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A business case analysis for the Vulture program

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A Business Case Analysis for the Vulture Program

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December 2010

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The Vulture program is an initiative being developed by the Defense Advanced Research Projects Agency (DARPA). The end goal of the Vulture program is to develop a high altitude long endurance (HALE) unmanned aerial vehicle (UAV) that is capable of maintaining a 1,000-pound payload on station for five years. The DARPA goals for the Vulture program include, at a minimum, the development and demonstration of advanced reliability technologies for the proposed future Vulture system. It is envisioned that Vulture will provide affordable, persistent coverage over an area of interest for surveillance and communications relay missions.

The purpose of this study is to estimate the potential cost savings and identify other benefits associated with the potential operational use of Vulture. This study conducts a business case analysis (BCA) comparing the estimated costs of the Vulture program to those of the Global Hawk and Global Observer systems. Sensitivity analyses are performed on the cost variables, as well as a general risk assessment for Vulture.

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A BUSINESS CASE ANALYSIS FOR THE VULTURE PROGRAM

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Submitted in partial fulfillment of the requirements for the degree of

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A BUSINESS CASE ANALYSIS FOR THE VULTURE PROGRAM

ABSTRACT

The Vulture program is an initiative being developed by the Defense Advanced Research Projects Agency (DARPA). The end goal of the Vulture program is to develop a high altitude long endurance (HALE) unmanned aerial vehicle (UAV) that is capable of maintaining a 1,000-pound payload on station for five years. The DARPA goals for the Vulture program include, at a minimum, the development and demonstration of advanced reliability technologies for the proposed future Vulture system. It is envisioned that Vulture will provide affordable, persistent coverage over an area of interest for surveillance and communications relay missions.

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LIST OF ACRONYMS AND ABBREVIATIONS

AEHF – Advanced Extremely High Frequency

AO – Area of Operations

AV – Air Vehicle

BAA – Broad Agency Announcement

BCA – Business Case Analysis

C3 – Command Control and Communications

CER – Cost Estimating Relationship

CHHAPP – Composite Hull High Altitude Powered Platform

CONOPS – Concept of Operations

DARPA – Defense Advanced Research Projects Agency

DoD – Department of Defense

FSD – Full Scale Demonstrator

HAA – High Altitude Airship

HALE – High Altitude Long Endurance

ISR – Intelligence Surveillance and Reconnaissance

LCC – Life Cycle Cost

LH$_2$ – Liquid Hydrogen

MCS – Mission Control Station

MOUO – Mobile User Objective System

NPV – Net Present Value

O&S – Operations and Support

OCO – Overseas Contingency Operations

PV – Photovoltaic

R&D – Research and Development

RDT&E – Research Development Test and Evaluation

ROI – Return On Investment

SRR – System Requirements Review

TMP – Technology Maturation Plan

TRL – Technology Readiness Level

TSCI – Trans-Sahara Counter-terrorism Initiative

UAV – Unmanned Aerial Vehicle

USAF – United States Air Force

WGS – Wideband Global SATCOM System

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EXECUTIVE SUMMARY

The Vulture program is a Defense Advanced Research Projects Agency initiative to develop a high altitude long endurance (HALE) unmanned aerial vehicle (UAV) capable of maintaining a 1,000-pound payload on station for five years.

The purpose of this study is to analyze the potential cost savings and other benefits associated with the potential operational use of Vulture. This study establishes three potential operational scenarios (Trans-Sahara Region, Afghanistan/Pakistan, and China/North Korea) in which persistent surveillance would be required and develops a business case analysis for Vulture. Using these three operational scenarios, the business case analysis proceeds by completing the following:

- Baseline analysis and comparison of fleet requirements and net present value (NPV) life cycle costs (LCC) for Vulture, Global Hawk, and Global Observer systems
- Return on investment analysis for Vulture in comparison to Global Hawk and Global Observer
- Sensitivity analysis of several cost factors on the life cycle cost and return on investment comparisons
- Risk assessment analysis for Vulture

The results of the business case analysis of the three systems to perform the persistence surveillance mission in the operational scenarios for 15 years are summarized as follows:

- <u>Fleet Requirements</u>
    - 4 total Vulture aircraft are required to support the mission requirements. In comparison, 20 Global Hawk aircraft would be required, or 11 Global Observer aircraft would be required

  - 4 Vulture sorties every five years, 2152 annual Global Hawk sorties, or 277 annual Global Observer sorties are required

- Life Cycle Costs

The estimated net present value life cycle comparison over a 15-year period between Vulture, Global Hawk, and Global Observer are summarized in Table 1.

Table 1. Estimated NPV life cycle costs (FY10 $M) over 15 years to support the scenarios.

Cost Category	**Global Hawk**	**Vulture**	**Global Observer**
Investment	2,549.64	1,618.49	251.74
Operations & Support	2,547.47	0.00	228.38
Total NPV LCC Cost	5,097.11	1,618.49	480.12

  - The estimated NPV cost to purchase and operate the Vulture for 15 years in the three operational scenarios identified is $1,618M (FY10$)
  - The expected NPV life cycle cost savings of using Vulture over Global Hawk is 68%
  - The annualized return on investment of Vulture versus Global Hawk is 5.23%.

- Sensitivity Analysis
  - Vulture becomes an increasingly more attractive option over Global Hawk as mission distance is increased
  - Vulture air vehicle cost is the major driver of Vulture life cycle costs
  - The future cost of solar energy technology will be a major driver of Vulture air vehicle costs, and therefore, life cycle costs

    - As Vulture estimated total air vehicle costs approach $200M per unit, Vulture is no longer an attractive option to Global Hawk from an annualized return on investment point of view

- Risk Analysis
    - Power generation and component longevity for an atmospheric five year endurance system are primary technological risk areas
    - Vulnerability and susceptibility assessments may reveal attrition risks that will greatly increase program life cycle costs
    - Low technology readiness level of the proposed system increases the design maturation risk

Based on the cost and benefits estimated in this analysis, the Vulture program will perform the persistent surveillance mission at a lower cost than the Global Hawk system. This analysis also reflects the Vulture currently as a more expensive option than Global Observer. Future study is recommended, among others, on the comparison between Vulture and Global Observer as both developmental systems continue to mature and estimated costs become more accurate. Given the potential savings Vulture provides over the existing Global Hawk system, there are significant potential benefits to be garnered by pursuing the Vulture program and continuing to evaluate its attractiveness as the technology and design matures.

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I. INTRODUCTION

A. PURPOSE OF THE STUDY

This study provides a business case analysis (BCA) that estimates and compares the costs of acquiring and operating the developmental Vulture unmanned aerial vehicle (UAV) to those of the Global Hawk and Global Observer. Department of Defense (DoD) demand for technology is outpacing DoD's ability to support requirements. Two notable examples are intelligence, surveillance, and reconnaissance (ISR) taskings and command, control, and communications (C3) bandwidth requirements. Meeting the increasing demand for ISR and C3 assets will enable improvements in doctrine, and ultimately, force effectiveness, but it is important to meet the demand in the most cost effective way. Augmenting these requirements with additional assets as currently employed would be more costly than current operations, and additional assets may take an excessive amount of time to field. High altitude long endurance (HALE) UAVs capable of supplementing current capabilities and relaying communications may be a promising solution.

A recent DoD initiative to provide additional ISR and C3 capability is the Vulture program, which is managed by the Defense Advanced Research Projects Agency (DARPA). The Vulture program's end product will be a HALE UAV capable of maintaining a 1,000-pound payload on station for 5 years. Three contractors competed in the first phase of the Vulture program to build a subscale model of their respective solutions. Recently, The Boeing Company won DARPA's Vulture Phase II contract to build a full scale demonstrator (FSD). Thus, for the purposes of this report, the Vulture program's final product is generically referred to as "Vulture." According to DARPA,

> The Vulture air vehicle program is an exploratory development program to develop the capability to deliver and maintain a single airborne payload on station for an uninterrupted period of at least 5 years using a heavier-than-air platform system. It is envisioned that this program will, at a minimum, develop and demonstrate advanced reliability technologies for air vehicle systems. Other advanced technologies may also be developed and demonstrated depending upon the nature of the architectures proposed by offerors… The Vulture program will research and develop technologies and systems which will enable the military to deliver and maintain a 1000

> lb, 5 kW airborne payload for an uninterrupted period of at least 5 years with an on-station probability of 99% and with a high probability of mission success. The architectures selected and the specific approaches taken by the offerors will determine the range of technical areas that are developed, including, but not limited to, environmental energy collection, high specific energy storage, extremely efficient propulsion systems, precision robotic refueling, autonomous materiel transfer, extremely efficient vehicle structural design, and mitigation of environmentally-induced loads.[1]

Further, DARPA is very straightforward in its constraints on Vulture's propulsion. It specifically states, "The Government is not interested in approaches that use either radioactive energy sources or employ any form of buoyant flight for this application."[2]

This study will use Lim's methodology employed in his Global Observer BCA thesis[3] to examine the cost savings and other benefits gained by the acquisition and operational use of Vulture. This MBA Professional Report conducts the Vulture program business case analysis with a baseline analysis, sensitivity analysis, and a general risk assessment for Vulture. The BCA compares the performance of Vulture with Global Hawk and Global Observer in three operational scenarios performing 24/7/365 ISR and communications missions. Life Cycle Costs encompass investment costs as well as operating costs over a 15-year period in this analysis.

B. PROBLEM STATEMENTS

There is increasing pressure on DoD to cut costs. The FY 2011 President's Budget requests $708.2 billion for DoD, including $548.9 billion in Base funds and $159.3 billion in Overseas Contingency Operations (OCO) funds.[4] Acquisition reform

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[1] Defense Advanced Research Projects Agency, *Vulture Program: Broad Agency Announcement (BAA) Solicitation 07-51*, (Arlington, VA: DARPA/TTO, 2007). <https://www.fbo.gov/?s=opportunity&mode=form&id=5bffbe1738e2769b8e8b99d8e6e29b2e&tab=core&_cview=1> (2 June 2010), 4.

[2] Defense Advanced Research Projects Agency, *BAA Solicitation 07-51*, 4.

[3] Thiow Yong Dennis Lim, "A Methodological Approach for Conducting a Business Case Analysis (BCA) for the Global Observer Joint Capability Technology Demonstration (JCTD)" (M.S. thesis, Naval Postgraduate School, 2007).

[4] Department of Defense, *Fiscal Year 2011 Budget Request Overview. February 2010*, (Washington, D.C.: OUSD(C), 2010), 1–1.

continues to be a major issue as DoD attempts to use the authorized budget more effectively and efficiently, and efforts are being made to improve financial transparency and oversight.[5] To that end, system life cycle costs will be increasingly important when deciding a program's cost effectiveness over its life. UAVs are no exception to this requirement.

1. High Cost of Global Persistent Surveillance

Providing persistent surveillance with ISR satellites or the current UAV fleet requires additional assets to support such mission needs. Because ISR satellites orbit the earth in non-geostationary orbits, they do not loiter over a specific area. To task ISR satellites with a "real-time" requirement, there must be several of them on orbit in a particular ISR system. Individual satellites require at least one orbit to be repositioned. Once they are placed on orbit, there is comparatively little upkeep, which is primarily station keeping and tasking. Research, Development, Test, and Evaluation (RDT&E) and procurement expenses make up the bulk of the satellite costs. These costs alone can range in the billions of dollars per satellite.

Current operational ISR UAVs use fossil fuels as a source of power, meaning they can only stay aloft for one to two days. Developmental UAVs, such as Global Observer and Zephyr, can stay aloft for one to two weeks. In either case, this contrasts sharply with satellites operating on orbit for over a decade and Vulture remaining aloft for 5 years. Achieving 24/7/365 persistent surveillance in a given area with current UAVs would be costly due to the sheer number of sorties required, amount of fuel consumed, burden of logistics, and amount of maintenance necessitated by their heavy use.

2. Shortage of DoD Communications Bandwidth

DoD has an increasing need for capacity to transmit data, or bandwidth. The Pentagon maintains several satellite systems for its high priority communications, but for years, DoD has not had enough satellites to relay all of its communications-related audio,

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[5] Department of Defense, *Fiscal Year 2011 Budget Request Overview. February 2010*, (Washington, D.C.: OUSD(C), 2010), 1–3.

video, and digital data. It has had to lease commercial satellite communications capacity to support the bulk of its lower priority communications. As shown in Figure 1, commercial communications satellite use has been growing steadily in both bandwidth and cost over this decade.

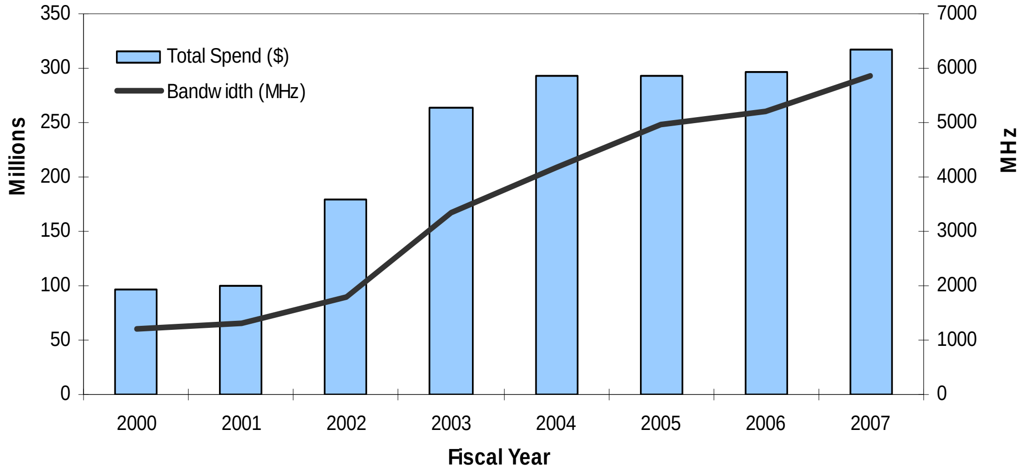

Figure 1. Growth of DoD use and expenditures on commercial communication satellite service.[6]

DoD-leased satellite bandwidth is not expected to decrease until systems such as the Navy's Mobile User Objective System (MOUO) and the Air Force's Advanced Extremely High Frequency (AEHF) and Wideband Global SATCOM System (WGS) satellites are launched and activated. The majority of the satellite launches are tentatively scheduled to begin in 2011.[7] Even once these assets are deployed, the likelihood exists that requirements will outpace newly acquired capabilities.

C. RESEARCH METHODOLOGY, LIMITATIONS, AND ASSUMPTIONS

To accomplish the goals outlined in section A, this BCA used the methodology developed by Lim in his BCA of the Global Observer UAV.[8]

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[6] Defense Information Systems Agency, *Commercial SATCOM Update*, (Arlington, VA: SATCOM PMO, 2009), 18.

