A CARRIER-PIGEON UAS FOR SOUTH POLE DATA TRANSFER

A Thesis
presented to
the Faculty of California Polytechnic State University,
San Luis Obispo

In Partial Fulfillment
of the Requirements for the Degree
Master of Aerospace in College of Engineering

by
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December 2018

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ABSTRACT

A Carrier-Pigeon UAS for South Pole Data Transfer

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The assessment of feasibility of an Unmanned Aircraft System (UAS) that is specifically tailored—in performance, operating and support characteristics, and payload—to support hardware-based data transfer from South Pole Station in Antarctica to a location of high connectivity has been undertaken. Due to the specific location of the Amundsen-Scott South Pole station and competing demands from other governmental agencies, satellite connectivity requirements for data transfers cannot be met at the South Pole. In the recent decades, the advancement in UAS capabilities have overwhelmingly extended their operational reach in military and commercial reconnaissance and surveillance missions. This UAS has the potential to supplement research data transfer in environments – such as the South Pole – where communications are extremely limited. The methodology used to determine feasibility of the Carrier Pigeon UAS are; trade studies for similar UAS, hand calculations, initial constant diagrams, and assessment of command, control, and support. The outputs determined the proposed system is feasible to meet personnel, climate, altitude, range, and payload requirements of a continuous “Carrier-Pigeon” UAS that enables high volumes of rapid data via hard disk drive transfer from the Amundsen-Scott South Pole Station to Christchurch, New Zealand.

Keywords: UAS, Carrier-Pigeon, Antarctica, Amundsen-Scott South Pole Station, Data Transfer

ACKNOWLEDGMENTS

I'd like to thank my parents for the continuous support throughout my journey in life. I would also like to thank them for showing me by their actions what consistent hard work looks like. You are truly the hardest working people I know. I would also like to thank the Aerospace Engineering department for being a second family for me. Without your encouragement, positive outlook, and help this would have never been possible.

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Chapter 1

INTRODUCTION

In the aerospace industry, the aircraft design process is a multifunctional set of activities that is undergone by engineers in different disciplines - such as aerodynamics, structures, controls, and propulsion to build an aircraft for a set of requirements. The freedom of decision making narrows as the aircraft moves along each design phase. This study is focused on the technical feasibility work prior to the conceptual detailed design phase of an Unmanned Aircraft System (UAS) - specifically, aimed at the primary objective of; is there a sound physical solution to the functional needs, answering the question of whether or not this potential solution is feasible [1].

1.1 Research Objective

The aim of this research is to answer whether a physical sound system would be feasible for a UAS to fly a mission non-stop from the South Pole Station in Antarctica, to a location off the continent of Antarctica, carrying a payload of physical scientific data to supplement data transfer multiple times during the austral winter. In order to answer technical feasibility more specifically, requirements and constraints of the system will be derived. The UAS system must meet range requirements, payload requirements, size requirements, maintenance requirements, and logistical requirements. At the very start of design, the systems developer has just started to gather information. During this phase, all the assumptions are still not validated and the systems developer has to further investigate the decisions that need to be made. In this research; rudimentary aircraft sizing parameters were performed by simple hand calculations and coded graphs; published papers were researched; trade studies conducted; and discussions with Antarctica operations experts were held to answer the technical feasibility assessment question. The appropriate method to understand the technical feasibility assessment of the system will change based upon the information and resources available. This research will not be on an in-

depth computer comparison of several coded designs. Rather an assessment of technical feasibility on whether such an undertaking of conceptual design should occur.

1.2 Requirements and Constraints prior to Design

The technical feasibility assessment is one of the most difficult and important developments prior to undertaking serious design work. The feasibility assessment does not contain black and white checklists to gain the correct answer, rather it is derived from a system of constraints and requirements that will either drive conceptual design or determine that the system developer not to take any further advancement in the project. The systems requirements and constraints become even more important for a novel application, because very little historical documentation is usually available to lean on.

1.3 Technical Feasibility Assessment

The technical assessment requires the systems developer to use both analytical thinking and a number of calculations to provide a concrete yes or no on the further development of more design. Analysis and identification of system requirements and constraints are developed from stepping through “back of the napkin” sketches, discussion of the aircraft mission, and overall system requirements revisions. The technical feasibility assessment will follow the general approach below in Figure 1.1.

Figure 1.1 Technical Feasibility Architecture

The unique location and extreme environment of Antarctica for the “Carrier-Pigeon” UAS feasibility assessment is cause for an interdisciplinary nature of multiple assessments. Specifically, making a case with sound technical data for understanding physical limitations of the environment for both operations, personnel and governmental procedures, and data transfer requirements. The factors that will affect design requirements will not just be limited to the proposed flight mission. Design requirements will have extensive research conducted to understand government contracts for personnel support, environmental effects of UAS operation within the Antarctic region, and supply chain management at the South Pole Station for maintenance and deployment. These unconventional derived requirements will be analyzed to determine whether it is worth the continued effort for full conceptual design phase of the “Carrier-Pigeon” UAS. The research is finished when the answer to the feasibility question is determined.

