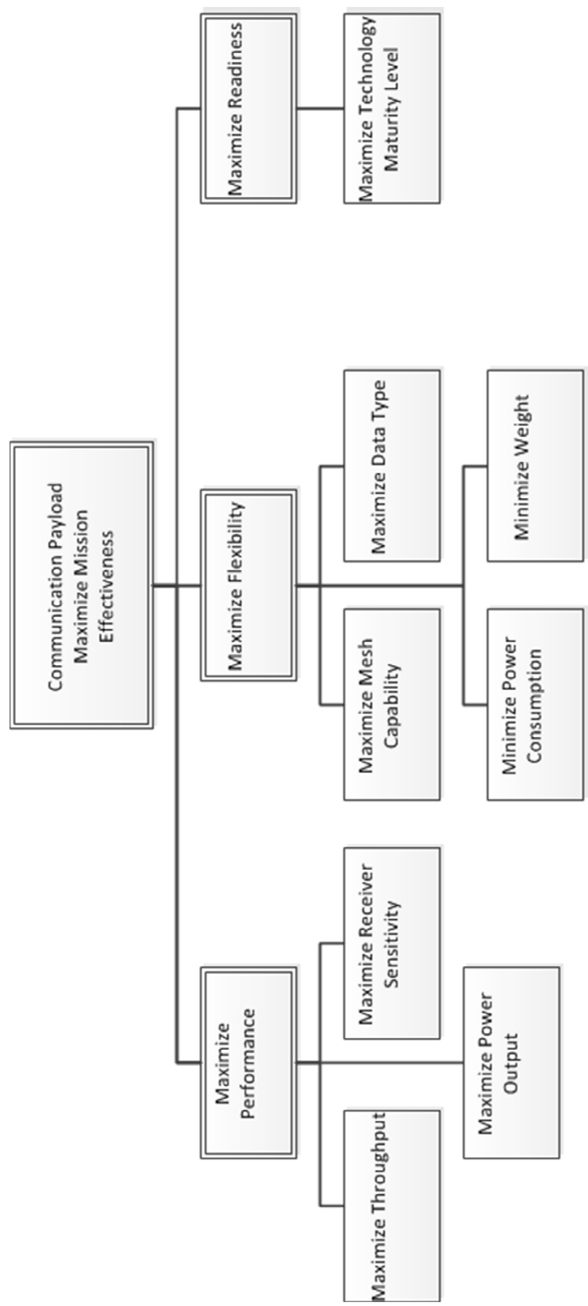

Figure 139. Enlarged Communication Payload Effectiveness Hierarchy

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APPENDIX B. APPROXIMATING VALUE FUNCTIONS IN EXCEL

The first steps to approximating a function are to plot the points of the value function, add a trend line and then cycle through different regression types using Excel's built in functionality. The process is depicted in Figure 140. Initially, the trend line provided by Excel does not resemble the authors' desired function, so different polynomial equations are examined for best fit.

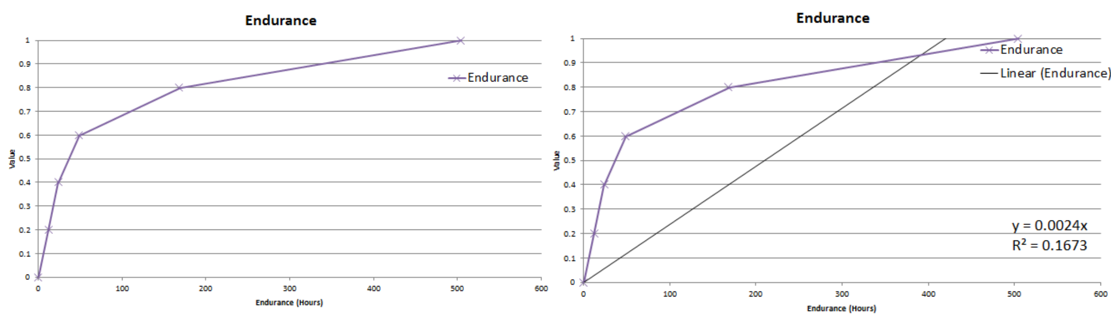

Figure 140. Discrete Values and Linear.

Additional data points are added into the authors' value function to improve the regression's congruence as shown in Figure 141. The fit of the trend line improves as more points are added to the function.

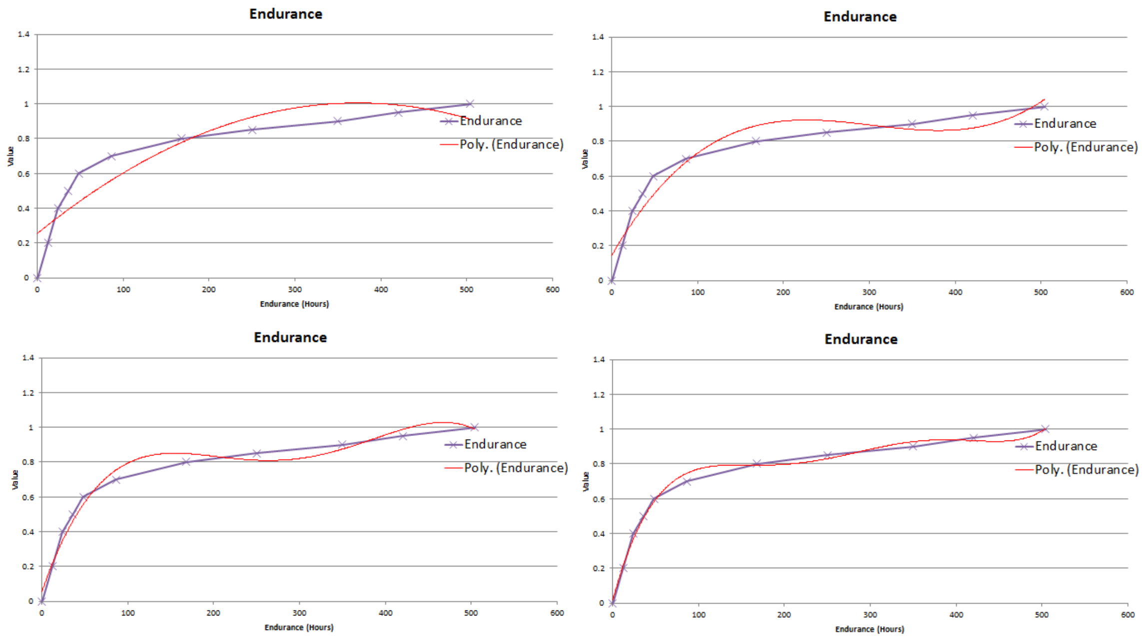

Figure 141. 2nd through 5th Order Polynomial best fit lines starting top Left and Moving Counterclockwise

In this case, each increase in polynomial order improves the fit of the trend line to the original value function. However, even the 5th order polynomial equation peaks too early.

A 6th order polynomial equation produces a trend line that meets the authors' expectations for the original endurance value function, as depicted in Figure 142. The purple line shows the original points for the value function and the red polynomial line shows the line generated by the 6th order equation.