[7] Department of Defense, *Fiscal Year 2011 Budget Request Program Acquisition Costs by Weapon System*, (Washington, D.C.: OUSD(C), 2010), 7–2, 3, 8.

[8] Lim, "Global Observer," 7.

As with any analysis, the accuracy of this BCA’s results is dependent on the accuracy of the data sources. The estimated cost savings, though specific to the operational scenario, can be used to estimate the savings for similar scenarios.

Basic assumptions made for this analysis include:

- Whenever a choice is made between higher and lower costs due to ambiguous data, the higher cost was used for Vulture to support conservative conclusions.
- Where information was not available, estimates were used based on reasonable assumptions.

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II. BACKGROUND

This section provides pertinent background information to assist the reader in understanding the BCA. First, persistent ISR and C3 capabilities are defined in the context of DoD requirements. Second, current technologies employed for surveillance and reconnaissance are addressed in the form of UAVs and satellites and how they relate to persistent ISR and augmenting communications. Third, emerging technologies in high altitude airships are presented in the same light. Fourth, the fundamentals of solar power technology and its integration with UAVs are discussed. Fifth, DARPA's Vulture program is described.

A. PERSISTENT SURVEILLANCE AND COMMUNICATIONS BANDWIDTH

Authorized ISR taskings push the limits of current ISR systems, and requests for ISR taskings exceed current DoD capabilities. "Surveillance" is defined by DoD as "the systematic observation of aerospace, surface, or subsurface areas, places, persons, or things, by visual, aural, electronic, photographic, or other means."[9] What commanders in theater want is "persistent surveillance," defined by DoD as:

> A collection strategy that emphasizes the ability of some collection systems to linger on demand in an area to detect, locate, characterize, identify, track, target, and possibly provide battle damage assessment and retargeting in near or real-time. Persistent surveillance facilitates the prediction of an adversary's behavior and the formulation and execution of preemptive activities to deter or forestall anticipated adversary courses of action.[10]

Persistent surveillance requires a continual tasking burden on ISR assets. Current ISR assets are either space-based and used by many organizations and agencies, or they are airborne and do not have the ability to loiter on station long enough to provide this persistence without flying multiple sorties.

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[9] Department of Defense, *Joint Publication 1-02: Department of Defense Dictionary of Military and Associated Terms 12 April 2001 (As Amended Through April 2010)* (Washington, D.C.: J-7, 2010), 456.

[10] Ibid., 358.

Another area of concern to DoD is that bandwidth requirements for C3 also exceed capabilities provided by current systems. "Bandwidth," for the purposes of this paper, refers to the data transmission rate rather than a band of frequencies dedicated to a particular communication system. After orbital insertion of satellites, technology continues to evolve on the ground, fostering new requirements for digital communication capabilities as well as an ever-increasing demand for communication bandwidth. DoD dedicated satellite constellations operated by the United States Air Force (USAF) handle the majority of high priority DoD communications, but they are rapidly becoming obsolete in technological capability. Newly employed technologies on the ground require higher data rates for transmission of real-time video, battlefield maps, and targeting data in support of tactical military operations.[11] As a result, DoD is turning to the commercial sector to satisfy its bandwidth requirements. As Rosenberg writes, "Industry experts estimate that 80 percent of all satellite bandwidth that the Defense Department uses is purchased by the Defense Information Systems Agency from companies such as Inmarsat, Intelsat and Iridium. That percentage is expected to climb north of 90 percent in the near future."[12]

B. CURRENT TECHNOLOGIES

There are three primary types of technologies either being used or being developed for DoD's surveillance and communication purposes.[13] These are:

- Fossil-fueled UAVs (flexible deployment, but limited loiter capability)
- Satellites (inflexible deployment, but persistent loiter capability)
- High Altitude Airships (relatively flexible deployment, with persistent loiter capability)

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[11] Department of Defense, *Fiscal Year 2010 Budget Request Summary Justification. May 2009,* (Washington, D.C.: OUSD(C), 2009), 1–50.

[12] Barry Rosenberg, "DOD's Reliance on Commercial Satellites Hits New Zenith," *Defense Systems*, 25 February 2010, <http://www.defensesystems.com/Articles/2010/03/11/Cover-story-The-Satcom-Challenge.aspx> (3 June 2010), 1.

[13] Lim, "Global Observer," 9.

These technologies are presented along with their pros and cons to illustrate their utility in performing persistent surveillance and communication bandwidth augmentation missions.

1. Fossil-Fueled UAVs

As the name implies, unmanned aerial vehicles are aircraft that fly without a human onboard. They are reusable aircraft that are either remotely piloted or programmed to fly autonomously in a pre-designated flight plan. UAVs are rapidly deployed and capable of carrying an array of payloads, making them vital sensor assets.[14] The primary attraction of UAVs is that they present no risk of losing a pilot, and they can perform missions that would be considered undesirable by pilots.

Some UAVs currently being used by the DoD include the MQ-1 Predator, MQ-9 Reaper, and RQ-4 Global Hawk. Such UAVs, which are capable of supporting payloads for ISR and C3 missions, burn hydrocarbon fuels. They are designed to perform a mission, or tasking, and return to base. They are not designed with the ability to be refueled in-flight. This means they have a range or loiter time limited to the amount of fuel they can carry, which for typical medium and high altitude UAVs, is limited to between one and two days. To maintain persistent surveillance and communication relay, these UAVs would need to fly a large number of sorties. This translates into increased operational costs due to high fuel consumption, increased maintenance, and constant operational burdens.

2. Satellites

Satellite constellations designed for a specific mission (such as ISR or communications) are capable of persistent 24/7/365 coverage. A single satellite, because it must orbit the earth, typically passes out of the line of sight with respect to a ground observer, and thus is not capable of persistent 24/7/365 coverage. A geosynchronous satellite is an exception to this, but such a system is beyond the scope of this professional report. In essence, single satellites are capable of increasing the mission capability of a specific system, but alone do not guarantee persistent coverage. Because satellites must

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[14] Lim, “Global Observer,” 9.

be operated in conjunction with similar satellites to obtain 24/7/365 on-station capability, they must be designed and procured with the intent of interoperability.

Further complicating the cost of satellite systems is the fact that a satellite acquisition program must accomplish a plethora of tasks related to engineering, fabricating, testing, and integrating components and technologies. Though contractors are described as developing “prototypes,” it is worth noting that these “prototypes” are the actual satellites that will be placed on orbit for operational use. Of course, this is following successful completion of a series of rigorous tests to determine operational functionality as well as launch and environmental survivability. It is not economically feasible to create satellites that will not be used. Where the construction and procurement of a UAV is measured in millions of dollars, satellite construction and procurement is measured in billions of dollars.

For example, there are significant outlays for the AEHF communications satellite program for RDT&E and procurement. These amounts are broken out in Table 2. The total cost for the 12-year AEHF program to date, including the latest costs for FY10, is approximately $8.5 billion. This amounts to just over $2.1 billion for each of the four planned AEHF satellites.[15] This figure will grow substantially with additional RDT&E, integration, satellite component procurement, subsequent launches, and future operational costs.

Table 2. AEHF program budget breakout per FY ($M).[16] [17]

FY	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010***
RDTE	37.2	54.6	89.8	229.8	459.6	802.6	775.8	607.3	639.2	617.3	612.3	386.4	464.3
Procurement	0.0	0.0	0.0	0.0	0.0	0.0	0.0	78.2	521.9	0.0	149.9	165.6	1843.5
Total Per FY	37.2	54.6	89.8	229.8	459.6	802.6	775.8	685.5	1161.1	617.3	762.2	552.0	2307.8

*Indicates latest available FY10 budget information as of publication of this paper.

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[15] Department of Defense, *Fiscal Year 2006-2010 Budget Request Summary Justifications*, (Washington, D.C.: OUSD(C), 2005–2009).

[16] Department of Defense, *Program Element # 0603430F: Advanced EHF MILSATCOM (Space)*, (Washington, D.C.: USAF, Feb. 1999–May 2009).

[17] Department of Defense, *Fiscal Year 2006–2010*.

Other limitations to satellites exist as well. First, they are not retrievable. Once they are launched, they must either be used or retired. Second, they must be designed for a specific purpose; they cannot be physically upgraded or maintained on orbit. This means satellites are very susceptible to becoming obsolete due to their inability to keep up with technological advances. Third, placing them on orbit carries considerable risk. Launch failures cause the loss of a satellite before orbital insertion, and vibration damage from launch could result in an unusable or only partially mission capable space vehicle. Finally, the space environment degrades satellites over time by affecting both hardware and software.

3. High Altitude Airships

Airships, also known as dirigibles or blimps, have been used by the military since the early 1900s. This technology has been revisited in recent years to investigate support to HALE missions. There are several versions of new airships under development that will be (and in some cases are) capable of unmanned flight in scenarios requiring 24/7/365 time-on-station.

Lockheed Martin won DARPA's ISIS program contract. The company states:

> High Altitude Airship (HAA), an un-tethered, unmanned lighter-than-air vehicle, will operate above the jet stream in a geostationary position to deliver persistent station keeping as a surveillance platform, telecommunications relay, or a weather observer. The HAA also provides the Warfighter affordable, ever-present Intelligence, Surveillance and Reconnaissance and rapid communications connectivity over the entire battle space.[18]

Aerostar and its partner, Southwest Research Institute, developed the Composite Hull High Altitude Powered Platform (CHHAPP), also referred to as the HiSentinel airship. It flew a 60 lb payload to 74,000 feet in a five hour flight.[19]

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[18] Lockheed Martin, "High Altitude Airship," *Products*, 2010, <http://www.lockheedmartin.com/products/HighAltitudeAirship/index.html> (4 June 2010).

[19] Aerostar International Inc., "Station Keeping Airships," *Near Space Applications*, <http://www.aerostar.com/aerospace/near_space.htm> (4 June 2010).

Although these platforms show a lot of promise for persistent 24/7/365 coverage, they are still unproven, and cost related information is not available.

C. HARNESSING SOLAR POWER FOR UNMANNED AERIAL VEHICLES

Marty Curry noted in a NASA Dryden Fact Sheet, "The first flight of a solar-powered aircraft took place on November 4, 1974, when the remotely controlled Sunrise II, designed by Robert J. Boucher of AstroFlight, Inc., flew following a launch from a catapult."[20] Since that time, scientists and engineers have struggled to perfect the technology involved with exploiting solar power and integrating that technology into unmanned aerial vehicles.

1. Solar Cells

Solar cells, also known as photovoltaic (PV) cells, convert sunlight into electrical energy through a process known as the PV effect. A PV cell is composed of two layers of different semiconductor materials in contact with each other: an "n-type" negatively charged layer, which contains excessive electrons, and a "p-type" positively charged layer, which contains an excess of "holes" for electrons to fill. By placing these materials together, a "p/n junction" is formed and creates an electric field. As solar energy is absorbed by the semiconductor materials, electrons are freed from their normal positions in atoms of a different or "doped" material. These electrons move in a direction dictated by the electric field towards the "holes" creating an electric current.[21]

A typical PV cell only produces a small amount of power, approximately 1 to 2 watts. Specific power output depends on the materials used, construction of the cell, and the amount and wavelength of light absorbed. In order to produce enough power to be

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[20] Marty Curry, "Solar Power Research," *NASA Dryden Fact Sheet*, 9 December 2009, <http://www.nasa.gov/centers/dryden/news/FactSheets/FS-054-DFRC.html> (3 June 2010).

[21] Department of Energy, "The Photoelectric Effect," *Solar Energy Technologies Program*, 5 January 2006, <http://www1.eere.energy.gov/solar/photoelectric_effect.html> (3 June 2010).

useful in any practical sense, many solar cells are connected to form a module, and multiple modules are connected together to form an array.[22]

2. Solar Powered UAVs

Applications for PV technology abound. In his thesis regarding the Zephyr UAV, Kwok stated,

> The range of possible applications of solar energy using PV cells is vast, from powering a simple calculator to powering a complex vehicle system. Over recent decades, this technology has also been integrated into UAVs, so that the flight endurance of UAVs is no longer dependent on the quantity of fuel that they can carry onboard, thus increasing their flight endurance significantly.[23]

Such increased flight endurance is a step forward in achieving the persistence of time on station needed for requested ISR taskings as well as to fill C3 gaps.

D. DARPA VULTURE

As mentioned earlier, DARPA's primary goals for the Vulture program are to develop a solar powered UAV capable of maintaining a 5 kW, 1,000-pound payload on station 99% of the time for five years. The Vulture program is a three phase program in which multiple contractors compete in Phase I to develop the best product, and then one contractor proceeds on to Phases II and III. Aurora Flight Science, Boeing, and Lockheed Martin were awarded Phase I contracts.[24]

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[22] Department of Energy, "PV Systems," *Solar Energy Technologies Program*, 30 December 2005, <http://www1.eere.energy.gov/solar/pv_systems.html> (3 June 2010).

[23] Kwok Yew Heng, "A Methodological Approach for Conducting a Business Case Analysis (BCA) of Zephyr Joint Capability Technology Demonstration (JCTD)" (M.S. thesis, Naval Postgraduate School, 2008).

[24] Defense Industry Daily, LLC, "DARPA's Vulture: What Goes Up, Needn't Come Down," *Defense Industry Daily*, 30 September 2009, <http://www.defenseindustrydaily.com/DARPAs-Vulture-What-Goes-Up-Neednt-Come-Down-04852> (2 June 2010).

1. Phase I

According to DARPA, the objectives of Phase I[25] were to:

- Conduct military utility analyses and develop a notional Concept of Operations (CONOPS) and system architecture for the objective Vulture system
- Conduct design trade studies to develop an objective system conceptual design
- Develop an affordable full scale demonstration system conceptual design that closes around the Broad Agency Announcement (BAA) requirements and is derived from the objective system design
- Develop a detailed technology maturation roadmap that defines a credible development program to meet the Vulture Phase II and III objectives
- Develop a subscale demonstrator conceptual design that will demonstrate key enabling technologies and system attributes of the full scale demonstration and objective systems
- Perform formal reliability and mission success analyses of the objective system and both demonstrator designs at the major subsystem/operational task level to establish the required reliability/mission success goals for the major subsystem/operational task level system elements
- Conduct a System Requirements Review (SRR) for the subscale demonstrator system

Aurora's Phase I HALE UAV, called "Odysseus," runs on solar power by day and at night uses batteries charged by the solar arrays. It is a three-piece modular design. The three UAVs can dock and separate in midair and have an overall wingspan of 160 feet. They can capture more of the sun's energy in a z-configuration during the day, and they can form a straight line for more efficient flight at night.[26]

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[25] Defense Advanced Research Projects Agency, *BAA Solicitation 07-51*, 6–7.