Chapter 2

BACKGROUND OF ANTARCTICA

In order to derive systems requirements and constraints for the unmanned aircraft system to solve the data transfer challenge at the South Pole, a brief look into how Antarctica was settled, acknowledgement of the research and international agreements, and an understanding to how remote a continent Antarctica is, must be undertaken. The historical background will help gain insight into requirements to develop the argument of why or why not a UAS tailored specifically for physical data transfer for extreme cold weather and long endurance is needed to undergo a detailed conceptual design phase.

2.1 History of Settlement

The ancient Greeks and Aristotle they thought there may be a land mass in the southern hemisphere since the world was round. Nothing could be confirmed until the late 1700's between the years 1772 to 1775 Captain James Cook finally crossed the Antarctic circle and circumnavigated Antarctica. Although he did not sight land, rock seen in icebergs showed that a southern continent existed [3]. Following Captain James Cook's discovery and his descriptions of the large number of whales and seals published in his travel logs, interest grew from eager explorers. During this time period, animal oil from whales and seals were in high demand. Expeditions were organized and wealth gained from unregulated sealers lead governments to look to the south. One such expedition by the Russian navy was Captain Thaddeus who made the first sighting of Peter I and Alexander Islands off the coast of Antarctica on January 27th, 1820. This time period was coined as the "Heroic Age" of Antarctic exploration. Explorations shifted from naval operations to land operations. The race was on for the first explorer to reach the south pole over land. The first explorer to reach the south pole was Roald Amundsen on December 14th, 1911. He beat English explorer Robert Scott by just a few weeks [3].

Once the south pole was conquered scientific research of the continent itself became the priority for expeditionary efforts. After World War II many countries began to establish bases on the Antarctic mainland. Seven countries made strategic land claims in Antarctica following the war - Australia, New Zealand, France, Norway, the United Kingdom, Argentina, and Chile. Below in Figure 2.1 is a graphical depiction of the land claims from the seven countries original countries.

Figure 2.1 International Land Claims [22]

2.1.1 Research and Antarctic Treaty

On December 1, 1959, the Antarctic treaty was signed that formed an international framework for the region that expanded to twelve countries (Argentina, Australia, Belgium, Chile, France, Japan, New Zealand, Norway, South Africa, United Kingdom, United States and Russia). The treaty put into place governance of the region including: freedom of scientific

investigation and the exchange of scientific findings, non-militarization of Antarctica and the Southern Ocean, and accommodating the positions of all parties on issues of sovereignty. The treaty stands to this day and acts as the foundation for cooperation for foreign governments to work together on scientific research and preservation of the continent. Research and activities that are conducted on the continent of Antarctica are governed by the Antarctic Treaty and four major international agreements in it, the first being signed in 1959. The original treaty signed has seven articles that set forth the guidelines for the basis of the twelve countries involved. The main three articles are below [22];

Article I: *Antarctica shall be used for peaceful purposes only.*

Article II: *Freedom of scientific investigation in Antarctica and cooperation toward that end.....shall continue.*

Article III: *Scientific observations and results from Antarctica shall be exchanged and made freely available.*

The other three agreements signed on to the Antarctic Treaty are;

- *Convention for the Conservation of Antarctic Seals in 1972*
- *Convention on the Conservation of Antarctic Marine Living Resources in 1980*
- *Protocol on Environmental Protection to the Antarctic Treaty*

The agreements are legally binding and built for the unique geographical, environmental, and political characteristics of the Antarctic [22]. The agreement of importance to the Carrier Pigeon UAS is the protocol on environmental protection to the Antarctic Treaty. This protocol protects Antarctica as a natural reserve devoted to peace and science. Under the protocol mineral resource exploration, mining and oil drilling are banned and the environment must be the fundamental consideration in the planning and conduct of all activities.

The environmental protection protocol will have an effect on the Carrier Pigeon UAS system feasibility because of the additional procedures and requirements needed for loss of vehicle, fuel dumping, and air operation regulations. The aircraft system will need a thorough recovery procedure or parachute recovery system on the event of a loss of communication. System procedures for course of actions in communications failure are critical to meeting protocol on environment protection.