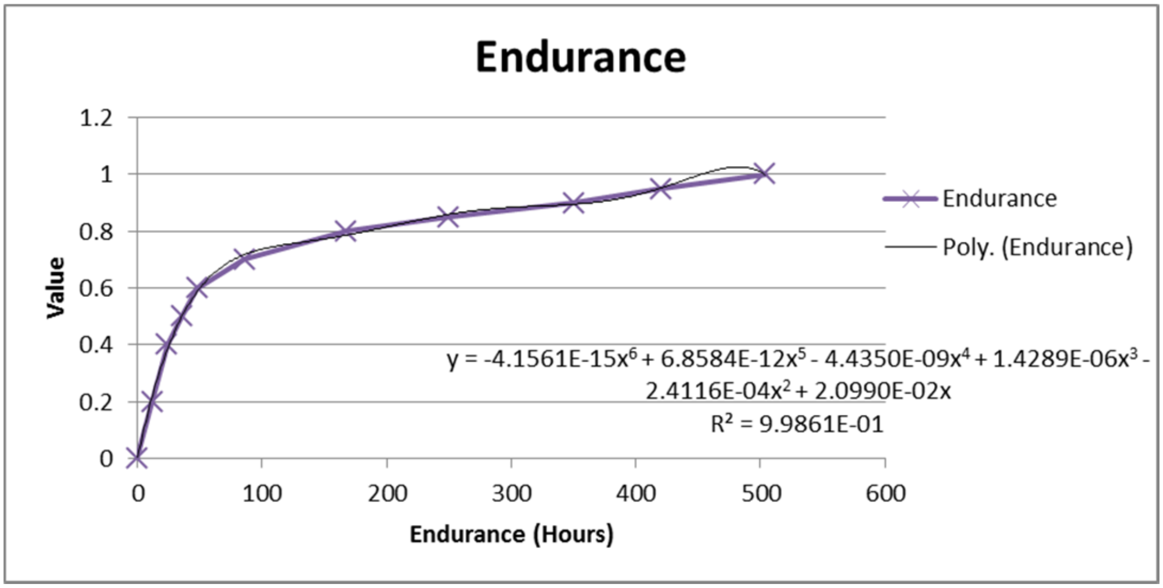

Figure 142. Endurance Value Function Approximation

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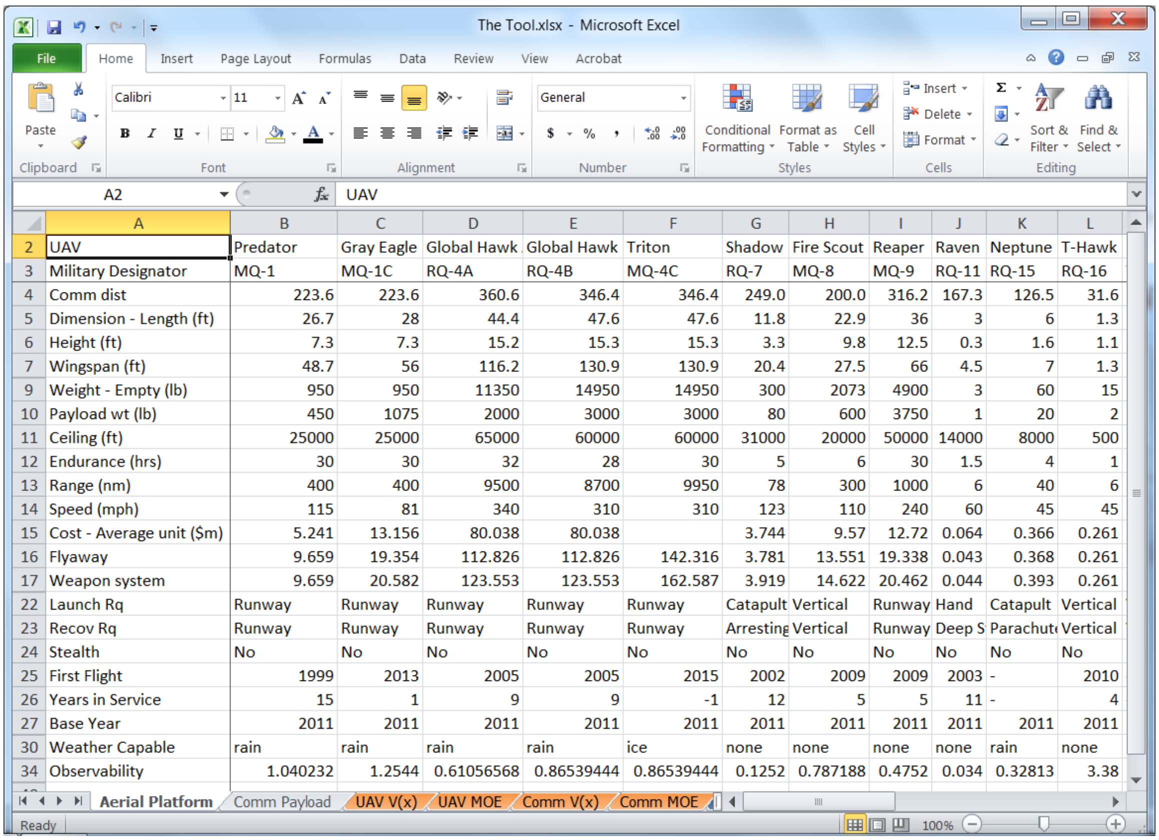
APPENDIX C. USING THE TOOL

The section describes how a decision maker can use the authors' Excel worksheets, otherwise known as The Tool, to fashion their own multi-objective, cost-effective analysis. The decision support tool is coded in Microsoft Excel and is customizable. This appendix provides some detail into using the Excel tool to evaluate the cost-effectiveness of a UAV solution. A screenshot of the first tab and all the worksheets' names can be seen in Figure 143.



	A	B	C	D	E	F	G	H	I	J	K	L
2	UAV	Predator	Gray Eagle	Global Hawk	Global Hawk	Triton	Shadow	Fire Scout	Reaper	Raven	Neptune	T-Hawk
3	Military Designator	MQ-1	MQ-1C	RQ-4A	RQ-4B	MQ-4C	RQ-7	MQ-8	MQ-9	RQ-11	RQ-15	RQ-16
4	Comm dist	223.6	223.6	360.6	346.4	346.4	249.0	200.0	316.2	167.3	126.5	31.6
5	Dimension - Length (ft)	26.7	28	44.4	47.6	47.6	11.8	22.9	36	3	6	1.3
6	Height (ft)	7.3	7.3	15.2	15.3	15.3	3.3	9.8	12.5	0.3	1.6	1.1
7	Wingspan (ft)	48.7	56	116.2	130.9	130.9	20.4	27.5	66	4.5	7	1.3
9	Weight - Empty (lb)	950	950	11350	14950	14950	300	2073	4900	3	60	15
10	Payload wt (lb)	450	1075	2000	3000	3000	80	600	3750	1	20	2
11	Ceiling (ft)	25000	25000	65000	60000	60000	31000	20000	50000	14000	8000	500
12	Endurance (hrs)	30	30	32	28	30	5	6	30	1.5	4	1
13	Range (nm)	400	400	9500	8700	9950	78	300	1000	6	40	6
14	Speed (mph)	115	81	340	310	310	123	110	240	60	45	45
15	Cost - Average unit ($m)	5.241	13.156	80.038	80.038		3.744	9.57	12.72	0.064	0.366	0.261
16	Flyaway	9.659	19.354	112.826	112.826	142.316	3.781	13.551	19.338	0.043	0.368	0.261
17	Weapon system	9.659	20.582	123.553	123.553	162.587	3.919	14.622	20.462	0.044	0.393	0.261
22	Launch Rq	Runway	Runway	Runway	Runway	Runway	Catapult	Vertical	Runway	Hand	Catapult	Vertical
23	Recov Rq	Runway	Runway	Runway	Runway	Runway	Arresting	Vertical	Runway	Deep S	Parachute	Vertical
24	Stealth	No	No	No	No	No	No	No	No	No	No	No
25	First Flight	1999	2013	2005	2005	2015	2002	2009	2009	2003	-	2010
26	Years in Service	15	1	9	9	-1	12	5	5	11	-	4
27	Base Year	2011	2011	2011	2011	2011	2011	2011	2011	2011	2011	2011
30	Weather Capable	rain	rain	rain	rain	ice	none	none	none	none	rain	none
34	Observability	1.040232	1.2544	0.61056568	0.86539444	0.86539444	0.1252	0.787188	0.4752	0.034	0.32813	3.38