[26] Defense Industry Daily, LLC, "What Goes Up."

Boeing is partnered with the British firm QinetiQ and has been refining the "Zephyr" Phase I HALE UAV. Its carbon-fiber configuration has a wingspan of 59 feet and weighs just 66 pounds. It is a single aircraft that makes use of amorphous silicon solar arrays to generate power during the day and charge its lithium sulfur batteries to run at night.[27] In July 2010, Zephyr broke the UAV record for longest flight time with a 14 day and 21-hour flight.[28]

Lockheed Martin's Phase I "solar-powered design is reportedly a single UAV over 300 feet long, with tails that rotate to collect the most sunlight and systems that capture photovoltaic energy from the Earth's albedo. The power feeds electric ring motors, which can drive propellers directly at a distance without using heavy gearboxes."[29]

2. Phase II

Phase I was completed in September 2009. The program is currently in Phase II, which has a planned budget of $155 million. Phase II "seeks to 1) Develop a robust system design that maximizes military utility; 2) mature critical enabling technologies; and 3) validate through simulation, ground test and flight demonstration that an aircraft of this class is achievable."[30]

The minimum objectives for Phase II[31] are to:

- Execute a technology maturation roadmap that systemically reduces performance and reliability risks to warrant any potential follow on execution of the Objective System development

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[27] Defense Industry Daily, LLC, "What Goes Up."

[28] QuinetiQ, "High Altitude Long Endurance UAV - Zephyr," *Unmanned Air Systems*, <http://www.qinetiq.com/home/defence/defence_solutions/aerospace/unmanned_air_systems/uav.html> (29 September 2010).

[29] Defense Industry Daily, LLC, "What Goes Up."

[30] Defense Advanced Research Projects Agency, *Vulture II Program Background Information*, (Arlington, VA: DARPA/TTO, 2009), <https://www.fbo.gov/?s=opportunity&mode=form&id=050595238d8ebcea9bff6e23d5c8ed70&tab=core&_cview=1> (2 June 2010), 2.

[31] Ibid., 4–5.

- Provide risk reduction through laboratory/field demonstrations of key major subsystems ability to achieve reliability/mission success objectives of the Objective System requirements
- Establish a Preliminary Design for the Objective System, from which the FSD detail airframe design will be derived
- Develop a detailed FSD design with traceability to the Objective System configurations. FSD should have the capability for recovery and re-launch
- Document and demonstrate flight airworthiness and conduct a minimum of 30 days continuous flight demonstration
- Provide full-scale aircraft flight demonstration and acquisition of structural/aeroelastic data and validation of software development design codes for objective aircraft design
- Deliver/update proposed military utility analysis, CONOPS, and a provide 5 year mission life cycle cost of the Objective System based on Phase II analysis and validations
- Deliver/update the detailed development approach and technology maturation plan (TMP) necessary to achieve an operational Objective System at the culmination of Phase II

Following the completion of these objectives, the contractor should be prepared to move to Phase III. The Phase II exit criteria[32] are:

- Key Subsystem Risk Reductions
- Objective and FSD Design
- FSD Technology Flight Demonstration

On September 14, 2010, DARPA awarded The Boeing Company an $89 million contract to develop and fly a FSD model of its version of Vulture, which Boeing Phantom

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[32] Defense Advanced Research Projects Agency, *Vulture II Program Background*, 4.

Works has named "SolarEagle." The contract stipulates that Boeing will make its first 30 day demonstration flight above altitudes of 60,000 feet in 2014. SolarEagle will be a high-aspect-ratio UAV with a 400-foot wingspan, which is needed to supply sufficient surface area for collecting solar power, as well as provide necessary aerodynamic performance. Major suppliers for Boeing's effort include Versa Power Systems and QuinetiQ, the British corporation that co-created Zephyr with Boeing.[33]

3. Phase III

The contractor will complete and execute their TMP to provide fiscal and technical information in support of a long term acquisition strategy. The objective is to conduct a full scale flight test in at least a one year demonstration to validate the system's capabilities. More detailed Phase III objectives will be developed following the evaluation of Phase II results and the contractor's TMP.[34]

E. BUSINESS CASE ANALYSIS

A business case analysis (BCA) is a fundamental tool that considers cost and other quantifiable and non-quantifiable factors to support investment decisions.[35] It assesses alternatives by weighing their total costs against their total benefits to arrive at an optimal solution. It considers how the alternatives meet the strategic objectives of a project or program, support performance measures, and impact stakeholders. A BCA typically determines:[36]

- The relative cost vs. benefits of different support strategies
- The methods and rationale used to quantify benefits and costs
- The impact and value of Performance/Cost/Schedule/Sustainment tradeoffs

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[33] The Boeing Company, "Boeing Wins DARPA Vulture II Program," *Media*, 16 September 2010, <http://boeing.mediaroom.com/index.php?s=43&item=1425> (29 September 2010).

[34] Defense Advanced Research Projects Agency, *BAA Solicitation 07-51*, 8–9.

[35] Defense Acquisition University, "Business Case Analysis (BCA)", *Acquisition Community Connection*, 10 March 2004, <https://acc.dau.mil/CommunityBrowser.aspx?id=32524> (14 October 2010).

[36] Defense Acquisition University, "Business Case Analysis (BCA)."

- Data required to support and justify a performance based logistics strategy
- Sensitivity of the data to change
- Analysis and classification of risks
- A recommendation and summary of the implementation plan for proceeding with the best value alternative

A BCA can be approached as an iterative process, reformatted and updated as necessary throughout a program's life cycle, as the program adapts to changes in the business and mission environments. No two BCAs are exactly alike due to variations in objectives, assumptions, constraints, risk and operating scenarios, thus it is necessary for a BCA to be customized for its specific case. As illustrated in Figure 2, a BCA consists of four steps: definition, data collection, evaluation analysis, and results presentation.

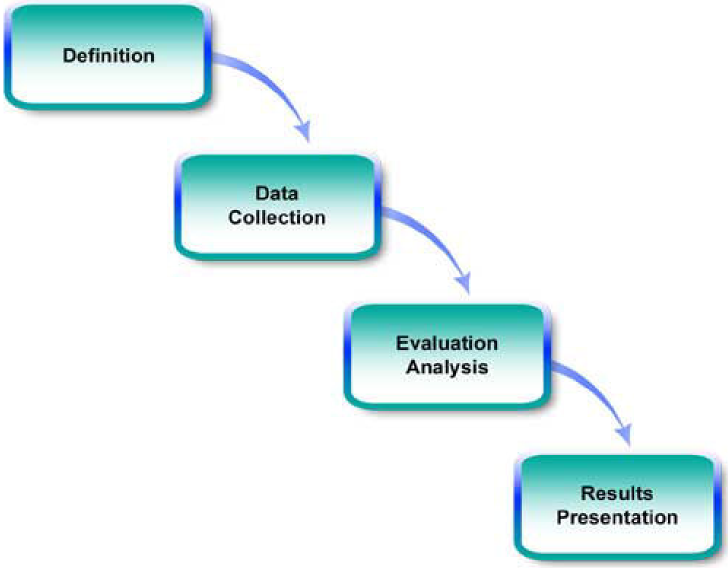

Figure 2. Steps in the BCA process.[37]

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[37] Defense Acquisition University, "Business Case Analysis (BCA)."

The steps of this process are:[38]

1. Definition

This stage describes the scope of the analysis. Assumptions and constraints are formulated to guide the analysis, and the number of alternatives the BCA will consider is set. At least two alternatives will be considered: adopting a decision, or maintaining the status quo.

2. Data Collection

In the data collection stage of the BCA, types of data needed are identified and classified, data sources are identified, and a methodology is created for obtaining the data. Data that cannot be found is estimated, and the methodology for estimating data is clearly explained. All data is vetted for accuracy and then normalized for comparisons (for example, comparing either only constant dollars or only current year dollars).

3. Evaluation Analysis

The third phase of the BCA uses the data collected in the previous phase to perform the necessary calculations. Both qualitative and quantitative data are used to build a case for each alternative. The alternatives are then compared to identify the best value option, providing the best combination of cost and performance. A risk analysis must also be performed to identify risks and potential mitigation strategies. This is accompanied by sensitivity analyses to determine the effect that changes in individual inputs, assumptions, and constraints will have on the model's output (for example, the effect that an increase or decrease in the cost of fuel or labor will have on the total cost of each alternative).

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[38] Defense Acquisition University, "Business Case Analysis (BCA)."

4. Results Presentation

The final phase of the BCA is the presentation of the results. Here, conclusions are drawn from the output of the evaluation analysis and are based on the initial objectives of the BCA. Quantitative data is presented in graphs and charts. The meanings of all results are clearly explained. Attention is paid to unexpected, outlying or easily misinterpreted results. Finally, a recommended course of action is presented for decision makers, bringing closure to the BCA.

III. VULTURE BUSINESS CASE ANALYSIS

The purpose of this analysis is to compare the benefits of Vulture to those of the existing Global Hawk ISR platform and the developmental Global Observer HALE UAV platform.

This section describes the three representative scenarios used to compare the costs of Vulture, Global Hawk, and Global Observer. The Zephyr system was initially included in this analysis, but the inclusion was determined to be inappropriate because Zephyr is unable to meet the minimum payload requirements of Vulture. The business case analysis compares the costs of these platforms performing continuous operations (i.e., round-the-clock ISR and communication relay missions). The scenarios used in the analysis will be explained in section A. The available data will then be analyzed in section B. This is followed by a computation of the return on investment in section C, and sensitivity analyses on the input data and assumptions in section D.

A. OPERATIONAL SCENARIOS

The operational scenario of this analysis is based on a strategic employment plan of these ISR and communications platforms (i.e., the Vulture, Global Hawk, or the Global Observer) over three areas of interest, which relates to the U.S. National Security Strategy. These ISR missions require continuous coverage and may also perform tactical battlefield communications missions in the area. Three operationally realistic scenarios were chosen to represent potential long-, mid-, and short-range missions performed by the platforms. The following three regions were used to develop the tasking requirements for the analytical scenarios:

- <u>Trans-Sahara Region</u>: To support the Trans-Sahara Counter-terrorism Initiative (TSCI). This represents the long-range mission.
- <u>Afghanistan/Pakistan</u>: To support global overseas contingency operations. This represents the short-range mission.

- <u>China / North Korea</u>: To maintain U.S. surveillance of nuclear facilities and military defenses in the region. This represents the mid-range mission.

1. Scenario Information

The operationally realistic scenarios described below were used in estimating the life cycle costs of the ISR platforms.

a. Trans-Sahara Region

The deployment of a strategic ISR asset (Global Hawk, Global Observer, or Vulture) would significantly enhance the U.S. forces' ISR capabilities in support of TSCI. In addition, with the heavy reliance on commercial satellite communications due to the lack of existing ground-based networks, the Vulture would also function as an airborne data relay for in-theatre communications. Due to the large geographical region to be covered, the mission requires two UAV assets (based on the UAV sensor footprint) to cover this North African region. The Trans-Sahara Region scenario represents a long distance mission requirement.

b. Afghanistan/Pakistan

The deployment of an ISR asset (Global Hawk, Global Observer, or Vulture) would significantly enhance the U.S. forces' ISR capabilities for global overseas contingency operations in the Afghanistan/Pakistan region. Again, with heavy reliance on commercial satellite communications due to the lack of existing ground-based networks, Vulture would also function as an airborne communications satellite for in-theatre communications. The mission only requires one UAV asset to cover this region. The Afghanistan/Pakistan scenario represents a short distance mission requirement.

c. China/North Korea

The deployment of a strategic ISR asset (Global Hawk, Global Observer, or Vulture) for persistent surveillance of the China/North Korea region would enhance

U.S. surveillance of nuclear facilities and military defenses in the region. The mission requires one UAV asset to cover this region. The China/North Korea scenario represents a mid-distance mission requirement.

2. UAV Operating Bases

For the purpose of comparison, it is assumed that the Global Hawk, Global Observer, the Vulture missions can be launched from either of the following two existing Global Hawk operating bases. These bases are:

- Anderson Air Force Base (Guam) – Current Global Hawk Forward Operating Base
- Al Dhafra Air Base (United Arab Emirates) – Existing Expeditionary Global Hawk Forward Operating Base

3. Selection of UAV Operating Base

Table 3 illustrates the distances from the nearest operating base (rounded to the nearest 10 nautical miles) to the various Areas of Operations (AO). For the purpose of computing distances, the following locations were used as proxies for the respective AO:

- Trans-Sahara Region: Niger-Algeria-Mali boundary
- Afghanistan/Pakistan: Kabul
- China/North Korea: Pyongyang

Table 3. Selection of operating base to launch the UAV.

	Area of Operation	**Nearest UAV Operating Base**	**Distance (nm)**
1	Trans-Sahara Region	Al Dhafra AB	2810
2	Afghanistan/Pakistan	Al Dhafra AB	980
3	China/North Korea	Anderson AFB	1860

Figure 3 shows the geographical locations of the various AOs and the UAV operating bases. The AOs are represented by dashed ellipses, and the operating bases are represented by stars.

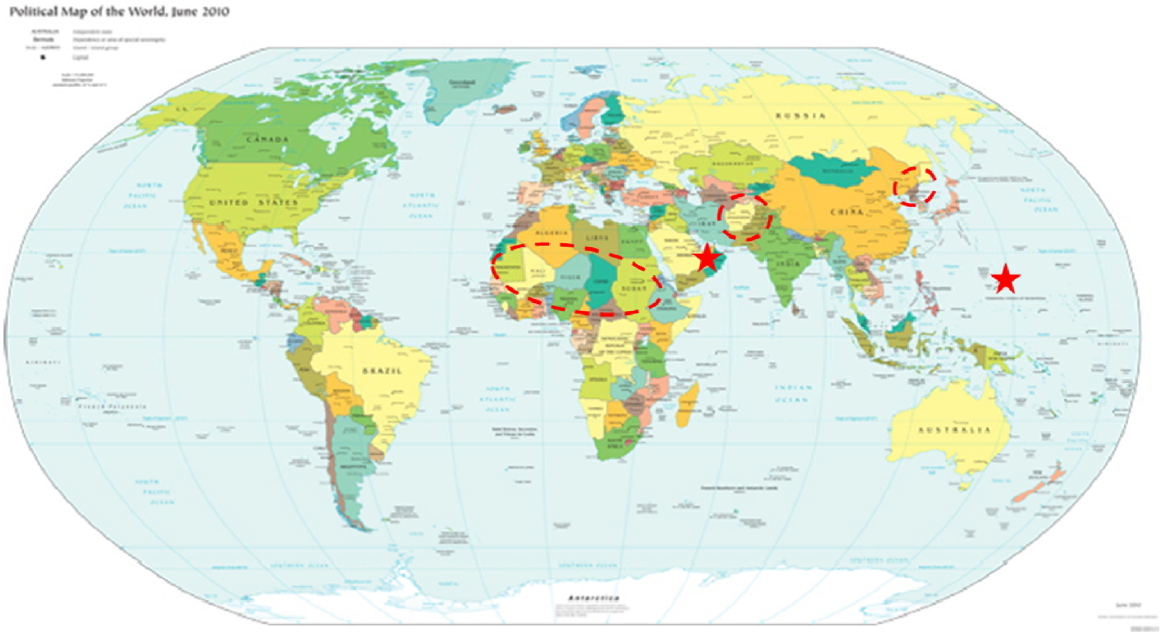

Figure 3. World map with annotation of UAV operating bases and AOs.[39]

B. DATA ANALYSIS

The following sections provide an analysis of the data based on the aforementioned operational scenarios.