The Antarctic Treaty also established a governance of air operations at the South Pole. The Council of Managers of the National Antarctic Programs publishes a Flight Information Manual. This document publishes resolutions, regulations, and guidelines to air operations in the Antarctic region for all nations in accordance with the Treaty [41]. The document the United States adopts for air operations is the US Antarctic Program Interagency Air Operations Manual. Oversight of the on-ice operations of the civil aircraft is NSF-delegated to the Department of Interior/Office of Aviation Services (OAS). Joint use of the USAP airspace in Antarctica requires close coordination between the DoD and the NSF. That is achieved through bi-weekly meetings of the Air Operations Planning Board (AOPB). The USAP airspace is managed and controlled by the Space and Naval Warfare Center [21]. Working closely with the NSF, Department of Interior, and the USAP to ensure system requirements meet air operations planning board is the utmost of importance. Understanding the Antarctic Treaty impacts the feasibility assessment systems success and or failure of employment capabilities, sustainment and maintenance.

2.1.2 Aviation at the Pole

It is difficult to appreciate the amazing unmanned aerial systems (UAS) capabilities of today without fully understanding what came before. There have been numerous bursts of innovation and eras of widespread employment for UAS. There have also been long periods where the technologies were all but forgotten. Brilliant achievements have been followed by decades of dormancy. Systems that we now take for granted usually have predecessors that

achieved some success or were utterly unsuccessful. Only in the past two decades have we achieved a true golden era where UAS's have established a large presence in military operations. UAS development has paralleled manned aviation from the beginning of flight and cruise missiles since World War I [14]. The technologies migrate between these domain from one program to the next. The predecessors of UAS in the recent decades, especially in-flight endurance has been the key design parameter to allow the conceptual design feasibility of the “Carrier-Pigeon” UAS. One example of the exceptional capability of UAS endurance is the ScanEagle that flew across the Atlantic Ocean 2000 nautical miles without refueling powered by a diesel engine [18].

The first powered flight in Antarctica took place in 1928 when an Australian, George Wilkins, made a 20-minute flight in the Antarctica Peninsula. The most famous Antarctica flight is probably that of American Rear Admiral Evelyn Byrd, who in 1929 made the first flight over the South Pole. The three-man crew just made it - having to jettison empty fuel tanks and their emergency food supplies to avoid crashing into the Transantarctic Mountains [40]. Primarily in the Antarctic region aviation has been dominated by manned aircraft. Manned air operations are limited only during the austral Summer due to weather considerations and runway maintenance.

Only in recent years has Unmanned Aircraft Systems been utilized for research efforts. The Meridian UAS is an example of one such research effort. The Meridian design mission was to takeoff from the South Pole ice runway, fly to a designated area, then use low frequency radar to perform measurements of ice sheets. The successful deployment of the system on December 31, 2009 was a culmination of work since 2005 and has paved the way for further UAS mission for scientific studies. Other studies that utilized UAS include penguin migration documentation [23], observations of the atmosphere and surface state [24], and investigation of the Cryospheric Evolution of the Central Antarctic Plate [25].

Much of the heavy lifting for aviation in Antarctica has been carried out by United States military. The military has enhanced already existing manned aircraft platforms in order to meet mission requirements for both weather and logistics requirements. The Air National Guard of the New York 109th Airlift Wing provides ski equipped C-130 (LC-130) for air support between Antarctica and New Zealand and within Antarctica. The U.S Air Force from the 62nd Airlift Wing provides airlift support between Christchurch, New Zealand, and McMurdo Station, Antarctica. PHI company provides helicopter support within Antarctica. The British Antarctic Survey also provides manned aviation support heavily to Antarctica region. They operate a fleet of five aircraft; four De Havilland Canada Twin Otters and one De Havilland Canada Dash-7 equipped with modifications to allow them to carry out multiple mission. The Twin Otter is in heavy use in Antarctica mostly known for its rugged design and proven performance in cold weather [39].

Requirements and Constraints derived from Chapter 2.1:

1. Comply with Antarctic Treaty protocol for environmental protection

- No fuel dumping.
- System must have loss of communication and recovery procedure for down aircraft.
- UAS needs to maintain contact with ground control station and have communication range over 1500 NM. System needs communication hand off from Antarctica GCS to high connectivity location GCS.

2. Runway independent for flights during austral Winter

- Manned aircraft flights only during austral Summer. South Pole Skiway non-operational during austral winter.

3. Comply with governance of air operations

- Comply with US Department of Interior OAS for regulations.
- Coordinate with Space and Naval Warfare Center for airspace management.

2.2 Antarctica Geography

Antarctica is totally covered in glacier ice. There are two major areas of ice that differ both in their physical characteristics and history in Antarctica. They are the East and West Antarctic Ice Sheets. The East Antarctic Ice Sheet is older, thicker, and larger than the West Antarctic Ice Sheet [38]. The East Antarctic Ice Sheet is where the physical location of the Amundsen-Scott South Pole station. The location of take-off for the “Carrier-Pigeon” UAS and the primary focus for derivation of feasibility requirements.