Figure 143. Screenshot of the Tool

The first worksheet named Aerial Platform contains the aerial platform data. The second worksheet titled Comm Payload contains the communication payload data. The third worksheet titled UAV V(x) contains the value functions and importance weights for the aerial platform. The fourth worksheet titled UAV MOE consists of the MOE results and graph for the aerial platforms. The fifth worksheet named Comm V(x) contains the value functions and importance weights for the communication payloads. The sixth and last worksheet titled Comm MOE consists of the MOE results and graph of the communication payloads.

Each column of the "Aerial Platform" worksheet represents a single aerial platform. Each row describes an attribute. Each column of the "Comm Payload" worksheet represents a single communication payload, and the rows describe the communication payload's attributes. The third worksheet contains all the value functions and the importance weights as shown in Figure 144.

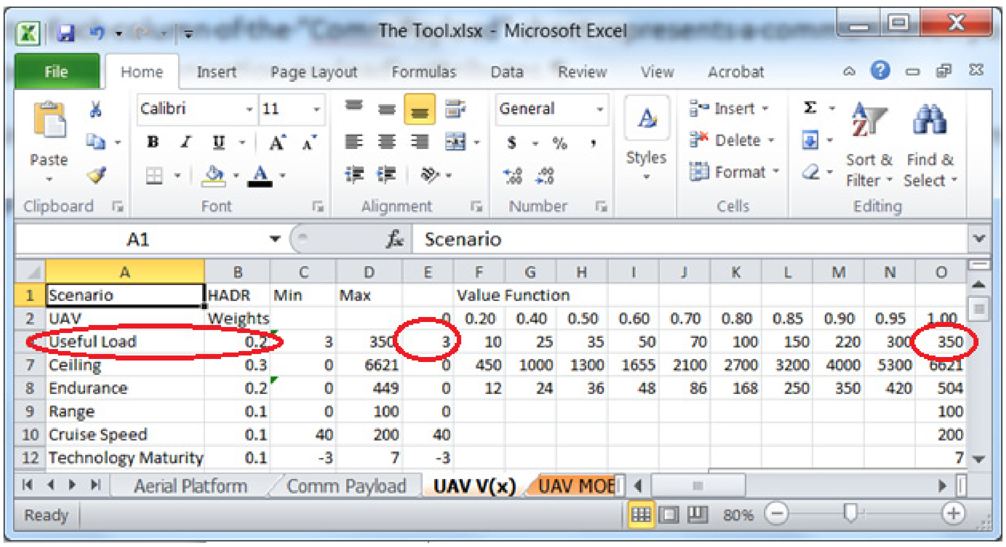


Figure 144. UAV V(x)Spreadsheet

To use the "UAV V(x)" worksheet, first input the attributes in column A and importance weights in Column B. Determine the maximum attribute value that is worth 0, and the minimum attribute value that is worth 1 and place those in columns E and O, respectively. To create a linear equation, delete all values between the two. To create a curved function, select data points representing the curve for as many points between 0 and 1 as necessary to describe the function. Create a graph using the values (0 to 1) as the x-axis and attribute values as the y-axis to make an x-y chart. For example, plot the

Useful Load values as the Series X values, and the 0 to 1 values as the Series Y, as shown in Figure 145.

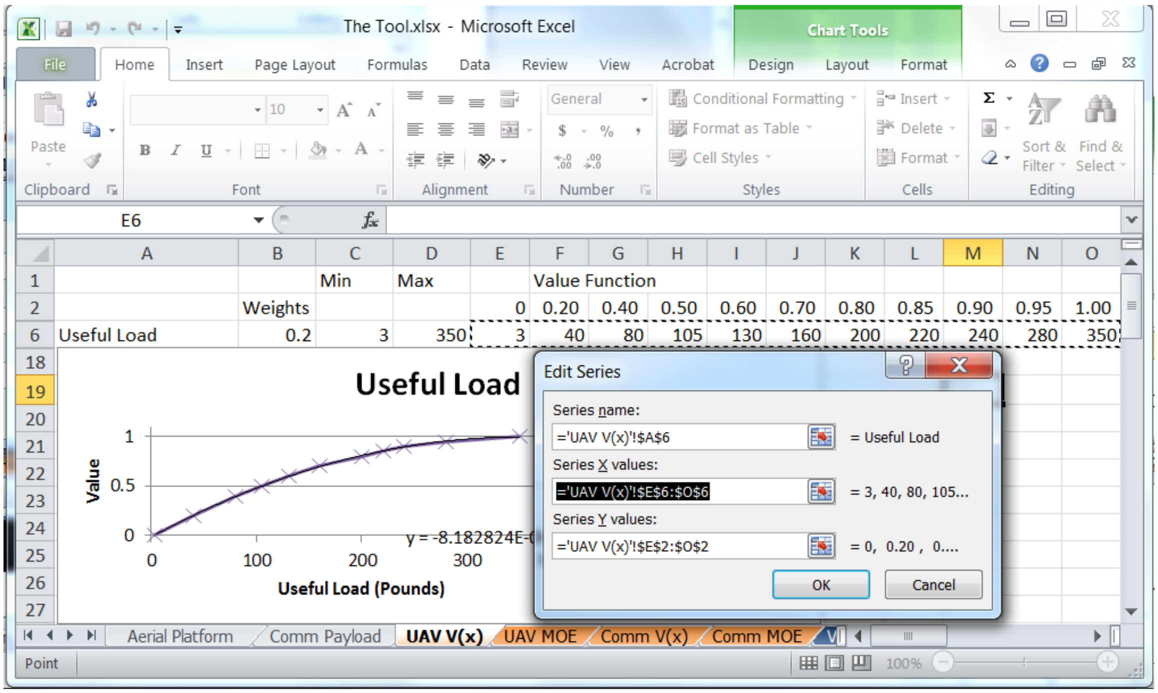


Figure 145. Plotting the Graph

Add a trend line to the graph and select the linear or polynomial option, select the "Display equation on chart" and "Display R-squared value on Chart" check-boxes as seen in Figure 146.