1. Minimum Number of UAVs Required for Persistent Surveillance

A UAV mission sortie typically consists of a launch from its operating base, travel time to the designated AO, a loiter period in which the UAV performs the mission, and finally the return trip to its operating base for maintenance, refueling and re-launch. To perform persistent surveillance, another UAV overlaps this mission so that it arrives at the AO just as the first UAV is leaving. Figure 4 illustrates the typical mission sortie profile of a UAV.

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[39] Central Intelligence Agency, “Political World Map,” *The World Factbook*, <https://www.cia.gov/library/publications/the-world-factbook/docs/refmaps.html> (10 Sep 10).

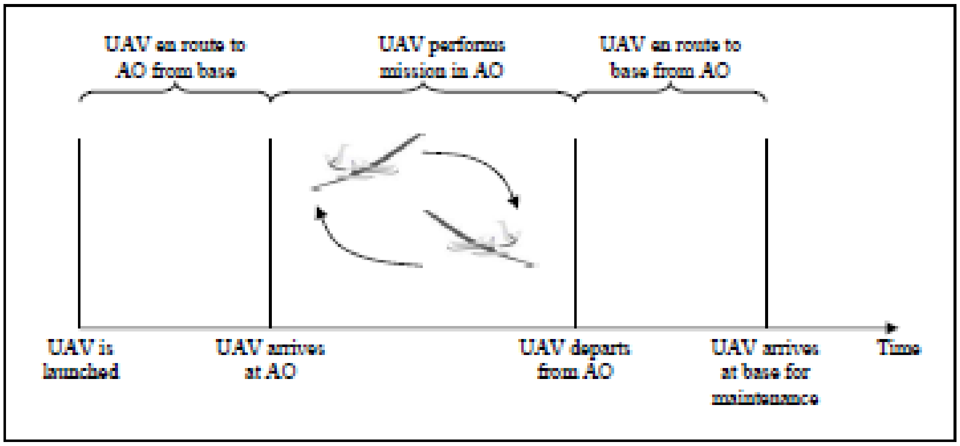

Figure 4. Typical UAV mission sortie profile.[40]

The number of UAVs required represents the total quantity of vehicles needed to ensure 24/7/365 surveillance of the AO, taking into account the typical sortie mission duration, as well as required maintenance and mission preparation time.

Table 4 summarizes the cruise speeds and flight endurance times for Global Hawk, Vulture, and Global Observer used in this analysis.

Table 4. Cruise speed and endurance times for Global Hawk and Vulture.

Attribute	**Global Hawk**[41]	**Vulture**[42]	**Global Observer**[43]
Cruise Speed (knots)	335	79	110
Endurance (hrs)	31	43,800	168

The following assumptions were made in computing the minimum number of UAVs required for persistent surveillance of the AO:

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[40] Lim, "Global Observer," 37.

[41] Marty Curry, "Global Hawk – Performance & Specifications," *NASA Dryden Fact Sheet*, 7 April 2009, <http://www.nasa.gov/centers/dryden/news/FactSheets/FS-054-DFRC.html> (20 October 2010).

[42] Defense Advanced Research Projects Agency, *BAA Solicitation 07-51*, 4.

[43] Lim, "Global Observer," 37.

- The returning UAV will have one hour of spare flight time (i.e., reserve fuel load) remaining when it arrives back at base.
- The time required for maintenance is assumed to take an average of 36 hours after each mission sortie for the Global Hawk and Global Observer. This takes into account that maintenance can be as short as a few hours (for normal refueling operations), or possibly as long as a week (for complete structural maintenance and inspection after the UAV is deployed for a certain number of missions).
- The Vulture requires no maintenance time because once a Vulture finishes its five-year mission it is not expected to be re-used.
- Weather factors, such as headwind or tailwind, which may affect a UAV’s travel time, are not taken into account in the analysis.
- The time taken to climb to cruise altitude is assumed to be negligible compared to the UAV’s flight endurance.
- Aerial spares for redundant coverage are not required.
- Global Hawk and Global Observer are assumed to have one ground spare for each AO. Due to the expected mission duration and reliability of Vulture, there is assumed to be zero ground spares required for Vulture.
- Vulture’s sensor footprint (coverage) is assumed to be equal to that of Global Hawk and Global Observer. This assumption is based on Vulture’s intended operating altitude of 65,000+ feet while Global Hawk operates at 55,000 feet.

For each AO, the minimum number of UAVs required for persistent surveillance is computed based on the following formula:

$$\mathit{Number\ of\ UAVs\ required}$$

$$= \left[\frac{\mathit{Mission\ Cycle\ Time}}{\mathit{UAV\ \ Loiter\ Time}}\right] x\ \mathit{UAVs\ On\ Station} + \mathit{Ground\ Spare}$$

$$\mathit{where\ Mission\ Cycle\ Time}$$

$$= \mathit{UAV\ \ Loiter\ Time} + \mathit{Roundtrip\ Transit\ Time} + \mathit{UAV\ \ Maintenance\ Time}$$

Based on this formula, the UAV fleet size requirements for persistent surveillance in each scenario are shown in Table 5.

Table 5. Minimum of UAVs required to perform missions in all three scenarios simultaneously.

Scenario	Global Hawk	Vulture	Global Observer
Trans/Sahara	11	2	5
Afghanistan/Pakistan	4	1	3
China/North Korea	5	1	3
Total Fleet Size	20	4	11

Based on the three operational scenarios, the total Vulture fleet size to support the 24/7/365 persistent surveillance requirement is 4 UAVs in any given year. In comparison, 20 Global Hawks or 11 Global Observers would be needed to meet the same requirement. It should also be noted that due to the Vulture's high ratio of loiter time to transit time (more than 1000:1 in all scenarios), additional Vultures are only needed in the fleet to cover its transit time once every five years when the Vulture is replaced. In comparison, the ratio of loiter time to transit time for Global Hawk and Global Observer is approximately 4:1 and 7:1, respectively. Given that the Vulture coverage lapse is 1/300th of the total mission time for each Vulture on average, this study assumes there are no spare Vultures in the fleet for any of the scenarios just to cover the transit time once every five years. It is assumed that the use of other resources would be used as a supplement during the transit time coverage lapse.

2. Annual Number of Sorties Required for Persistent Surveillance

In addition to fleet size, the number of sorties required also has a bearing on the total cost of a program. A higher number of sorties required results in increased operating and support costs and a greater risk of take-off and landing mishaps. The number of sorties required per year for a given scenario is computed based on the following formula:

$$\text{Number of Sorties Required per year}$$

$$= \left[\frac{365 \times 24}{\text{UAV Loiter Time}}\right] \times \text{UAVs On Station}$$

Figure 5 represents the annual number of sorties required for each UAV in relation to distance between the AO and the operating base.

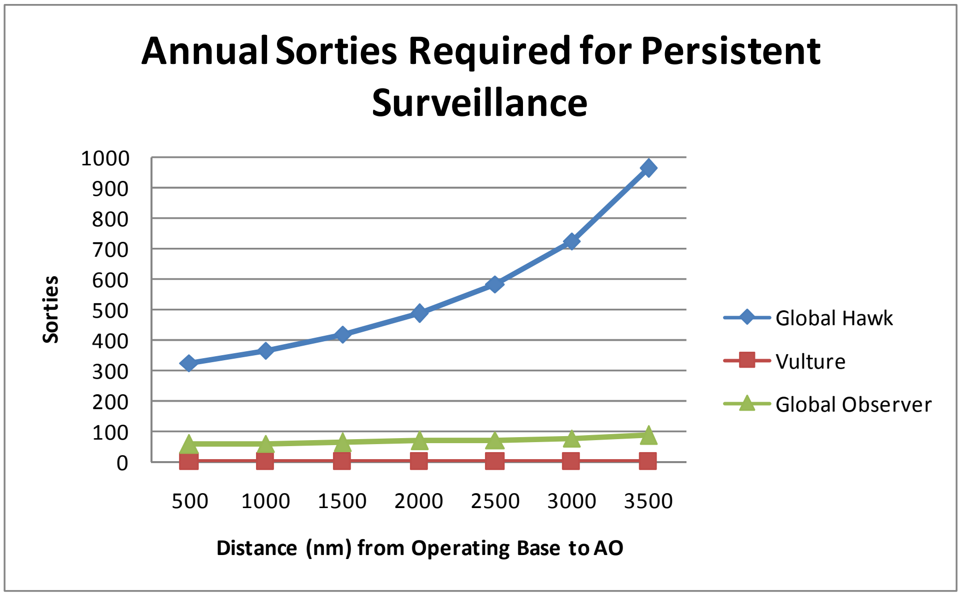

Figure 5. Annual UAV sorties required in relation to mission distance.

For the specific operational scenarios analyzed in this study, Figure 6 reflects the number of sorties required by Global Hawk and Global Observer. A total of 2,152 Global Hawk sorties or 277 Global Observer sorties would be required each year to support the three operational scenarios with 24/7/365 surveillance. By comparison, a total of four Vulture sorties would be required to support the three operational scenarios (one for each UAV required in each AO). Additionally, no further Vulture sorties would be required for the next four years, while Global Hawk and Global Observer sortie requirements recur annually.

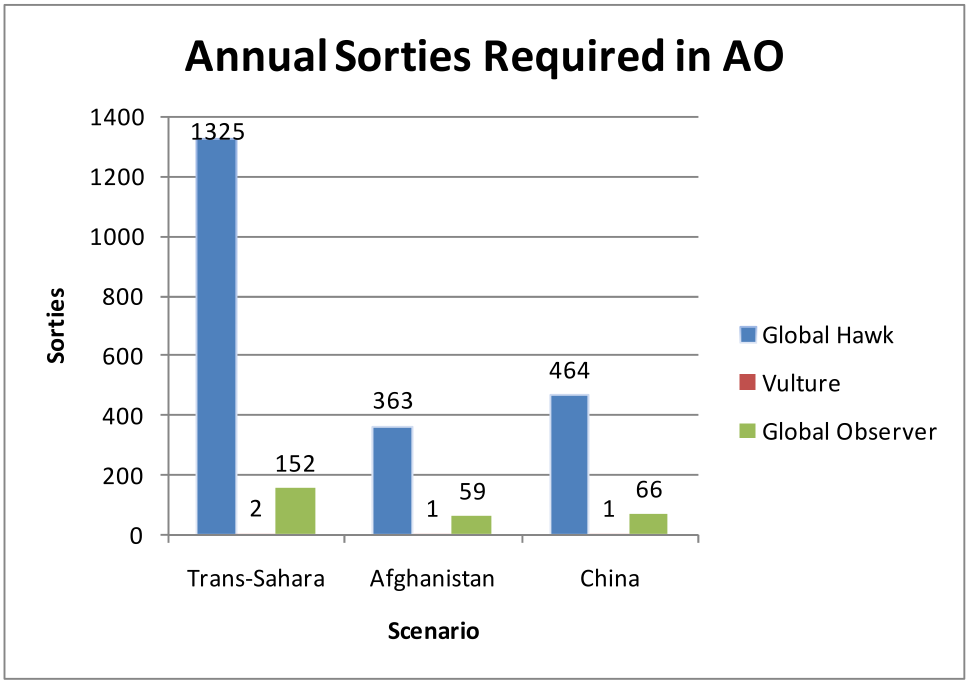

Figure 6. Annual sorties required for each scenario.

3. Utility of the UAVs

The utility of a UAV can be defined as the proportion of loiter time to total mission time. The utility is represented by the following equation:

$$UAV\ Utility = \frac{UAV\ Loiter\ Time}{UAV\ Mission\ Cycle\ Time}$$

$$where\ Mission\ Cycle\ Time$$

$$= UAV\ Loiter\ Time + Roundtrip\ Transit\ Time + UAV\ Maintenance\ Time$$

The utilities for Global Hawk, Vulture, and Global Observer are indicated in Figure 7. Due to the high endurance of Vulture, nearly 100% of its mission cycle time is spent on station.

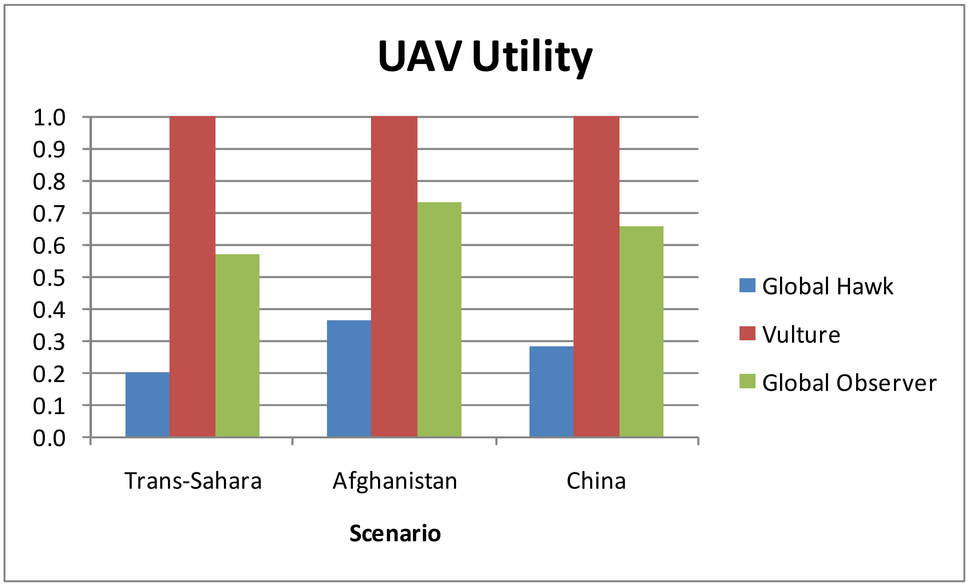

Figure 7. UAV utility for each scenario.