Most of Antarctica lies in the Eastern Hemisphere. East Antarctica is known as Greater Antarctica and West is known as Lesser Antarctica. Lesser Antarctica has a smaller land area and is surrounded by the Weddell Sea and the Ross Sea on either side. A physical boundary divides Eastern and Western Antarctica which are the Transantarctic Mountains. In conjunction with East and West Antarctica land masses there are several islands north of the Antarctica Peninsula. Some islands are only connected to the continental land mass seasonally while others are permanently linked by ice. Along with small islands much of Antarctica’s coast is sprawled with ice shelves. The two largest ice shelves being the Ross Ice Shelf in the Ross Sea and the Ronne Ice Shelf in the Weddell Sea [38].

Antarctica is considered the “highest continent on Earth” because of the thickness of ice sheets. Antarctica has a 2000 m above sea level average surface elevation. In East Antarctica or Greater Antarctica, the Ice Sheet known as “Dome A” has a surface elevation of over 4000 m [38]. The South Pole Station is located in East Antarctica at an elevation of 9,301 ft. The below graphic displays the cross-sectional area of the Ross Ice shelf in West Antarctica with 2000 m

average surface elevation due to the thickness of the ice sheets and not the actual bedrock of the continent.

Figure 2.2 Ice Thickness on Antarctica

Above in reference 2.2 depicts the location of A to B in plan view illustrating the East and West Antarctica along the Ross Ice Shelf.

Requirements and Constraints derived from 2.2:

- 1. UAS must be maintained, deployed, and stored at elevation of 9,301 ft.**
- 2. Cruise altitude of 19,000 ft. for passage over Transantarctic Mountains**

2.3 Historical Weather Data

Antarctica's climate is extreme cold. Climate is defined as the average weather for a region over a period of time with the two main features being temperature and precipitation.

Climate is influenced by latitude and altitude, solar radiation, ice and snow cover, air mass influences, oceanic heat exchange, mountain barriers, prevailing winds and land and sea distribution. There are large variations in climate across the Antarctic continent mainly because of differences in latitude, altitude, and distance from the Southern Ocean.

The Antarctic climate as a whole can be discussed in terms of three different climate areas: the interior climate, the coastal climate, and the climate of the Antarctic Peninsula [38]. The coldest and driest areas are inland, where the ice sheets form high plateaus. In these areas, extremely cold air descends to create persistent high pressure that brings settled conditions with relatively low wind speeds. Temperatures during the summer are rarely above -20°C and during the winter months temperatures are around -60°C . There are several factors that combine to make Antarctica one of the coldest places on Earth. Unlike the Arctic region, Antarctica is a continent surrounded by an ocean which means that interior areas do not benefit from the moderating influence of water. With 99% of its area covered with snow and ice, the Antarctic continent reflects most of the sun's light rather than absorbing it [38]. The extreme dryness of the air causes any heat that is radiated back into the atmosphere to be lost instead of being absorbed by the water vapor in the atmosphere. In the winter, the size of Antarctica doubles as the sea water freezes, effectively blocking heat transfer from the warmer surrounding ocean [49].

2.3.1 Katabatic Winds

Winds in the Antarctic region are highly variable based upon specific location on the continent, time of season, and elevation. A thorough analysis of the effects of surface winds for feasibility of design requirements will need to be considered for the UAS design. Understanding wind limitations and requirements for launch and mission profile is one of the cornerstone measures to whether or not this system could be feasible.

The directional constancy and topographic control of the Antarctic surface wind field has been largely attributed to the influence of katabatic processes [37]. The processes resulting from katabatic forcing are active and can equally well explain the principal characteristics of the Antarctic surface wind regime throughout the year. There have been many numerical simulations that have shown adjustments in the pressure and wind fields take place when stable air impinges on the continental orography – the physical geography of the mountains. As well as heavily documented from the early explorers noting that the katabatic wind stream was “a river, rather a torrent, or air (rushing) from the hinterland year after year, replenished from a source which never fails...”. The Antarctic ice massif acts to block the flow of stable air toward the continent. The subsequent adjustment process results in a horizontal pressure field that is shaped by the slope and direction of the terrain. The forcing of such flows leads to strong cooling of air adjacent to the ice surface producing a “sloped-inversion” pressure gradient force directed downslope. A previous research study had collected wind data from ten locations over a period of thirteen years. Five locations on the interior of the Antarctic continent and five locations on the coastal regions of the Antarctic [37]. Below are the ten geographic locations mapped on Antarctic in Figure 2.3.

Figure 2.3 Weather Data Collection Location [37]

The table below lists the resultant wind direction, directional constancy, and the deviation angle. Along with the length recorded of data in years N.