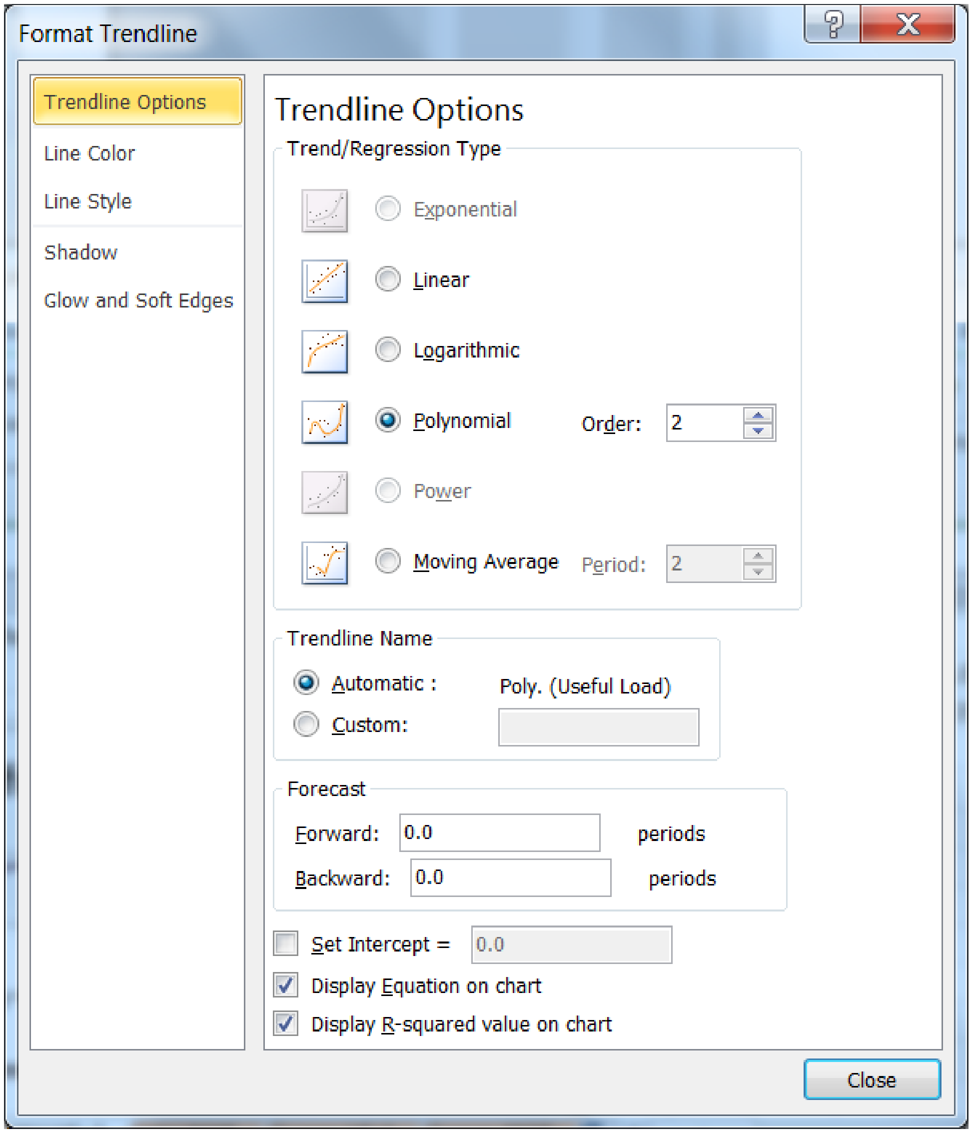


Figure 146. Trend Line Options

As described previously in Chapter IV, cycle through linear and polynomial regressions until the regression line adequate depicts the function and then click "Close." The equation for your regression line must be transcribed into columns P through V of the same row. For example, a 2nd order equation is shown for the useful load in Figure 147.

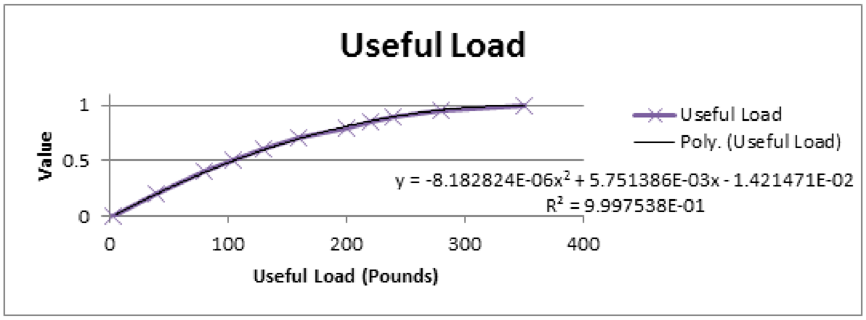
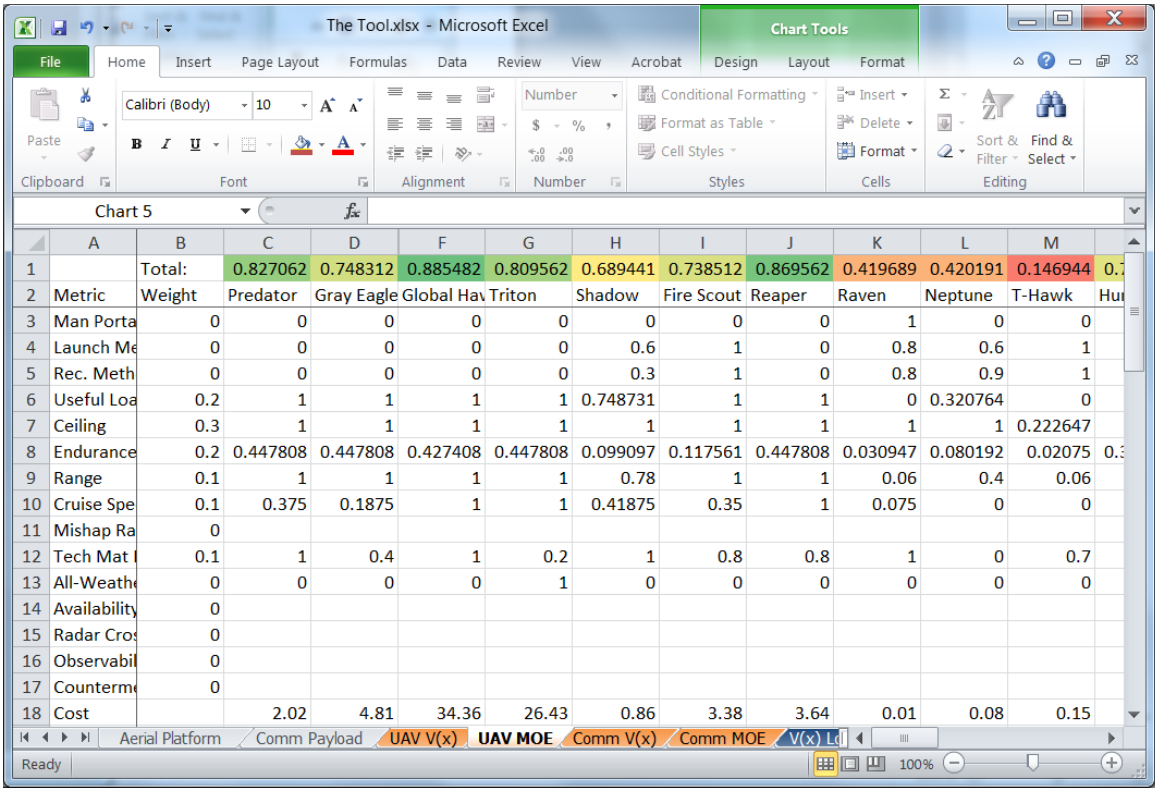


Figure 147. Example Value Function

A second order polynomial follows the form $y = ax^2 + bx + c$. In the example, a = -8.182824E-06, b = 5.751386E-03, and c= -1.421471E-02. Those values must be entered into columns T, U, and V, under the headers of X2, X, and C (C stands for constant). If a 6th order polynomial equation is chosen, columns P through V are necessary. The more points transcribed, the more accurate the value function will be. Repeat this step until all attributes have weights and value functions.

The worksheet titled UAV MOE combines the importance weights and value functions and compares each platform against the others, as seen in Figure 148.