4. Life Cycle Cost

For this analysis, a UAV program's life cycle cost consists of investment and operations and support (O&S) costs over the life of the program. It is assumed that the life of the program is 15 years in this analysis. To compute and compare the life cycle costs of Vulture, Global Hawk, and Global Observer, several assumptions were made:

- All costs are computed and presented in FY10 dollars. Inflation indices were provided by SAF/FMCE.[44]
- A real discount rate of 2.45% was used to compute net present values.[45]
- Investment costs for Global Hawk and Global Observer all occur in Year 0. It is assumed that these aircraft will be useful for the life of the program, no matter the usage rate.

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[44] United States Air Force SAF/FMCE, *USAF Raw Inflation Indices Based on OSD Raw Inflation Rates Base Year (FY) 2010*, (Washington, D.C.: SAF/FMCE, 2010).

[45] Office of Management and Budget, "OMB Circular No. A-94 Appendix C," December 2009, <http://www.whitehouse.gov/omb/circulars_a094_a94_appx-c> (17 Aug 2010).

- Investment costs for Vulture occur every five years to replace the expiring Vultures, and prior to the year the air vehicle enters operation. Therefore, Vulture investments for the air vehicles and payloads occur in Year 0, Year 5, and Year 10.
- Mission Control Station investment costs for all three UAV systems only occur in Year 0 and are operational for the life of the program.
- Fuel, maintenance, and repair costs are assumed to be the only O&S costs that are differentiable between the UAV systems. Other O&S costs, such as costs associated with launches, data links, manpower, etc., are assumed to be equal for all systems analyzed.
- Attrition is assumed to be zero for all systems. This includes attrition associated with take-offs, mission performance, and landings.

The investment cost category consists of acquisition costs for the air vehicle (AV), Mission Control Stations (MCS), and payloads. The O&S cost category consists of costs for fuel, maintenance, and repair. The basis of cost estimates for each of the analyzed costs is listed in Table 6.

Table 6. Basis of cost estimates for each UAV system for each cost category.

Cost Category	**Global Hawk**	**Vulture**	**Global Observer**
Air Vehicle	Actual cost	CERs & subject matter expert	BCA
Mission Control	Actual cost	Analogy to Global Hawk	BCA
Payload	Actual cost	CERs & assumed cost factor	BCA
Fuel	Actual cost	N/A	Estimated cost
Maintenance & Repair	10% capital cost	N/A	BCA

A detailed description of each individual cost is broken down in the following paragraphs. Table 8 provides a summary of the total net present value life cycle costs estimated in this analysis.

a. Air Vehicle Cost

UAV cost estimating relationships (CERs) provided by the office of the Deputy Assistant Secretary Army (Cost & Economics) that were developed from traditional fossil-fuel powered UAV data,[46] estimate the cost of a Vulture vehicle to be from $6M to $475M based on the given requirements of the system. Based on the range of these estimates, this study assumes the average unit cost of a Vulture AV for the production of 12 aircraft (to support the three given scenarios for 15 years) is estimated to be $100.0M per AV in the base case. This average unit cost is the sum of the estimated costs of the major components of the Vulture AV. The solar energy collection and storage capability required by the aircraft incurs a significant portion of the cost of the total platform. Assuming an estimated energy requirement of 500 kW for Vulture, and an estimated industry average cost of $100 per watt for the solar cells needed to supply and store the power, the estimated cost of solar energy collection and storage per air vehicle is $50M. Another $50M is estimated for the costs of structures, avionics, and other required equipment and software.[47] Sensitivity analysis of these Vulture cost assumptions will be performed in Section D to analyze the impacts that alternative cost projections have on NPV LCC and ROI computations. The cost of a Global Hawk is $97.7M per AV.[48] The cost of a Global Observer is $15.8M per AV.[49]

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[46] Deputy Assistant Secretary Army (Cost & Economics), *Unmanned Air Vehicle System Acquisition Cost Estimating Methodology*, (Washington, D.C.: DASA-CE, 2004), 17–23.

[47] Daniel Nussbaum, Vulture BCA Meeting, Naval Postgraduate School, Monterey, CA, 18 October 2010.

[48] Department of Defense, *Selected Acquisition Report: Global Hawk (RQ-4A/B)*, 31 December 2009, (Washington, D.C.: OUSD(C), 2010), 26.

[49] Flight International, "Aerovironment Details New Global Observer Variants," *Flight International*, 14 February 2006, <http://www.flightglobal.com/articles/2006/02/14/204655/aerovironment-details-new-global-observer-variants.html> (12 August 2010).

b. Mission Control Station Cost

The cost of a Global Hawk MCS is estimated to be $3.3M[50] per aircraft supported. It is assumed that an MCS for Vulture is equivalent in complexity and requirements per aircraft supported, and therefore, will incur a cost of approximately $3.3M per aircraft as well. The actual cost of a Vulture MCS may be larger or smaller than a Global Hawk MCS, but in either case, it is not expected to be a significant cost driver as a percentage of total acquisition cost. The cost of a Global Observer MCS is assumed to be $1.6M per air aircraft based on the Global Observer BCA.[51]

c. Payload Cost

The payload for the Vulture will be required to have an endurance of five years since there will be no planned maintenance of the Vulture once launched. Therefore, the cost of a payload for Vulture was estimated using the cost per pound of current Global Hawk payloads and scaling the cost by a notional extended endurance cost factor of five.[52] This cost multiplier is intended to capture costs resulting from the higher payload reliability and technology required by a five year payload life span. A sensitivity analysis was performed on this scaling factor to understand its impact on the Vulture NPV LCC. The sensitivity analysis can be found in section D.8 of this chapter. As a result, the estimated cost of a Vulture payload is $50.3M. The average payload cost for Global Hawk is $26.5M,[53] and the payload cost of Global Observer is $5.5M.[54]

d. Fuel Cost

The Vulture air vehicle will be completely powered by solar technology and will therefore incur zero fuel costs over the life of the aircraft. To calculate the fuel

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[50] United States Air Force SAF/FMB, *United States Air Force FY11 Budget Estimates Aircraft Procurement, Air Force Volume 1*, February 2010, (Washington, D.C.: SAF/FMB, 2010).

[51] Lim, “Global Observer,” 43.

[52] Nussbaum, Vulture BCA Meeting.

[53] DoD SAR, *Global Hawk (RQ-4A/B),* 26.

[54] Lim, “Global Observer,” 43.

cost for the Global Hawk and Global Observer systems, their fuel cost per sortie can be calculated, and then that cost per sortie can be combined with the annual sortie requirements to calculate the annual fuel cost for each system.

The FY11 cost of JP8 fuel for Global Hawk is $3.03/gallon.[55] The specific gravity of JP8 is 0.80,[56] and the gallon-to-pound conversion rate is 0.120. Therefore, the cost of JP8 is $0.29/lb. A Global Hawk has a fuel capacity of 15,400 pounds.[57] Given these numbers, the cost of fuel per sortie for a Global Hawk is $4,481.

Global Observer's per sortie fuel requirements of liquid hydrogen (LH_2) may be similarly calculated. The cost for LH_2 in FY11 is $3.76/lb.[58] Therefore, at a cost of $3.76/lb, and a fuel capacity of 1000 pounds,[59] the cost of fuel per sortie for a Global Observer is $3,760.

The annual fuel cost for both Global Hawk and Global Observer may be estimated by multiplying the cost of fuel per sortie by the number of annual sorties required to support the three scenarios. It is assumed that nearly the entire fuel capacity of the aircraft will be used for each sortie. All fuel not used in transit will be used to maximize loiter time to increase aircraft mission utility and decrease total number of sorties required (less a negligible remaining amount of reserve fuel). The annual fuel costs are listed in Table 7.

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[55] Defense Logistics Agency Energy, "FY2011 Prices for Publication," *DLA Energy*, <http://www.desc.dla.mil/DLA%20Energy_files/FY2011_Prices_for_publication.pdf> (14 September 2010).

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[58] Defense Logistics Agency Energy, "FY2011 Prices for Publication."

[59] Lim, "Global Observer," 43.

Table 7. Annual total cost of fuel to support scenarios.

UAV	Cost/lb	Capacity (lbs)	Cost/sortie	Sorties/year	Annual Cost
Global Hawk	$0.29	15,400	$4,481	2,152	$9.64M
Global Observer	$3.76	1,000	$3,760	277	$1.04M

The annual costs of fuel to support these aircraft would increase if fully burdened fuel costs were used for the calculations.

e. Maintenance and Repair Costs

The Vulture AV will remain in flight for the entirety of its five year endurance, and after five years have passed, the Vulture AV will not be recovered. A new AV will be launched in its place. Consequently, once launched, it is not expected to have any maintenance or repairs performed. Therefore, it is assumed that there will be zero maintenance and repair costs to support the Vulture program.

Analysis of FY05 and FY06 Global Hawk data indicate that the annual maintenance and repair costs are approximately 10% of the acquisition cost of the operating inventory.[60] This ratio is assumed to be equivalent for Global Observer as well. Given this data, the annual maintenance and repair cost is estimated to be $9.8M for each Global Hawk and $1.6M for each Global Observer.

f. Summary of Costs

Taking into account these five cost factors and their associated assumptions, Table 8 provides the net present value of total life cycle cost (real discount factor of 2.45%) in FY10 $M to acquire and operate each respective UAV in the three scenarios described over 15 years.

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[60] Lim, “Global Observer,” 45.

Table 8. Total life cycle NPV cost to support three scenarios (FY10 $M).

Cost Element	Global Hawk	Vulture	Global Observer
Investment Costs			
Air Vehicle	1,953.51	1,068.40	173.35
Mission Control Station	65.38	13.08	17.34
Payload	530.76	537.01	61.04
Investment Subtotal	**2,549.64**	**1,618.49**	**251.74**
Operations & Support Costs			
Fuel	119.84	0.00	12.94
Maintenance & Repair	2,427.62	0.00	215.44
O&S Subtotal	**2,547.47**	**0.00**	**228.38**
Total NPV LCC	**5,097.11**	**1,618.49**	**480.12**

C. RETURN ON INVESTMENT

The return on investment (ROI) analysis was conducted by computing the ROI for Vulture when compared with Global Hawk. Afterwards, several non-quantified benefits are provided.

1. Vulture-Global Hawk ROI

The ROI for Vulture in comparison to Global Hawk is based on the net present value of life cycle costs of the UAV programs over 15 years to support the three scenarios described in Section A of this chapter. From Table 8, the NPV of life cycle savings in comparison to Global Hawk of Vulture are $3,479M, and the NPV of the Vulture investment is $1,618M. The annualized ROI over 15 years can be calculated using the following formula:

$$ROI = \left(\frac{Net\ Present\ Value\ of\ Savings}{Net\ Present\ Value\ of\ Investment}\right)^{1/15} - 1$$

Therefore, the annualized return on investment for Vulture is 5.23% when compared to using the Global Hawk for the same mission scenarios over 15 years.

2. Non-Quantified Benefits

In addition to the life cycle costs and savings previously discussed, the Vulture platform also has benefits not quantified in this study:

- High utility rate of mission cycle time (see Figure 7) for Vulture provides 24/7/365 persistent surveillance with each individual air vehicle.
- The ability of re-tasking Vulture and positioning it to support quick-reaction tactical ground operations.
- The Vulture platform may be used as a communications relay station in lieu of leasing commercial satellite bandwidth.
- Only one sortie every five years per Vulture essentially eliminates all additional manpower and risks associated with maintenance, repair, constant sortie generation, takeoffs, and landings that other UAVs incur to support the same missions (see Figure 5).
- Vulture is 100% solar powered, resulting in zero carbon emissions.
- Improved sensor resolution over space-based assets.[61]
- Less required transmit/receive power between connecting devices than satellites.[62]
- No logistics tail.[63]
- Absence of an in-country footprint.[64]

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[61] Defense Advanced Research Projects Agency, "DARPA's Vulture Program Enters Phase II," 15 September 2010. <http://www.darpa.mil/news/2010/NewsReleaseVultureII.pdf> (2 November 2010).

[62] Ibid., 1.

[63] Ibid.

[64] Ibid.

D. SENSITIVITY ANALYSES

Due to the number of unknowns regarding actual future costs of the Vulture program, a variety of sensitivity analyses were conducted to provide a decision maker with multiple points of reference when making a program decision. The cost factors for the sensitivity analyses performed and the ranges of values considered are in Table 9.

Table 9. Sensitivity analysis cost factors, ranges, and base case values.

Cost Factor	Range of Values	Base Case Value
Discount factor	1% – 7%	2.45%
Period of analysis	10 – 30 years	15 years
Mission distances	980 – 2810 nautical miles	980 – 2810 nautical miles
Additional R&D	$0 – $3,000M	$0
Vulture air vehicle cost	$50 – $500M	$100M
Cost of solar energy	$50 – $500/W	$100/W
Payload endurance cost factor	1 – 7	5
Cost of JP8 Fuel	$2.00 – $4.50/gal	$3.03/gal

The effects of these cost factors may be identified by tracking the change in life cycle costs of the systems as the cost factor is changed. Unless stated otherwise, the NPV life cycle costs represent the total NPV system costs to support 24/7/365 persistent surveillance for the three scenarios discussed (Trans-Sahara, Afghanistan/Pakistan, and China/North Korea).

1. Discount Factor Sensitivity

Figure 8 shows how the NPV LCCs of each system are affected by changes in the discount factor. Global Hawk has considerably more costs in the out-years than the other systems analyzed. Its NPV is therefore the most sensitive of the three systems as the discount factor varies from 1% to 7%. The real discount factor in the base case is 2.45%.

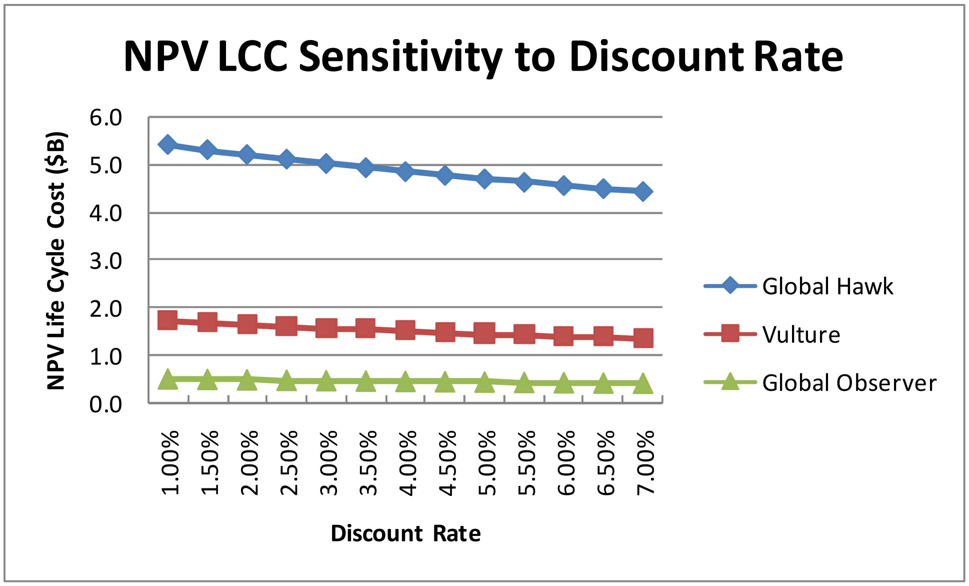

Figure 8. NPV LCC sensitivity (FY10 $B) to discount rate.