Location	N	Resultant Wind (m s ⁻¹ , deg)	Directional Constancy
Interior Stations			
Pionerskaya	1	9.3, 131°	0.92
Charcot	1	8.6, 163°	0.91
Vostok	16	4.1, 243°	0.81
Amundsen-Scott	16	4.6, 39°	0.79
Byrd	14	6.6, 13°	0.86
Coastal Stations			
Cape Denison	2	19.0, 161°	0.97
Port Martin	2	16.9, 146°	0.94
Mawson	15	9.8, 130°	0.93
Mirny	17	9.7, 127°	0.9
Molodezhnaya	11	8.4, 126°	0.85

Table 2.4 Wind Statistics

The winds in Antarctica due to the Katabatic forcing flow downhill. The South Pole sits atop a plateau at 9,301 ft. and forcing the wind to flow away in directions to the lower region of the coastal area. Below in Figure 2.5 depicts the flow of prevailing winds toward the coastal regions of Antarctica from the plotted data from Table 2.4.

Figure 2.5 Resultant Wind Direction

Surface winds on the coastal region and near-interior of the continent are of less importance than the interior, because the UAS conducts mission start from the South Pole station which is located in the interior. But the coastal and near-interior regions are still of significance to understand the wind regime throughout the continent. The individual candidate routes have separate missions encountering different wind aloft (prevailing) profiles which will be looked at in later chapters.

The two-dimensional surface wind models are representative of sound data from historical documentation. The surface wind model also represents ideal conditions for katabatic winds so the resultant wind is somewhat stronger than in regions. In order to compensate for induced error in model results this conceptual design model is highly desired for candidate route wind analysis. This model wind profile illustrates the rather homogeneous surface winds for the interior at an average surface wind speed of 8 m/s. The graphic below is the wind profiles for coastal, near interior, and interior wind profiles of the model.

Figure 2.6 Wind Profiles [37]

For deriving wind directions at South Pole station, the Greenwich meridian is defined north, and 90 °E is defined east. Prevailing winds are from northerly to easterly directions, with high wind-speed cases mainly from the north. This characteristic is represented by all three model grid points surrounding the site where the measurements were performed. Wind roses for the grid points around the South Pole Station show little variation, indicating that the region around is homogeneous. The wind rose data corresponds with the two-dimensional wind surface models for average wind speed around 10 m/s.

Figure 2.7 South Pole Wind Roses [35]

2.3.2 Winds Aloft

The surface winds during launch and climb will not have as significant effect on the UAS as will the winds aloft during cruise stage. Majority of the Carrier Pigeon UAS cruise stage will occur over the continent of Antarctica, but all UAS candidate routes will encounter the southern hemisphere's prevailing winds once off the continent. In cruise stage, prior to reaching the Antarctic coast the UAS will have tailwinds, due to the Katabatic winds moving from the South Pole toward the coast. Once the aircraft reaches the coast, prevailing winds will have a horizontal wind vector component acting on the aircraft at cruise altitude of 16,000 ft. In order to understand the winds aloft and a discussion with experiment Antarctica weather man Arthur Cayette was conducted. Access was granted for the use of the Antarctic Mesoscale Prediction System (AMPS). The AMPS is an experimental, real-time numerical weather prediction capability that provides support for the United States Antarctic Program, Antarctic science, and international Antarctic efforts. The AMPS produces numerical guidance from the Weather Research and Forecasting (WRF) model [50]. The closest winds aloft flight level the model generated to the Carrier Pigeon UAS mission cruise of 16,000 ft. was MSL 25,000 ft. The model was utilized at 25,000 ft. to investigate the wind speed and direction. A sample snapshot of winds aloft speed was exported from the model and seen below in Figure 2.8. A more in depth historical average will need to be investigated, the AMPS model suggested a majority wind aloft speed range between 30 – 70 m/s off the continent of Antarctic at 25,000 ft. for the time period collected. Although the Carrier Pigeon UAS will be cruising at a significantly lower altitude, the range of wind speeds will need to have heavy emphasis on route design optimization considerations. A potential option for the Carrier UAS is for the aircraft to fly with prevailing winds during its route. This will mitigate direct flight into cross winds, which will save fuel and operational risk on loss of aircraft.

Figure 2.8 AMPS Winds Aloft at 25,000 ft. [50]

2.3.3 Temperature Inversion – Winter/Spring

Surface based temperature will have an effect on ground control station operations, handling requirements, and operational maintenance for the Carrier-Pigeon UAS feasibility. So, it is worthwhile to examine the annual temperature cycle to understand the surface-based temperature inversion that exists in Antarctica for UAS feasibility. This inversion is a key role player in aspects of its climate, specifically near-surface winds and atmospheric radiation. A significant inversion exists at the surface of the Antarctic in every month but December and January. Since the Antarctica is in the southern hemisphere, December and January are Antarctica's Summer months.