	A	B	C	D	F	G	H	I	J	K	L	M
1		Total:	0.827062	0.748312	0.885482	0.809562	0.689441	0.738512	0.869562	0.419689	0.420191	0.146944
2	Metric	Weight	Predator	Gray Eagle	Global Hav	Triton	Shadow	Fire Scout	Reaper	Raven	Neptune	T-Hawk
3	Man Porta	0	0	0	0	0	0	0	0	1	0	0
4	Launch Me	0	0	0	0	0	0.6	1	0	0.8	0.6	1
5	Rec. Meth	0	0	0	0	0	0.3	1	0	0.8	0.9	1
6	Useful Loa	0.2	1	1	1	1	0.748731	1	1	0	0.320764	0
7	Ceiling	0.3	1	1	1	1	1	1	1	1	1	0.222647
8	Endurance	0.2	0.447808	0.447808	0.427408	0.447808	0.099097	0.117561	0.447808	0.030947	0.080192	0.02075
9	Range	0.1	1	1	1	1	0.78	1	1	0.06	0.4	0.06
10	Cruise Spe	0.1	0.375	0.1875	1	1	0.41875	0.35	1	0.075	0	0
11	Mishap Ra	0										
12	Tech Mat I	0.1	1	0.4	1	0.2	1	0.8	0.8	1	0	0.7
13	All-Weath	0	0	0	0	1	0	0	0	0	0	0
14	Availability	0										
15	Radar Cros	0										
16	Observabil	0										
17	Counterm	0										
18	Cost		2.02	4.81	34.36	26.43	0.86	3.38	3.64	0.01	0.08	0.15

Figure 148. UAV MOE

Each cell from C3 through C17, for as many platforms as are in the "Aerial Platform" sheet, should contain a value between 0 and 1. If any other value appears, then there is an error in the transcription process that must be remedied before continuing. If value function where less of a raw score is better, like observability or payload weight, then having less than the minimum earns a "1", not a "0", while having more than the maximum earns a "0". This is corrected by exchanging the "<" and ">" in the "IF" statements in the following excel command, listed in red.

=IF('Aerial Platform'!B10<'UAV V(x)'!$C6,0,IF('Aerial Platform'!B10>'UAV V(x)'!$D6,1,'UAV V(x)'!$Q6*('Aerial Platform'!B10)^5+'UAV V(x)'!$R6*('Aerial Platform'!B10)^4+'UAV V(x)'!$S6*('Aerial Platform'!B10)^3+'UAV V(x)'!$T6*('Aerial Platform'!B10)^2+'UAV V(x)'!$U6*('Aerial Platform'!B10)+'UAV V(x)'!$V6))

Cost data is updated via the "Cost Data.xlsx" file, and imported to cell C18 (and continuing for each cell from D18, E18s, and on for each platform) for plotting on the graphs. Use the logarithmic scale when there are large differences in the costs of the alternatives considered.

Repeat the same process for the “Comm V(x)” and “Comm MOE” worksheets in and compare the results as necessary to determine the most cost-effective options to match your preferences.

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APPENDIX D. DETAILED MOE

Starting on the following page, a breakdown in landscape format is provided of how each aerial platform and communication scored for each attribute. For each scenario, a figure is provided listing the aerial platforms on the top and the communication payloads on the bottom. Above each aerial platform or communication payload is the color-coded MOE for that scenario. See Figures 149–151.

Metric	Weight	Predator	Gray Eagle	Global Hav	Triton	Shadow	Fire Scout	Reaper	Raven	Neptune	T-Hawk	Hummingb	Blackjack	UCAS-D	Wasp	PTDS 74K	RAID Towe	Cerberus T	TIF-25K
	Total:	0.856905	0.808312	0.893426	0.796637	0.672316	0.757515	0.863358	0.414089	0.420191	0.146944	0.744941	0.569903	0.734078	0.228494	0.781725	0.503197	0.492242	0.686891
Useful Load	0.2	1	1	1	1	0.748731	1	1	0	0.320764	0	1	0.533134	1	0	1	0.946131	0.946131	0.946586
Ceiling	0.3	1	1	1	1	1	1	1	1	1	0.222647	1	1	1	0.408909	0.939085	0.046569	0.010051	0.829504
Endurance	0.2	0.534525	0.394685	0.46713	0.383187	0.099097	0.153199	0.416789	0.030947	0.080192	0.02075	0.334079	0.235129	0.170389	0.015607	1	1	1	0.893611
Range	0.1	1	1	1	1	0.59	1	1	0.054	0.4	0.06	1	0.55	1	0.027	0	0	0	0
Cruise Speed	0.1	0.5	0.79375	1	1	0.4375	0.46875	1	0.025	0	0	0.78125	0.3125	1	0	0	0	0	0
Tech Mat Level	0.1	1	0.5	1	0.2	1	0.8	0.8	1	0	0.7	0	0.3	0	1	1	1	1	0.7

Metric	Weight	Wave Relay	Wave Relay Quad	Xiphos - 6RU	Xiphos - 1RU	WildCat II	Ocelot	Falcon III RF-7800W OU44	Falcon III AN/PRC-117G	Digital Data Link
	Total:	0.285233157	0.492209157	0.946494016	0.772134316	0.372892783	0.301653157	0.394619034	0.44351046	0.219835036
Throughput	0.3	0	0.68992	1	0.9	0	0	0.328	0	0
Power Output	0.25	0.012332627	0.012332627	0.987716064	0.410277264	0.048651134	0.012332627	0.001956135	0.11828184	0.009260143
Receiver Sensitiv	0.15	0.3	0.3	0.9875	0.9875	0.5	0.6	0.2	0.95	0.25
Mesh	0.1	1	1	1	1	1	1	1	1	0
Traffic Type	0.1	0.8	0.8	0.8	0.8	1	0.8	0.8	1	0.8
Technology Matı	0.1	0.5715	0.5715	0.7144	0.7144	0.8573	0.2857	0.8573	0.7144	1.0002

Figure 149. HADR Scenario: MOE Breakdown

	Total:	0.768534	0.730352	0.9	0.904	0.2	0.596634	0.8646	0.1	0.083068	0.0494	0.614182	0.402616	0.875057	0.1	0.5	0.6	0.6	0.4494
Metric	Weight	Predator	Gray Eagle	Global Hav	Triton	Shadow	Fire Scout	Reaper	Raven	Neptune	T-Hawk	Hummingb	Blackjack	UCAS-D	Wasp	PTDS 74K	RAID Towe	Cerberus T	TIF-25K
Useful Loa	0.1	1	1	1	1	1	1	1	0	0.830675	0	1	0.853871	1	0	1	1	1	1
Ceiling	0.2	0.34267	0.526158	1	1	0	0.070912	1	0	0	0	0.070912	0.041145	0.875286	0	0	0	0	0
Endurance	0.3	1	1	1	1	0	0.75	1	0	0	0	1	1	1	0	1	1	1	1
Range	0.2	1	1	1	1	0	0.96426	1	0	0	0	1	0	1	0	0	0	0	0
Tech Mat I	0.1	1	0.2512	1	0.04	1	0.646	0.646	1	0	0.494	0	0.09	0	1	1	1	1	0.494
All-Weath	0.1	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	1	1	0