A change in discount rate within this range would not change the order of preference of the three systems from an LCC perspective.

The change in Vulture ROI with Global Hawk as the base, as discount rate is adjusted, is presented in Figure 9. The change in discount rate has little effect on the ROI of Vulture.

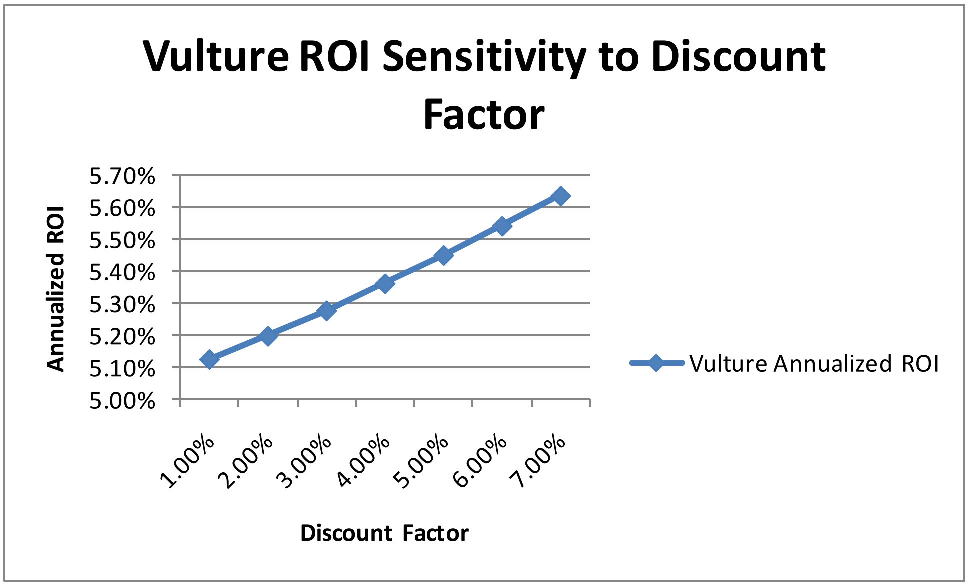

Figure 9. Vulture ROI sensitivity to discount factor with Global Hawk as the base.

2. Period of Analysis Sensitivity

The period of analysis in the base case is 15 years. For each additional year of analysis, Vulture becomes more attractive in comparison to Global Hawk, but less attractive in comparison to Global Observer. The results of this sensitivity analysis are provided in Figure 10. The Vulture program's LCC function moves by steps rather than linearly as a result of the investment costs that are incurred every five years to replace the previous Vulture AVs and payloads. The other systems do not experience similar steps from acquisition costs because as stated previously, an assumption for the investment of Global Hawk and Global Observer was that investment would only be required in Year 0.

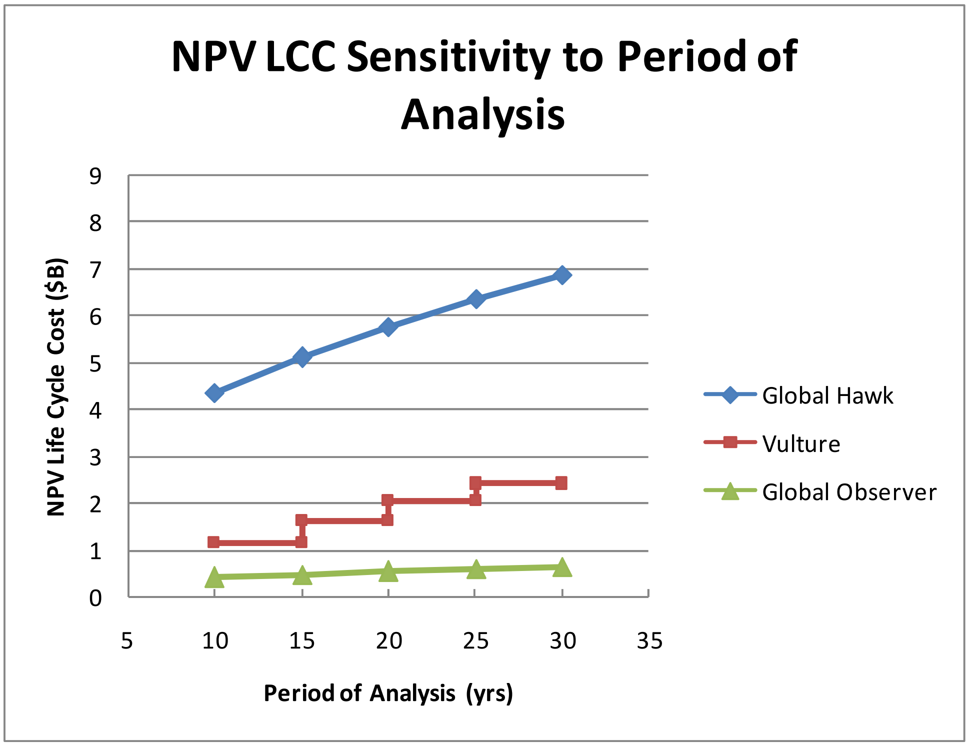

Figure 10. NPV LCC sensitivity (FY10 $B) to period of analysis.

Figure 11 illustrates the return on investment sensitivity to these varying periods of analysis. As the period of analysis increases, the annualized ROI of Vulture, with Global Hawk as the base, decreases.

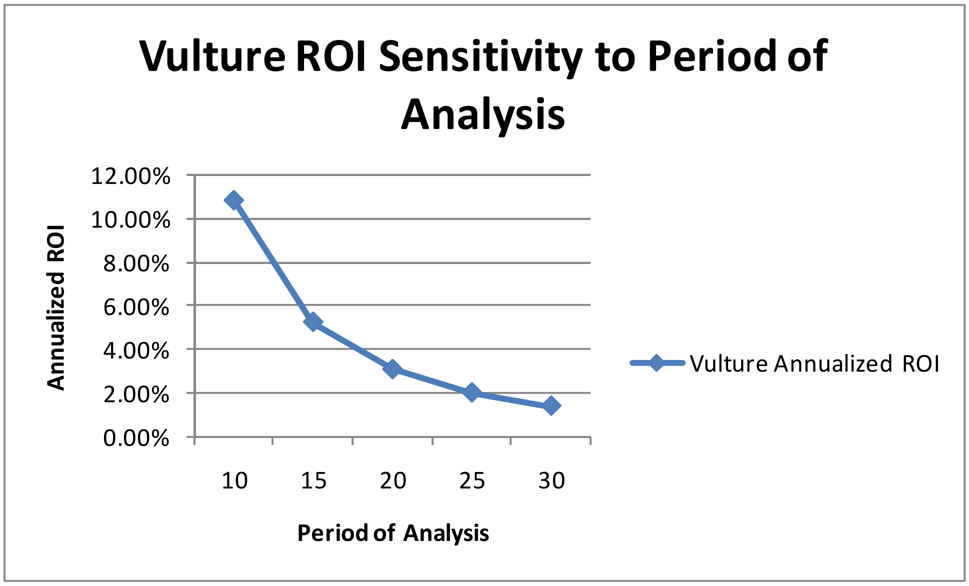

Figure 11. Vulture ROI sensitivity to period of analysis with Global Hawk as the base.

3. Mission Distance Sensitivity

The base case assumes three scenarios of varying lengths. These scenarios consist of a short (Iraq/Afghanistan) mission distance of 980 nm, a mid-range (North Korea/China) mission distance of 1860 nm, and a long (Trans-Sahara region) mission distance of 2810 nm. Figure 12 summarizes the NPV LCC costs for each system to support one persistent surveillance mission over 15 years. In this analysis, the base case assumption of two UAVs required for the Trans-Sahara region was adjusted to require only one UAV, for comparative purposes to the other scenarios.

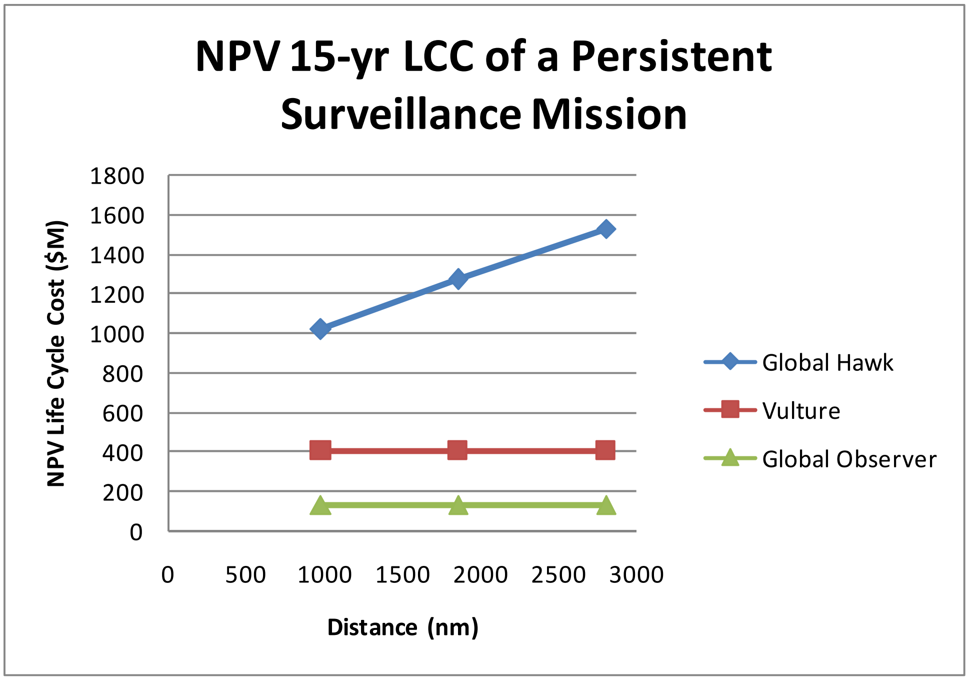

Figure 12. NPV LCC sensitivity (FY10 $M) to mission distance.

The costs for Vulture remain constant as mission distance is lengthened because its extended endurance requires only one vehicle and one sortie for all distances analyzed. The costs for Global Observer only increase a negligible amount as distance increases. Additional Global Observer sorties are required, but the cost of those additional sorties has a minimal effect on overall cost. There are no additional Global Observer systems required to support the distances analyzed in this sensitivity analysis because the system's mission endurance is still adequate to meet the distance requirements with sufficient remaining loiter time. The costs for Global Hawk increase significantly as mission distance increases. The Global Hawk cost increase is largely the result of nearly two times as many annual sorties being required between the short (363 sorties) and long (663 sorties) missions. Also, additional Global Hawks must be procured as distance is lengthened to cover reduced loiter time at those distances.

The ROI for Vulture in comparison to Global Hawk can also be computed for each mission distance to analyze distances at which Vulture provides a greater return on investment. As seen in Figure 13, Vulture provides a greater return on investment in comparison to Global Hawk as mission distance is extended.

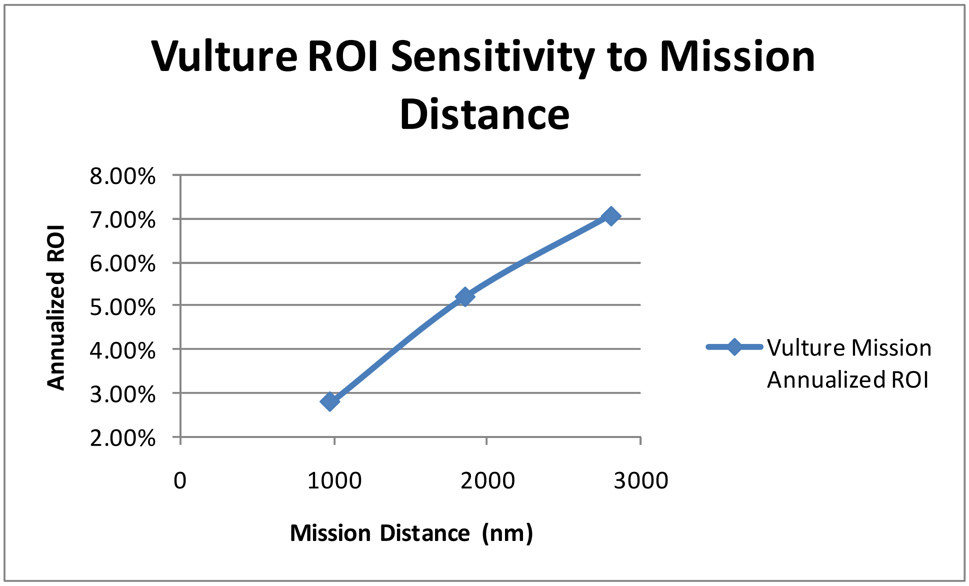

Figure 13. Vulture ROI sensitivity to mission distance with Global Hawk as the base.

4. Additional Vulture Research and Development Costs Sensitivity

The base case assumed no additional Vulture R&D costs would be required for the using organization, once acquired. However, it's possible that additional R&D costs would be incurred by a future program office. Figure 14 depicts additional R&D costs and their effect on the estimated Vulture NPV LCC.