The inversion exists because the snow-surface emissivity, or the effectiveness in emitting energy as thermal radiation, is greater than the atmospheric emissivity. When the energy absorbed at the surface from solar radiation is small, this inequality causes a temperature inversion. The seasonal cycle over the Antarctic is a “short-peaked” summer with rapidly changing transition seasons and a long coreless winter. Middendorf and Hann described coreless as the average temperature being nearly constant, with no well-defined core of minimum temperatures [4].

The standard deviation curve below in Figure 2.10 shows that winter temperatures are much more variable than summer temperatures. This is due in large part because during winter the temperature can be affected by clouds that may be much warmer than the actual surface, by changing wind speeds that affect the vertical mixing of the inversion layer, and by slight vertical motions due to convergence or divergence of the surface winds that move colder air up or warmer air down. This will affect the Carrier-Pigeon UAS operational cycle because the systems primary employment will be in the winter months where there is variable temperature and no manned aircraft transportation to the South Pole station. A systems requirement of the UAS is that it must be launched during winter. Winter operation missions will supplement data transfer architecture from satellite resources. Low-Earth orbit satellite infrastructure and their limitations on data transfer will be discussed in the next chapter.

Figure 2.9 Annual Temperature Cycle [4]

Since Antarctica is in the Southern Hemisphere and looking at the mean temperatures above in Figure 2.10 the seasons are; Summer is December and January, Autumn is February and March, winter is April-September; Spring is October and November. This is the reverse of the seasons seen in the northern hemisphere.

There is a rapid warming of temperature near the surface with an isothermal layer above that from about 250-900 m. Climbing in altitude higher, the temperature profile moves to a more normal lapse. Below in Figure 2.10 is a temperature profile measured at the South Pole on September 25, 2001. The data above 660 hPa was collected from a radiosounding with an RS80. A radiosonde is a meteorological instrument which is hung from a balloon and released into the atmosphere. As the balloon goes up the radiosonde records air pressure, temperature, and relative humidity and sends this information back to earth via radio waves [5]. In graph (a) the full tropospheric sounding is shown and in graph (b) from 0 to 500 m are enlarged. The surface pressure was 674 hPa. Analyzing the graph (b) at 40 m above the surface the temperature is 15 K

higher than at the surface. At 100 m above the surface the temperature has moved to a total increase in temperature of 23 K.

Figure 2.10 Temperature Profile at South Pole [4]

Temperature inversions occur more than half the time in the near surface layer during the summer, but the inversions are often smaller than 1 K over the first 20 m. While inversions almost always occur in the lower layer, the strongest inversions in the lower layer 20 m are no stronger than the strongest in the upper layer. Below in Figure 2.11 the distributions and statistics of air temperature the temperature profile of 22 m (named T_{22}) and labeled as (a), 13 m (named T_{13}) labeled as (b), and 2 m (named T_2) labeled as (c). In the Summer temperatures, over 98% fall between an 18 K range between -38°C and -20°C. Looking at the T_{22} and T_2 shows the evidence that there is an inversion for air to be colder at 2 m than at 22 m. The distribution of the difference

between T_{22} and T_2 confirms that in the summer inversions occur more than half the time in near-surface layer [4].

Figure 2.11 Average Annual Summer Temperature [4]

The winter data is much more variable and the temperatures are a lot lower. The T_2 data with a range of 34.7 K which is almost twice the summer. The distribution between T_2 and T_{22} are more visible along with the T_2 skewed positively, showing how easy the surface can be warmed in winter. Below in Figure 1.13 shows the temperature distributions in the winter, illustrating that temperature inversions are more common in the winter.

Figure 2.12 Average Annual Winter Temperature [4]

This cold weather research data confirms that the temperature inversions in the winter are more common and the average temperature is a significant amount lower than the summer. An average temperature of -49°C . The near surface temperature will be almost as cold as it will be at cruise altitude of 15,000 ft. The ease of ground control handling, personnel required for launch, and cold weather system design requirements are derived in chapter 6 based on this Antarctic cold weather data.