	Total:	0.225	0.2231554	0.606875	0.606875	0.7694867	0.28	0.2152275	0.934390925	0.1925
Metric	Weight	Wave Relay	Wave Relay Quad	Xiphos - 6RU	Xiphos - 1RU	WildCat II	Ocelot	Falcon III RF-7800W OU44	Falcon III AN/PRC-117G	Digital Data Link
Power Output	0.25	0	0	1	1	0.706554144	0	0	0.9974637	0
Receiver Sensitiv	0.25	0.3	0.3	0.9875	0.9875	0.5	0.6	0.2	0.95	0.25
Power Consump	0.05	1	1	1	1	1	1	1	1	0
Traffic Type	0.3	0	0	0	0	1	0	0	1	0
Weight	0.05	1	0.963108	0	0	0.956963281	1	0.90455	0.7505	1
Technology Mat	0.1	0.5	0.5	0.6	0.6	0.7	0.3	0.7	0.6	0.8

Figure 150. Long-Range Scenario: MOE Breakdown

	Total:	0.351932	0.297599	0.353332	0.247008	0.536103	0.619893	0.383759	0.896924	0.533155	0.379199	0.532489	0.516317	0.331397	0.732334	0.55	0.45	0.45	0.4994
Metric	Weight	Predator	Gray Eagle	Global Hav	Triton	Shadow	Fire Scout	Reaper	Raven	Neptune	T-Hawk	Hummingb	Blackjack	UCAS-D	Wasp	PTDS 74K	RAID Towe	Cerberus T	TIF-25K
Man Porta	0.25	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0
T.O. Meth	0.15	0	0	0	0	0.6	1	0	0.8	0.6	1	1	0.6	0	0.8	1	1	1	1
Rec. Meth	0.1	0	0	0	0	0.3	1	0	0.8	0.9	1	1	0.6	0.3	0.8	1	1	1	1
Useful Loa	0.05	1	1	1	1	1	1	1	0.029595	1	0.168513	1	1	1	0.010841	1	1	1	1
Ceiling	0.1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	0	1
Endurance	0.05	1	1	1	1	1	1	1	1	1	1	1	1	1	0.75	1	1	1	1
Tech Mat I	0.1	1	0.2512	1	0.04	1	0.646	0.646	1	0	0.494	0	0.09	0	1	1	1	1	0.494
Observabil	0.2	0.259658	0.362396	0.266661	0.215038	0.580516	0.526466	0.595795	0.977223	0.765773	0.106869	0.412447	0.786586	0.506986	0.221461	0	0	0	0

	Total:	0.77425543	0.425	0.519375	0.519375	0.648350429	0.78231411	0.527013881	0.507373185	0.756993615
Metric	Weight	Wave Relay	Wave Relay Quad	Xiphos - 6RU	Xiphos - 1RU	WildCat II	Ocelot	Falcon III RF-7800W OU440	Falcon III AN/PRC-117G	Digital Data Link
Throughput	0.1	0.675942	1	1	1	0.7331283	0.1231411	1	0	0.05642375
Power Output	0.05	0	0	1	1	0.706554144	0	0	0.9974637	0
Receiver Sensitivity	0.05	0.3	0.3	0.9875	0.9875	0.5	0.6	0.2	0.95	0.25
Mesh Capability	0.05	1	1	1	1	1	1	1	1	0
Power Consumption	0.2	0.65830614	0	0	0	0.473549461	1	0.435069404	0	0.9942562
Traffic Type	0.3	0.7	0.7	0.7	0.7	1	0.7	0.7	1	0.7
Weight	0.25	1	0	0	0	0	1	0	0	1
Technology Maturity Level	0.1	0.5	0.5	0.6	0.6	0.7	0.3	0.7	0.6	0.8

Figure 151. Tactical User Scenario: MOE Breakdown

SUPPLEMENTAL

A. EXCEL DOCUMENT: THE TOOL

The authors' decision support tool, christened The Tool, is available separately in Excel worksheet format. To obtain the support tool worksheet, contact the NPS Dudley Knox library.

Instructions on using the decision support tool are presented in Appendix C.

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LIST OF REFERENCES

AAI Corp. (2013). *Aerosonde Mark 4.7.* Retrieved January 30, 2014, from AAI Corp: http://www.aaicorp.com/sites/default/files/datasheets/AAI_AerosondeUAS_AAIAEROUASDS%200413.pdf

Aerosonde. (2010). *Aerosonde Mark 4.7.* Retrieved January 30, 2014, from Aerosonde: http://www.aerosonde.com/pdfs/aerosonde-mark-47.pdf

AeroVironment. (2012a). *Digital Data Link*. Retrieved March 7, 2014, from AeroVironment: http://www.avinc.com/downloads/DDLDataSheet2012.pdf

AeroVironment. (2012b, April 20). *U.S. Army places $20.4 million order for AeroVironment RQ-20A Puma AE small unmanned aircraft systems*. Retrieved March 14, 2014, from avinc.com: http://investor.avinc.com/releasedetail.cfm?ReleaseID=666018

AeroVironment. (2013). *Media gallery*. Retrieved March 15, 2014, from AeroVironment: https://www.avinc.com/img/media_gallery/UAS_WaspIII_prodimage_lg.jpg

AeroVironment. (2014a). *Raven*. Retrieved January 30, 2014, from AeroVironment: http://www.avinc.com/downloads/Raven_Gimbal.pdf

AeroVironment. (2014b). *UAS: Wasp AE*. Retrieved March 9, 2014, from AeroVironemt: http://www.avinc.com/uas/small_uas/waspAE/

airforce-technology.com. (2011). *RQ-11B Raven unmanned air vehicle (UAV), United States of America*. Retrieved March 7, 2014, from airforce-technology.com: http://www.airforce-technology.com/projects/rq11braven/

Altera. (2014). *Solving SWaP constraints in military applications*. Retrieved March 9, 2014, from Altera.com: http://www.altera.com/end-markets/military-aerospace/swap/mil-swap.html

Amazon.com. (2014). *Amazon Prime air*. Retrieved March 13, 2014, from Amazon.com: http://www.amazon.com/b?node=8037720011

American Forces Press Service. (2011, September 22). *Debt is biggest threat to national security, Chairman says*. Retrieved March 3, 2014, from Defense.Gov: http://www.defense.gov/news/newsarticle.aspx?id=65432

AR15.com. (2009, August 10). *AR15.com*. Retrieved March 9, 2014, from AR15.com: http://www.ar15.com/archive/topic.html?b=1&f=147&t=901934

Army Technology. (2012). *Persistent Threat Detection System (74K Aerostat), United States of America*. Retrieved March 14, 2014, from army-technology.com: http://www.army-technology.com/projects/persistent-threat-detection-system-us/

Aviation Week. (2009, September 30). *Vulture heads for full-scale demo*. Retrieved March 7, 2014, from AviationWeek.com: http://www.aviationweek.com/blogs.aspx?plckblogid=blog:27ec4a53-dcc8-42d0-bd3a-01329aef79a7&plckcontroller=blog&plckscript=blogscript&plckelementid=blogdest&plckblogpage=blogviewpost&plckpostid=blog:27ec4a53-dcc8-42d0-bd3a-01329aef79a7post:786b1ced-a2d9-4

Aviation Week. (2010, August 16). *HALE to hydrogen as Global Observer debuts*. Retrieved March 7, 2014, from AviaationWeek.com: http://www.aviationweek.com/Blogs.aspx?plckBlogId=blog:27ec4a53-dcc8-42d0-bd3a-01329aef79a7&plckPostId=Blog:27ec4a53-dcc8-42d0-bd3a-01329aef79a7Post:a37707fb-3f90-4369-91a8-1b0bd9d2d354

Barker, C. (2013, April 23). *TIF-25K Aerostat*. Retrieved March 7, 2014, from strategypage.com: https://www.strategypage.com/military_photos/military_photos_20130423214837.aspx