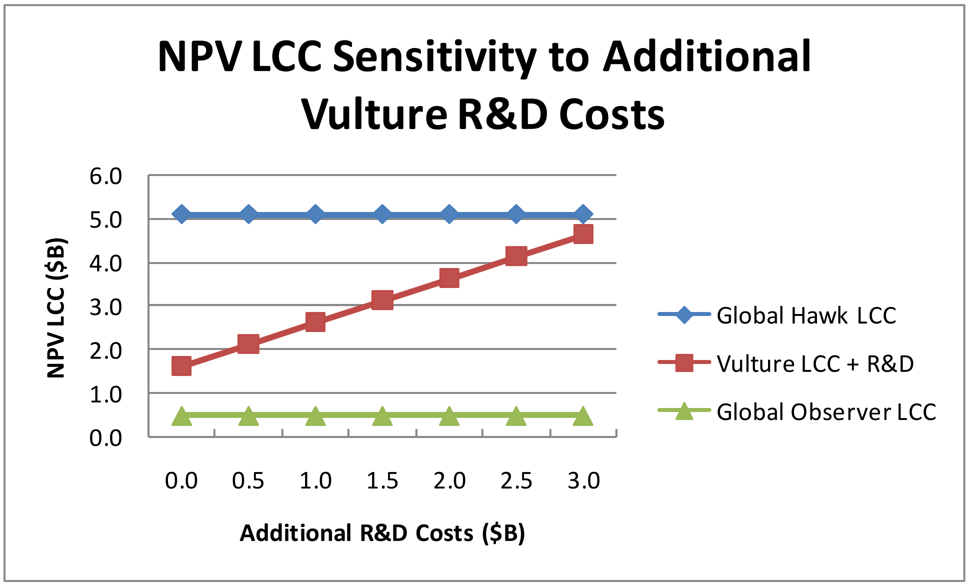

Figure 14. Vulture NPV LCC sensitivity (FY10 $B) to R&D costs.

Any additional R&D funds are assumed to occur in Year 0 of this analysis. The NPV LCC of Vulture remains lower than that of Global Hawk until approximately an additional $3.5B is invested in Vulture R&D. However, when only $1B of additional Vulture R&D is invested, the annualized ROI of Vulture in comparison to Global Hawk becomes negative, as seen in Figure 15.

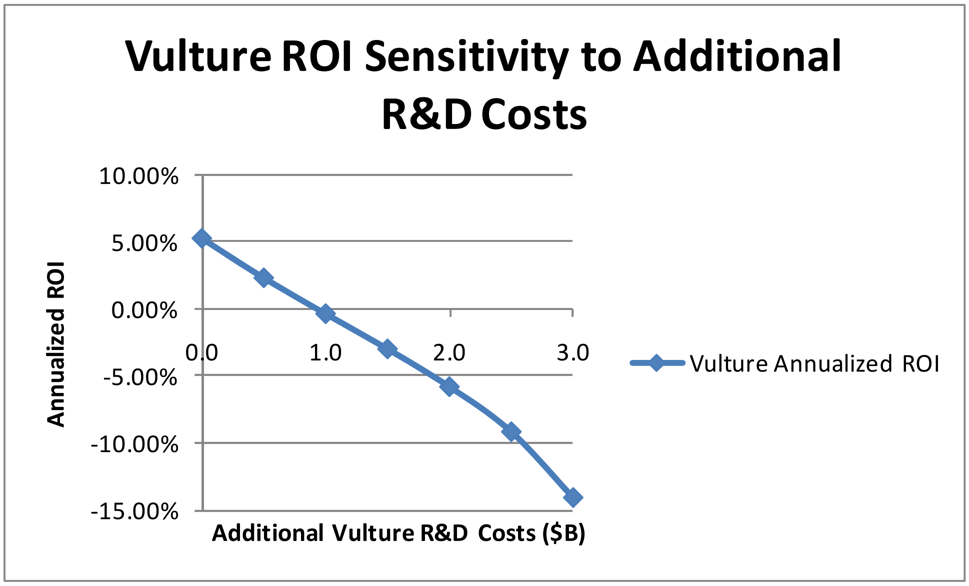

Figure 15. Vulture ROI sensitivity to additional Vulture R&D costs with Global Hawk as the base.

5. Vulture Air Vehicle Cost Sensitivity

Due to the lack of Vulture O&S costs in the Vulture base case assumption, the NPV LCC estimate of Vulture is greatly dependent on the investment cost, and therefore, the cost of the Vulture air vehicle. Given the lack of analogous military systems that operate on solar power and for five years with no maintenance, the reliable data with which to estimate the eventual air vehicle cost of the Vulture is limited. For example, UAV cost estimating relationships provided by the office of the Deputy Assistant Secretary Army (Cost & Economics) that were developed from traditional fossil-fuel powered UAV data,[65] estimate the cost of a Vulture vehicle to be from $6M to $475M

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[65] Deputy Assistant Secretary Army (Cost & Economics), *Unmanned Air Vehicle System Acquisition Cost Estimating Methodology*, (Washington, D.C.: DASA-CE, 2004), 17–23.

based on the given requirements of the system. With this range of cost estimations, the Vulture program's NPV LCC was analyzed for an AV costing between $50M and $500M. Figure 16 illustrates how the change in Vulture AV cost will affect its NPV LCC.

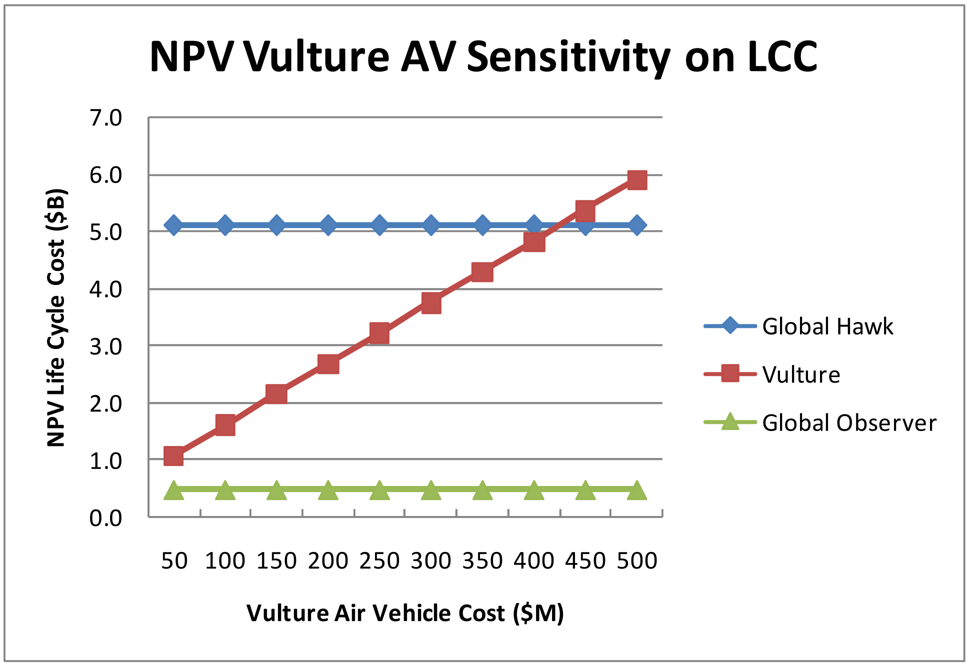

Figure 16. Vulture NPV LCC sensitivity (FY10 $B) to air vehicle costs.

The break-even point for NPV LCC between Vulture and Global Hawk occurs as the Vulture AV cost estimate reaches approximately $425M per air vehicle. As the future cost of the Vulture air vehicle becomes better known, Figure 16 may assist in determining the attractiveness of Vulture to Global Hawk in NPV LCC terms.

The ROI of Vulture is also greatly dependent on future air vehicle costs. It can be seen from Figure 17 that as the air vehicle cost of an individual Vulture exceeds approximately $200M, the annualized ROI for Vulture in comparison to Global Hawk becomes negative.

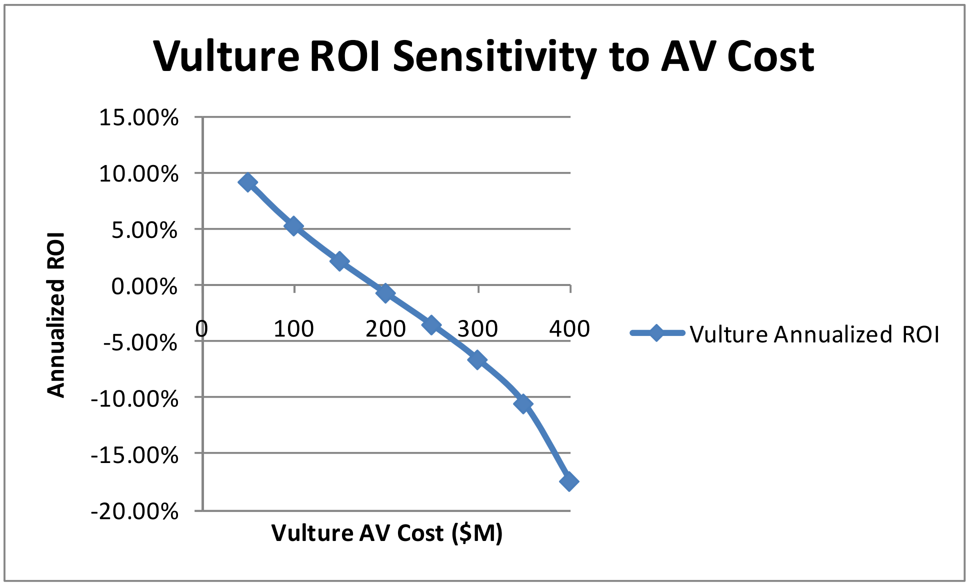

Figure 17. Vulture ROI sensitivity to Vulture air vehicle cost with Global Hawk as the base.

6. Air Vehicle and R&D Cost Range of Attractiveness

The Vulture air vehicle and R&D cost sensitivities above can be combined to estimate a relative range of attractiveness in NPV LCC terms for Vulture in comparison to Global Hawk. The shaded area below the line in Figure 18 represents the estimated combinations of Vulture air vehicle and R&D costs that still would result in a NPV LCC estimate less than that of Global Hawk.

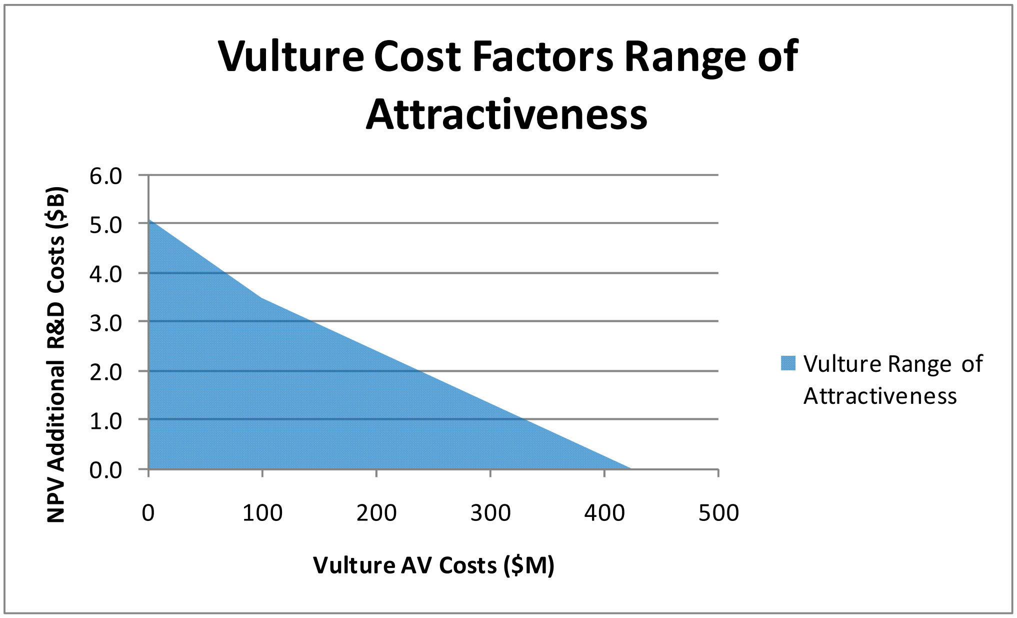

Figure 18. Vulture NPV LCC range of attractiveness for combinations of Vulture AV and R&D costs.

7. Cost of Solar Energy Sensitivity

It is expected that the cost to gather and store solar energy will be a major cost driver for the Vulture AV cost. In the base case assumption, it was estimated that the cost of solar energy ($50M at $100/W) would be approximately 50% of the total air vehicle cost. Future costs of solar energy may or may not go down as a result of commercial and military research and demand. Figure 19 reflects how the future cost of solar energy in $/W would affect the end cost of the Vulture AV. It assumes a constant $50M cost of AV structures and other components not related gathering and storing solar energy.

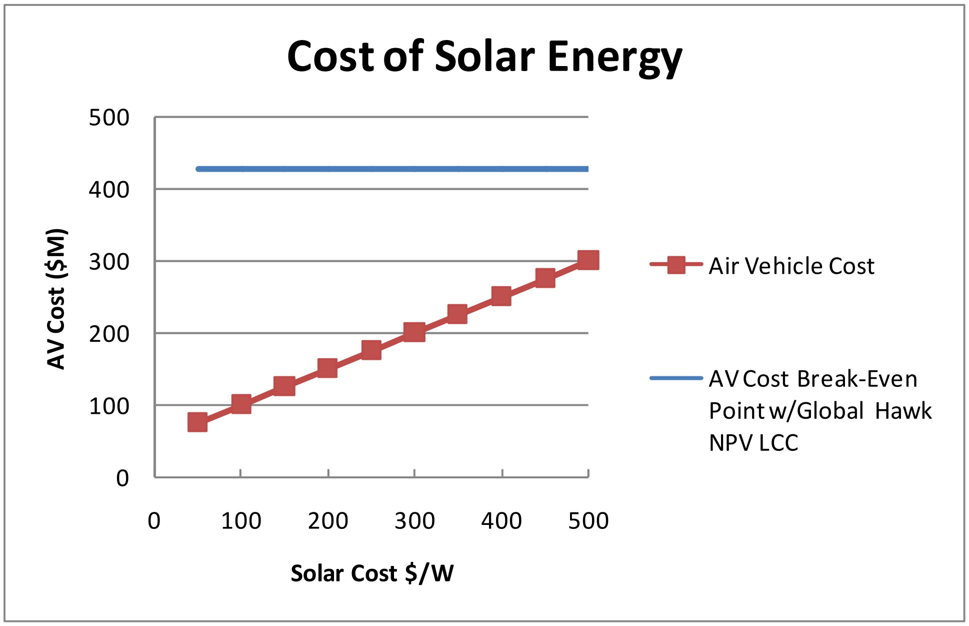

Figure 19. Vulture AV (FY10 $M) cost sensitivity to solar cost.

8. Payload Cost Sensitivity

The cost of the Vulture payload is also a significant cost driver in the NPV LCC base case assumption. With uncertainty regarding the cost of building a reliable payload that can operate for five years in Vulture's operating environment with no maintenance, the cost of a Vulture payload is expected to exceed the cost of current 1,000-pound payloads, which is approximately $10M. The base case assumes the cost factor to meet this increased reliability requirement is five,[66] which results in an approximate cost of $50M per payload. Figure 20 illustrates how the NPV LCC estimate of the Vulture program is altered by a change in the payload reliability cost factor. A range in this cost factor of 1 to 7 yields a payload cost range of $10M to $70M.