Requirements and Constraints derived from Chapter 2.3:

- 1. UAS must be capable of launch in 10 m/s winds**
- 2. System will have tailwind from South Pole to coastal region**
- 3. Propulsion and ancillary systems must be capable of heating**
 - Anti-icing system for control surfaces
- 4. Propulsion and system start up procedure for temperature inversion**

- Individual hangar and launcher will need enclosed structure for storage and start up procedure

Chapter 3

SOUTH POLE SATELLITE COVERAGE

Research at the Amundsen-Scott South Pole station is the main focus at the location. As mentioned previously, the IceCube Neutrino Lab is a particle detector and is just one of the research labs located at the South Pole. The IceCube Lab is the first of its kind, designed to observe the cosmos from deep within the South Pole ice. The lab searches for nearly massless subatomic particles called neutrinos. These high-energy astronomical messengers provide information to probe the most violent astrophysical sources: events like exploding stars, gamma-ray bursts, and cataclysmic phenomena involving black holes and neutron stars. The IceCube Lab collects a tremendous amount of data from this detector, about 1 TB of data a day to be exact. And the amount of data collected is increasing. The recent announcement in October 2018, of an additional \$30 million-dollar upgrade to the detectors equipment, the projected information collection is supposed to increase tenfold [6]. The IceCube Lab is just one example of a research lab at the South Pole that cannot upload the entirety of data retrieved from the particle detector South Pole due to satellite connectivity and transfer rate challenges. Causing the small team of scientist to spend massive amounts of time going through the arduous process of local data filtering. Chances of missing critical raw research data from local filtering is of high concern to the lab and the scientific community. This chapter analyzes the satellite systems architecture, the physical limitations, and the competing organizational arrangements to understand the need for a UAS Carrier-Pigeon system to supplement data transfer capabilities without the USAP incurring massive costs from launching another satellite.

3.1 Communications Need

In 2011 the National Science Foundation (NSF) Office of Polar Programs (OPP) commissioned the Aerospace Corporation to conduct an analysis of alternatives study addressing

future communication needs for the USAP. The results of the study helped to gain understanding to inform decisions on USAP communication architectures for planning 2015-2030. The science workshop brought together experts in the major fields that perform science with USAP. The goal was to ascertain how much communication infrastructure is necessary to support their current mission and future projection. Below Figure 3.1 illustrates the focus of the workshop on scientific communication needs, both the specific requirements for each area scientific research and the necessary science operations required to make these endeavors possible [13].

Figure 3.1 Communication Need

Figure 3.1 shows how the communication need is derived for science mission areas and for science operations. This committee workshop and analysis of alternatives showed the overwhelming need for alternatives to communication in the South Pole Station infrastructure. The Carrier Pigeon UAS could provide the South Pole Station with a proposed solution to the communication need if enough physical data was transferred over a specified period.

The South Pole Station major research is focused on photon astrophysics and particle astrophysics. Particle astrophysics research is conducted with the already discussed IceCube particle detector. In conjunction with IceCube that pulls 1 TB/day, photon astrophysics is conducted with the 10-meter South Pole Telescope (SPT). The SPT is the can detect millimeter and sub-millimeter waves that exist within the cosmic microwave background. The SPT is

demonstrating its value in the search for dark matter and dark energy and testing cosmological models for the origin of the universe. Currently, the science research involves a mixture of remotely scheduled observing and on-site caretaking. Below in Figure 3.2 John Kovac who spearheads the photon research reported the SPT data requirement per day at 120 gigabytes. Figure 3.2 shows how Kovac arrived at the data requirement in his report based on the hardware data pull [13]. Figure 3.2 is an aggregate of the data requirement at the South Pole for the current systems in operation.

Data Requirement				
Current System	No. of Detectors	Samples per Beam	Sec/Day	Result GB/Day
BICEP & SPUD	2048	5	86,000	20
SPT	960	5	86,000	60
POLAR-1	4000	-	-	120
IceCube	5,160	-	-	1000

Table 3.2 South Pole Hardware Data Pull

Kovac also presented to the committee a historical trend of South Pole Instrument Characteristics for data requirements. Highlighting that current instruments of SPUD, SPT-pol, and POLAR-1 use a 15 GB/Day, 60 GB/Day, and 120 GB/Day respectively. A future projection by Kovac showed that 1000 GB/Day will be the data requirement in the future. Several years later and this already reached.

Historical Trends of South Pole Instrument Characteristics						
	Observation Years	Where	Number of Detectors	Power (kW)	Data GB/Day	TCP/IP Hours/Day
Heroic Age	1962-1992	Snow	0-4	Generators	<.01	0
Python	1992-1997	Snow	2 or 4	<5	<.1	Few
Viper	1998-2000	MAPO	16	5	<.1	Few
DASI	2000-2003	MAPO	13	25	.1	12
ACBAR	2001-2005	MAPO	16	5	.3	12
QUAD	2005-2007	MAPO	62	10	1	12
BICEP	2006-2008	DSL	98	5	2	12
SPT-SZ	2007-2011	DSL	960	40	30	12
BICEP2	2010-2012	DSL	512	5	5	9
SPUD	2011-	MAPO	1536	30	15+	9
SPT-pol	2012-	DSL	1500	40	60	?
POLAR-1	2013-	DSL	4000	12	120	
Future			10000		1000	

Table 3.3 South Pole Historical Instrument Trends

Current data storage is on the order of 1.2 TB per day at South Pole station for IceCube, SPUD, SPT-pol, and POLAR-1. This will increase as the IceCube lab receives updated hardware equipment in the near future.