Boeing. (2014). *A160 Hummingbird*. Retrieved March 3, 2014, from Boeing.com: http://www.boeing.com/boeing/bds/phantom_works/hummingbird.page

Boston.com. (2008, June 3). *Raytheon wins $76 million Army contract*. Retrieved March 7, 2014, from Boston.com: http://www.boston.com/business/ticker/2008/06/raytheon_wins_7_3.html

Collier, C., & Kacala, J. (2008). *A cost-effectiveness analysis of tactical satellites, high-altitude long-endurance airships, and high and medium altitude unmanned aerial systems for ISR and communication missions*. (Master's thesis, Naval Postgraduate School). Retrieved from http://calhoun.nps.edu/public/bitstream/handle/10945/3934/08Sep_Collier.pdf?sequence=1

decodingtech.com. (2012, June 19). *Google's Project Loon*. Retrieved March 7, 2014, from decodingtech.com: http://decodingtech.com/googles-project-loon/

Defense Industry Daily. (2008, Feb 25). *Drone relay: PRC-152 radios + RQ-7 UAVs = front-line bandwidth*. Retrieved March 3, 2014, from Defense Indutry Daily: http://www.defenseindustrydaily.com/Drone-Relay-PRC-152-Radios-RQ-7-UAVs-Front-Line-Bandwidth-04753/

Defense Industry Daily. (2010, June 8). *US Army aerostat-based PTDS provide IED warning*. Retrieved March 7, 2014, from defenseindustrydaily.com: http://www.defenseindustrydaily.com/133M-to-Lockheed-Martin-for-US-Army-Aerostat-based-Warning-System-05835/

Defense Industry Daily. (2011a, June 23). *Cerberus: standing guard over US Military's forward bases*. Retrieved March 19, 2014, from defenseindustrydaily.com: http://www.defenseindustrydaily.com/cerberus-standing-guard-over-us-militarys-forward-bases-06129/

Defense Industry Daily. (2011b, Aug 24). *The USA's RAID Program: small systems, big surveillance time*. Retrieved March 19, 2014, from Defense Indutry Daily: http://www.defenseindustrydaily.com/ the-usas-raid-program-small-aerostats-big-surveillance-time-02779/

Defense Update. (2008). *Army deploys 300th RAID tower*. Retrieved March 11, 2014, from defense-update.com: http://defense-update.com/features/2008/november/231108_psds2_raid_sensors.html

DoD. (2012a). *Selected acquisition report MQ-1C Gray Eagle unmanned aircraft system.* Defense Acquisition Management Information Retrieval.

DoD. (2012b). *Selected acquisition report MQ-4C Triton unmanned aircraft system.* Defense Acquisition Management Information Retrieval.

DoD. (2012c). *Selected acquisition report MQ-8 vertical takeoff and landing tactical unmanned aerial vehicle Fire Scout.* Defense Acquisition Management Information Retrieval.

DoD. (2012d). *Selected acquisition report MQ-9 Reaper unmanned aircraft system.* Defense Acquisition Management Information Retrieval.

DoD. (2012e). *Selected acquisition report RQ-4A/B Global Hawk unmanned aircraft system.* Defense Acquisition Management Information Retrieval.

DoD. (2013). Unmanned systems integrated roadmap FY2013-2038. Reference Number: 14-S-0553.

DOT&E. (2012). *F/A-18E/F Super Hornet and EA-18G Growler*. Retrieved March 7, 2014, from Office of the Director, Operational Test and Evaluation: http://www.dote.osd.mil/pub/reports/fy2012/pdf/navy/2012fa18ef.pdf

FBO.gov. (2011). *Persistent Ground Surveillance System (PGSS) Aerostar TIF-25K Aerostats and associated spare parts.* Retrieved March 19, 2014 from FBO.gov: https://www.fbo.gov/index?s=opportunity&mode=form&tab=core&id=80fadce54d60b730cec1450698992244

Ferguson, C., & Harbold, D. (2001). *High altitude long endurance (HALE) platforms for tactical wireless communications and sensor use in military operations.* (Master's thesis, Naval Postgraduate School). Retrieved from http://calhoun.nps.edu/public/bitstream/handle/10945/1694/01Sep_Ferguson.pdf?sequence=1

Frew, E. (2008, December 12). Airbourne communication networks for small unmanned aircraft systems. *Proceedings of the IEEE, 96*(12), pp. 2008–2027.

Fry, J., & Tutaj, S. (2010). *A business case analysis for the vulture program.* (Master's thesis, Naval Postgraduate School). Retrieved from http://calhoun.nps.edu/public/handle/10945/10488

General Atomics. (2012a). *MQ-1C Gray Eagle*. Retrieved March 19, 2014, from ga-asi.com: http://www.ga-asi.com/products/aircraft/pdf/Gray_Eagle.pdf

General Atomics. (2012b). *MQ-9 Reaper*. Retrieved March 19, 2014, from ga-ais.com: http://www.ga-asi.com/products/aircraft/pdf/Predator_B.pdf

General Atomics. (2012c). *Predator C Avenger.* Retrieved January 30, 2014, from General Atomics Aeronautical: http://www.ga-asi.com/products/aircraft/pdf/Predator_C.pdf

General Atomics. (2013a). *Aircraft platforms*. Retrieved March 7, 2014, from General Atomics: http://media.ga.com/image-library/unmanned-aircraft-systems/aircraft-platforms/

General Atomics. (2013b). *MQ-1 Predator*. Retrieved March 19, 2014, from ga-asi.com: http://www.ga-asi.com/products/aircraft/pdf/MQ-1_Predator.pdf

Google. (2014). *Project Loon*. Retrieved March 6, 2014, from Project Loon: http://www.google.com/loon/

Hall, E. (2014, March 6). *U.S. National Debt clock*. Retrieved March 7, 2014, from brillig.com: http://www.brillig.com/debt_clock/

Halvorson, S. (2009). *3 RAID tower images*. Retrieved March 9, 2014, from Scott Halvorson: http://www.concentric.net/~halvorss/PicHTMLs/RAID.htm

Harris. (2012a). *AN/PRC-117G(V)1(C)*. Retrieved March 14, 2014, from Harris.com: http://rf.harris.com/media/AN-PRC-117G_WEB_tcm26-9017.pdf

Harris. (2012b). *RF-7800W.* Retrieved January 31, 2014, from Harris Corporation: http://rf.harris.com/capabilities/tactical-radios-networking/rf-7800w.asp

Harris. (2012c). *RF-7800W-OU440*. Retrieved March 14, 2014, from Harris.com: http://rf.harris.com/media/RF-7800W-OU440%20DataSheet_tcm26-13554.pdf

Harris. (2014). *RF-7800W HCLOS radio*. Retrieved March 5, 2014, from Harris.com: http://rf.harris.com/capabilities/tactical-radios-networking/rf-7800w.asp

Herbert, J. (2013, January 20). *Radio horizon*. Retrieved March 13, 2014, from continuoswwave.com: http://continuouswave.com/whaler/reference/radioHorizon.html

Insitu. (2013a). *Integrator system*. Retrieved March 7, 2014, from Insitu.com: http://insitu.com/systems/integrator

Insitu. (2013b). *ScanEagle options and capabilities.* Retrieved January 30, 2014, from Insitu.com: http://www.insitu.com/images/uploads/product-cards/ScanEagle_Options_and_Capabilities.pdf