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[66] Nussbaum, Vulture BCA Meeting.

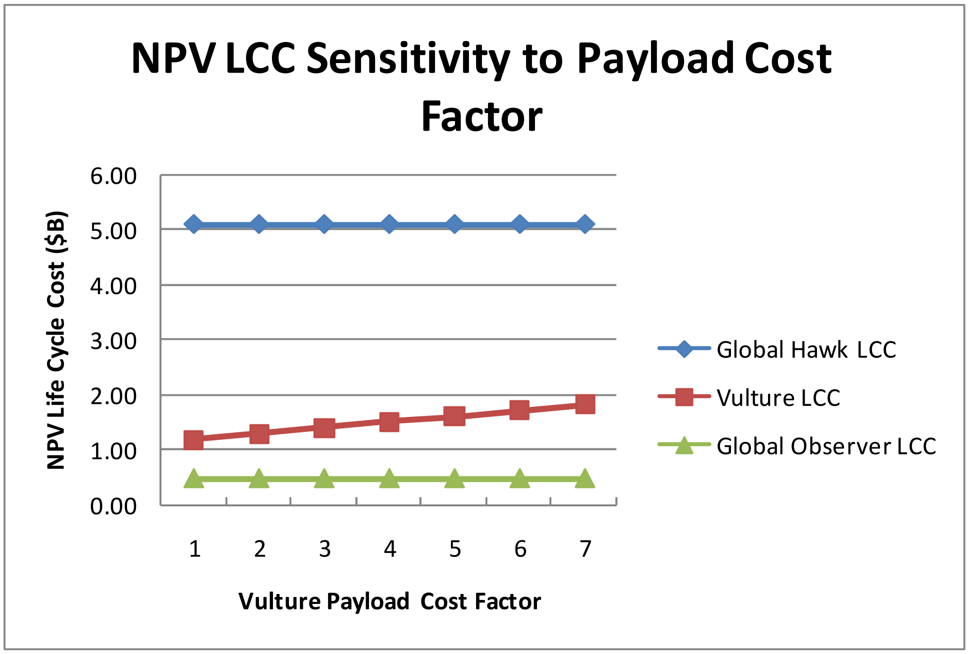

Figure 20. Vulture NPV LCC (FY10 $B) sensitivity to payload cost.

Just as the NPV LCC of Vulture increases as the Vulture payload cost factor increases, the return on investment of Vulture decreases as this cost factor increases. Figure 21 shows the change in Vulture ROI, with Global Hawk as the base, as the Vulture payload cost factor is increased.

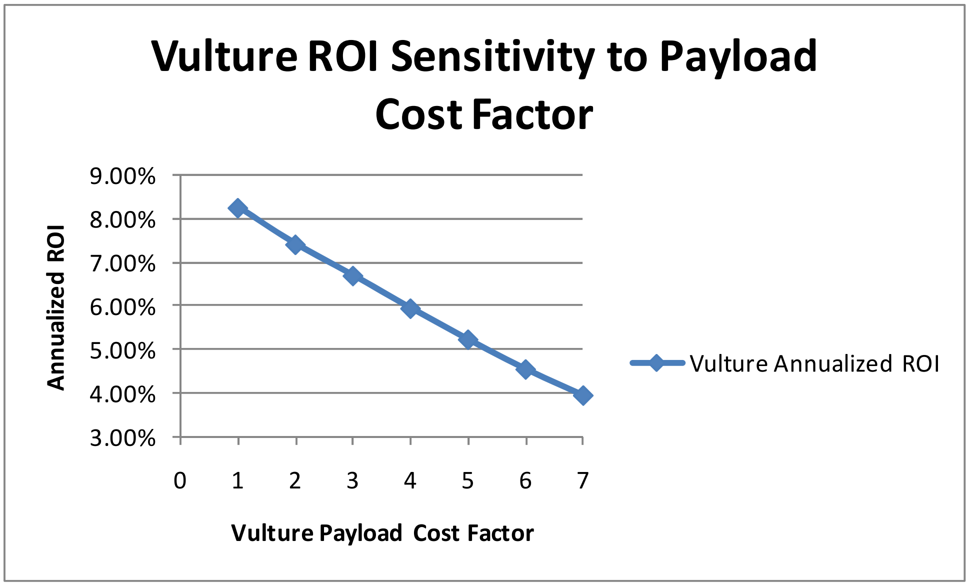

Figure 21. Vulture ROI sensitivity to Vulture payload cost factor with Global Hawk as the base.

9. Cost of JP8 Sensitivity

Similar to how the future cost of solar energy significantly impacts the NPV LCC estimate of Vulture, the future cost of JP8 impacts the NPV LCC estimate of Global Hawk to support the three persistent surveillance missions analyzed. The expected NPV LCC of Global Hawk as JP8 costs range from $2-4.50 per gallon is reflected in Figure 22.

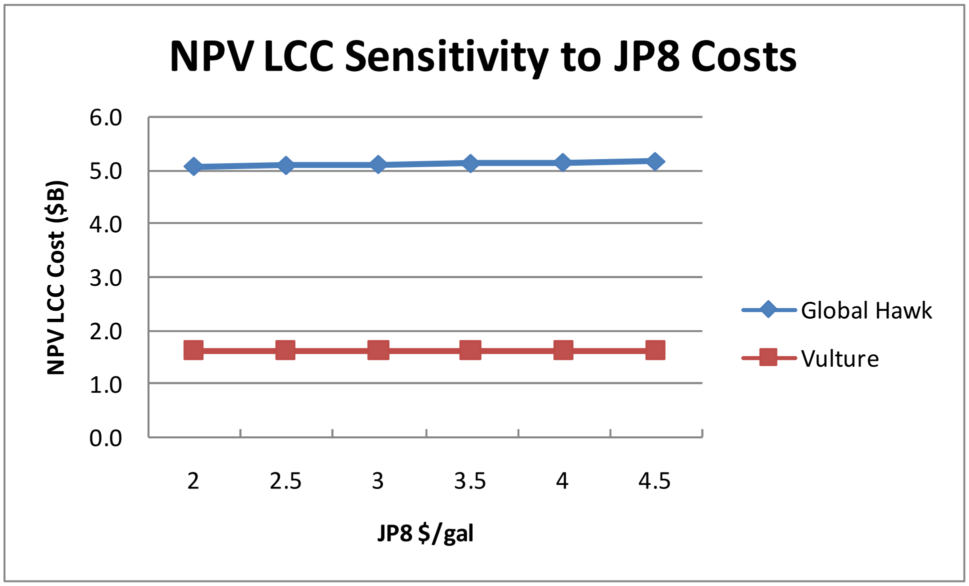

Figure 22. Global Hawk NPV LCC (FY10 $B) sensitivity to JP8 costs.

An increase in JP8 costs would also result in a corresponding change in Vulture ROI with respect to Global Hawk, as seen in Figure 23. Based on these two figures, it is not expected that a change in cost of JP8 within the relevant range will have a significant effect on the relative attractiveness of Vulture to Global Hawk.

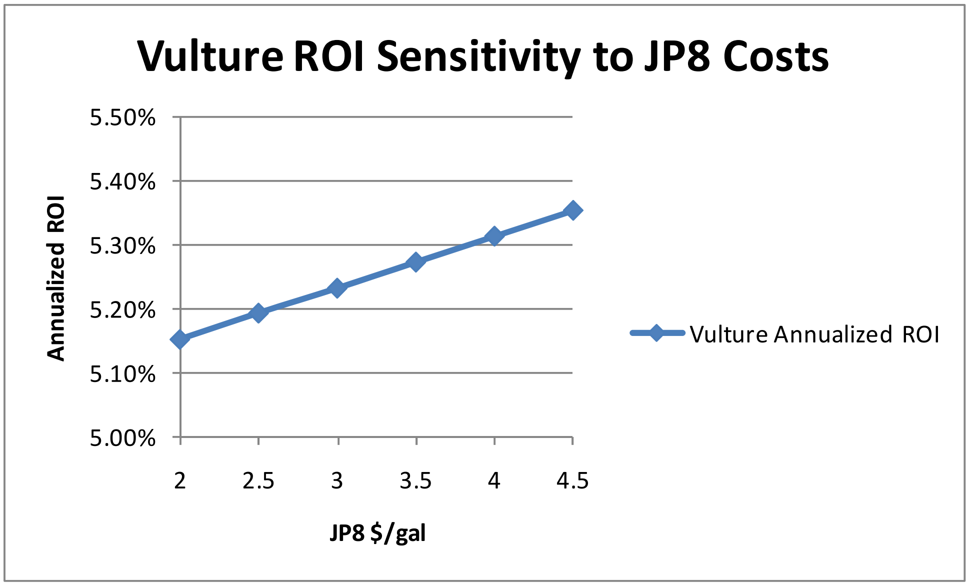

Figure 23. Vulture ROI sensitivity to JP8 costs with Global Hawk as the base.

E. RISK ANALYSIS

There are several potential sources of cost, schedule, and performance risk for Vulture. These risks relate to technology, threats, supplier capability, design maturation, and performance against the development plan.

1. Technological Risk

Two of the primary technological areas that increase risk associated with the Vulture program are power generation and component longevity. As seen in section D.7 of this chapter, the solar power system is a major cost driver to Vulture. Although solar cell technology is proven in space applications, degradation due to atmospheric effects such as moisture and fatigue caused by constant wing stresses provides significant risk over the life of a Vulture UAV. Longevity of components is also a major technological risk. The airframe, electric motors, batteries, solar cells, and payloads have to operate continuously for five years.

2. Threat Risk

Vulture must still undergo vulnerability and susceptibility assessments. It may prove to have a low survivability, making replacement through attrition a major factor in the program cost. This will influence the number of Vulture UAVs required to complete a mission as well as the locations of Vulture use.

3. Supplier Capability Risk

The industrial capability of future Vulture suppliers presents risk to procurement schedules. The contractor may not be able to keep pace with government demand at a competitive price if a large amount of time is necessary to build the UAV. Likewise, if the government must make sudden, unplanned procurements to replace lost vehicles, the contractor facilities may be incapable of supporting a sudden increase in output.

4. Design Maturation Risk

Vulture is currently at a very low technology readiness level (TRL). As future R&D is accomplished for HALE UAVs and associated technologies, designs are likely to change to incorporate new innovations. Technological advances following initial procurement of Vulture may render it obsolete and justify its redesign. Likewise, changes in design during the Engineering and Manufacturing Development phase of the program may create cost overruns and schedule slips.

5. Performance Risk

Performance risk against the program's development plan is closely associated with technological and design maturation risk. Should a specific performance parameter not be met, it must be addressed. This could include redesign, allowing time for further technological development and subsequent redesign. Performance risk is also an issue regarding mission utility of the UAV. It may be found that Vulture is incapable of meeting time on station requirements or longevity requirements, begetting feasibility questions of the vehicle in operational use.

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IV. CONCLUSIONS AND RECOMMENDATIONS

This report has presented a basic business case analysis regarding the use of Vulture HALE UAVs in lieu of Global Hawk UAVs or Global Observer HALE UAVs to maintain 24/7/365 persistent surveillance and battlefield communication capabilities in three distinct scenarios. Life cycle costs in the BCA consist of investment costs and O&S costs for each of the considered aircraft.

A. CONCLUSIONS

Based on the cost and benefits estimated in this analysis, the Vulture program will provide improvements in persistent surveillance capability at a lower cost than the Global Hawk system. Also, while the Vulture program appears more expensive than the Global Observer program in this estimate, both of these programs are very developmental at this point, and total system costs and capabilities may vary significantly from the estimates in this BCA. Further, the support element of Vulture does not entail handling JP8 fuel or liquid hydrogen, thereby mitigating associated risks, health hazards, and storage and transport issues that are present in the other systems.

The Vulture program has the potential to provide a significant new loiter capability for HALE UAVs and become a cheaper alternative to communications than satellite development or bandwidth leasing. Additionally, if the requirement for persistent surveillance escalates in the future, current technologies would be heavily burdened to support this mission. The Vulture program could relieve existing assets (such as the Global Hawk) from hundreds of sorties a year, extending their useful service life.

The promise of the Vulture program and its technologies are worth continuing to pursue at this early point in the program. It is too early to say whether the Vulture system as currently proposed will be a viable military asset when compared to other developmental projects. However, as illustrated by this BCA, there is potential for the Vulture to be an economically attractive alternative to support persistent ISR and communications missions.

B. RECOMMENDATIONS

Following this BCA, it appears that Vulture is a worthwhile investment for attaining future “persistent” ISR and C3 mission capability goals and augmenting the current UAV fleets. However, the factors supporting the benefits of Vulture should not be limited to those found in this BCA. The following recommendations provide a more comprehensive set of investigations and are presented for future consideration.

- As design matures, the effect of learning curves on the production of Vulture air vehicles should be investigated and applied to the BCA. Reduction in the procurement costs will make Vulture a more attractive option in shorter-range scenarios than those discussed in this paper.
- Relationships between ground control station costs and specific UAV types are lacking. Further inquiry should be made to establish CERs between UAVs and ground control stations.
- In the scenarios described above, it was calculated that the average number of required Vulture per mission would be fractionally (1/1000th) larger than the specified integer due to transit time requirements at the end of each five year Vulture rotation. It was assumed that the concept of operations would use other assets to cover this 30 hour or less surveillance gap by Vulture once every 5 years. A sensitivity analysis on the additional cost of different operational decisions to support this coverage gap and to perform full persistent capabilities should be performed.
- A BCA evaluating the use of specific types of aircraft versus the use of a mix of platforms to accomplish the persistent surveillance mission should be performed.
- Cost benefit analyses should be performed on the development and procurement of configurationally variant Vulture aircraft with respect to airframe size, payload capability (footprint), payload weight, design for landing/recoverability, and longevity (e.g., 1, 3, or 7 years, versus 5).

- ISR and communications payloads should be researched with respect to design for use in an atmospheric environment with high reliability for multi-year missions. Following this, a sensitivity analysis should be performed on the cost of payload versus capability.
- The threat vulnerability and susceptibility of Vulture will need to be assessed at some point. Such an assessment should be used in a BCA regarding attrition and mission survivability.
- Production facilities have capacity constraints, limiting the number of aircraft they can produce in a timely manner. Such constraints should be investigated with respect to specific scenarios and aircraft requirements to recommend guidance to future acquisitions as well as mission planning.
- This paper concerns the utility of Vulture compared with Global Hawk and Global Observer. However, with a 5 year on-station life, a BCA for replacing limited amounts of satellite assets should be conducted.
- Global Observer should be revisited to update cost figures and utility assessments. A more comprehensive BCA comparing only Global Observer and Vulture should be accomplished as well as an accompanying cost benefit analysis regarding liquid hydrogen technology versus solar technology.

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