Insitu. (2013c). *ScanEagle systems*. Retrieved March 7, 2014, from Insitu.com: http://insitu.com/systems/scaneagle

Keller, J. (2013). *Control and data-link radios for unmanned vehicles pushing the limits of SWaP*. Retrieved from http://www.militaryaerospace.com/articles/print/volume-24/issue-7/product-intelligence/control-and-data-link-radios-for-unmanned-vehicles-pushing-the-limits-of-swap.html

Lawler, P. (2010). *Cost implications of the Broad Area Maritime Surveillance unmanned aircraft system for the Navy flying hour program and operation and maintenance budget.* (Master's thesis, Naval Postgraduate School). Retrieved from https://calhoun.nps.edu/public/bitstream/handle/10945/5059/10Dec_Lawler.pdf?sequence=1

Menjivar, J. (2012). *Bridging operational and strategic communication architectures integrating small unmanned aircraft systems as airborne tactical communication vertical nodes.* (Master's thesis, Naval Postgraduate School). Retrieved from http://calhoun.nps.edu/public/handle/10945/17418

NASA SEWP. (2014). *NASA SEWP IV product list for Oceus Networks*. Retrieved March 14, 2014, from NASA SEWP: http://www.sewp.nasa.gov/cgi-bin/mfr_clin_list.pl?MFR=Oceus_Networks,spl1t,FORCE_3&ACTION=FIND

NASA SEWP. (2014). *NASA SEWP IV product list for Persistent Systems, LLC.* Retrieved March 14, 2014, from NASA SEWP: http://www.sewp.nasa.gov/cgi-bin/mfr_clin_list.pl?MFR=Persistent_Systems,_LLC,spl1t,IGOV&ACTION=FIND

Nicholas, T., & Rossi, R. (2011). U. S. unmanned aircraft systems, 2011. Fountain Valley, CA: Data Search Associates.

Northrop Grumman. (2012). *MQ-8B Fire Scout*. Retrieved March 19, 2014, from NorthropGrumman.com: http://www.northropgrumman.com/Capabilities/FireScout/Documents/pageDocuments/MQ-8B_Fire_Scout_Data_Sheet.pdf

Northrop Grumman. (2014a). *Media gallery*. Retrieved March 7, 2014, from NorthropGrumman.com: http://www.northropgrumman.com/MediaResources/Pages/MediaGallery.aspx?ProductId=GL-10001

Northrop Grumman. (2014b). *Triton*. Retrieved March 15, 2014, from NorthropGrumman.com: http://www.northropgrumman.com/Capabilities/Triton/Pages/default.aspx

Oceus Networks. (2011, August 5). *Introduction of 4G LTE Xiphos*. Retrieved March 7, 2014, from YouTube.com: http://www.youtube.com/watch?v=p2ANY04a50g

Oceus Networks. (2014). *Xiphos*. Retrieved March 5, 2014, from OceusNetowkrs.com: http://www.oceusnetworks.com/sites/oceusnetworks.com/files/oceus-ds-xiphos-7-13final.pdf

Perez, S., & Constine, J. (2014, March 3). *Facebook Looking Into Buying Drone Maker Titan Aerospace*. Retrieved March 13, 2014, from TechChrunch.com: http://techcrunch.com/2014/03/03/facebook-in-talks-to-acquire-drone-maker-titan-aerospace/

Persistent Systems. (2011). *Technology*. Retrieved January 30, 2014, from Persistent Systems: http://www.persistentsystems.com/technology.php

Persistent Systems. (2012). *Wave Relay*. Retrieved January 30, 2014, from Persistent Systems: http://www.persistentsystems.com/pdf/WaveRelay_WhitePaper_Technology_01.pdf

Persistent Systems. (2014). *Quad Radio Router*. Retrieved March 7, 2014, from Persistent Systems: http://www.persistentsystems.com/quad/

Raven Aerostar. (2014). *TIF-25K teathered aerostat*. Retrieved March 11, 2014, from RavenAerostar.com: http://ravenaerostar.com/solutions/aerostats/tif-25k

Rosenberg, B. (2010, February 25). *DoD's reliance on commercial satellites hits new zenith*. Retrieved March 1, 2014, from Defense Systems: http://defensesystems.com/articles/2010/03/11/cover-story-the-satcom-challenge.aspx

Selinger, M. (2013, October 9). *More capable comms*. Retrieved March 3, 2014, from KMI Media Group: http://www.kmimediagroup.com/special-operations-technology/436-articles-sotech/more-capable-comms/5098-more-capable-comms

Thiow Yong Dennis, L. (2007). *Network payload integration for the Scan-Eagle UAV.* (Master's thesis, Naval Postgraduate School). Retrieved from http://calhoun.nps.edu/public/bitstream/handle/10945/3114/07Dec_Lim_Thiow.pdf?sequence=1

Trellisware. (2014a). *TW-130 WildCat II*. Retrieved March 5, 2014, from TrellisWare.com: https://www.trellisware.com/wp-content/uploads/TW-130-WildCat-II-Product-Bulletin.pdf

TrellisWare. (2014b). *TW-600 Ocelot*. Retrieved March 9, 2014, from TrellisWare.com: https://www.trellisware.com/wp-content/uploads/TW-600_Ocelot_Product_bulletin.pdf

U.S. Army Center of Excellence. (2010). U.S. Army unmanned aircraft systems roadmap 2010-2035. Fort Rucker, AL.

UAVConsultingGroup.com. (2014). *Photo gallery*. Retrieved March 7, 2014, from UAVConsultingGroup.com: http://www.uavconsultinggroup.com/photogallery.php

Valerdi, R. (2005). *Cost metrics for unmanned aerial vehicles.* Cambridge, MA: Massachusetts Institute of Technology.

Wall, K., & MacKenzie, C. (2013). *Multiple objective decision making.* DRMI, Naval Postgraduate School.

Wall, M. (2013, March 9). *Russian satellite hit by Chinese debris highlights space junk threat*. Retrieved March 3, 2014, from Space.com: http://www.space.com/20146-russian-satellite-space-junk-threat.html

Wikipedia. (2013, July 7). *AN-PRC-117G FALCON III manpack radio*. Retrieved March 7, 2014, from Wikipedia.org: http://en.wikipedia.org/wiki/File:AN-PRC-117G_FALCON_III_manpack_radio_-_National_Cryptologic_Museum_-_DSC07959.JPG

Wikipedia.org. (2007, August 23). *File:Shadow-200.png*. Retrieved March 7, 2014, from Wikipedia.org: http://commons.wikimedia.org/wiki/File:Shadow-200.png

Wikipedia.org. (2011, December 11). *File: Boeing A160 Hummingbird VTOL-UAS.jpg*. Retrieved March 15, 2014, from Wikipediaorg: http://en.wikipedia.org/wiki/File:Boeing_A160_Hummingbird_VTOL-UAS.jpg

Wikipedia.org. (2014a, February 15). *Cellular network*. Retrieved March 7, 2014, from Wikipedia.org: http://en.wikipedia.org/wiki/Cellular_network

Wikipedia.org. (2014b, March 3). *Network topology*. Retrieved March 7, 2014, from Wikipedia.org: http://en.wikipedia.org/wiki/Network_topology

Wolfram Alpha. (2014). *Isosceles triangle*. Retrieved March 19, 2014, from Wolfram Alpha: http://mathworld.wolfram.com/IsoscelesTriangle.html

Yilmaz, B. (2013). Cost and effectiveness analysis on unmanned aerial vehicle (UAV) use at border security. Istanbul, Turkey: Turkish Air War College.

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