Requirements and Constraints derived from Chapter 3.1:

- 1. Payload volume capable of 2 X 10 TB of on-board physical storage**
- 2. Payload weight 3 lb. derived from 2 X external hard drive weights**
- 3. System will act as supplement physical transfer data and not primary**

3.2 LEO Routes

The Amundsen-Scott South Pole Station uses communication satellites that serve as relay stations, receiving radio signals from one location and transmitting them to another. The United States Antarctic Program utilizes the satellites for the transfer of South Pole science, operational, and weather data, as well as internet, telephone, and email services. The South Pole Station gets less than twenty-four hours of communication connectivity because of its physical location on Earth. The limited communication window is critical to understanding the need for the Carrier

Pigeon UAS. Since the South Pole Station does not receive enough satellite time due to the LEO route orbits and the time limits from competing organizations an alternative solution to data transfer via the Carrier Pigeon UAS is in high demand. The Carrier Pigeon UAS will supplement the already existing infrastructure to allow the South Pole Station to reach a data transfer to compete the information demands. The Carrier Pigeon UAS will allow for the station to reach a transfer demand in a cost-effective manner rather than incurring the costs to launch another satellite that will cost on the order of \$700 million like the last TDRS satellite program cost in 2007 [34].

The Earth's curvature blocks the South Pole from seeing most satellites because of the satellites geosynchronous orbit. The geosynchronous orbit is 22,236 miles above the equator that travels in the direction of Earth's rotation. All satellites are in elliptical orbits with an inclination parameter. Most of the inclination parameters are kept very small, less than $.5^{\circ}$, which makes them non-visible to the South Pole station. The geosynchronous orbit needed for the South Pole Station visibility is very high. This very high inclination describes the amount of north-south movement a satellite makes in its orbit over the twenty-four-hour period. Over the twenty-four-hour period of a geosynchronous satellite's orbit, the ground trace looks like a figure eight. Satellites with large inclinations have larger figure eights. When the lower lobe of the 8 extends below 8.7° degrees south, the satellite is visible to the South Pole Station [7]. Below in Figure 3.1 are the three satellites the South Pole utilizes and their respective figure eight ground trace. When the satellite ground trace dips below the equator is when the satellite is visible to the South Pole.

Figure 3.4 South Pole Satellite Ground Trace

3.2.1 Satellite Configurations

Currently there are three satellites that provide coverage at the South Pole; TDRSS Relay Satellite, DSCS (Defense Satellite Communications System), and Skynet Satellite.

The Tracking and Data Relay Satellite System (TDRSS), was built to communicate with the NASA Tracking and Data Relay (TDRS) satellites. There is one satellite in-service that is visible to SPTR2 (ground terminal) at the South Pole, which is the TDRS F6. The TDRS has a high and low rate transfer channel. The high rate channel offers transmission speeds up to 300 Mbps. The low rate channel offers a transmission of 7 Mb/s. The high rate channel provides data transfer for science and the low channel provides internet and telephone services to the South Pole network [7]. For comparison purposes, the average data rate for internet in the United States in 2017 is 18.75 Mbps [8]. The high rate channel is several orders of magnitude higher than the transmission speed of average internet, but is only visible for about two to four hours daily. The TDRS satellites are all shared with NASA and other organizations such as the International Space

Station, and Hubble Space Telescope. Scheduling the TDRS due to the competing organizations is not always consistent [7].

The second satellite in operational use at the Amundsen-Scott South Pole station is Defense Satellite Communication System, the DSCS-B7. This is a Department of Defense satellite in the constellation of military satellite communications. The satellite became operational in June 2016 and provides daily coverage of about three and half hours. The system uses a VSAT (very small aperture terminal) that provides a common systems architecture, operational management, and spare parts. The upload transmission rate is 10 Mbps and the download rate is 30 Mbps.

The third satellite in operational use is the Skynet Satellite Communications System with the Skynet-4. The Skynet-4 is the United Kingdom's Ministry of Defense military satellite communications system. The Skynet-4 was designed to operate without active positioning of the satellite. This resulted in a gradual increase of the satellite's orbit with respect to the equator, that drifted into a highly inclined geosynchronous orbit that provides visibility with the South Pole Station. The ground terminal at the South Pole Station uses an X-band antenna system along with the DSCS VSAT [7].

3.2.2 Data Transfer Speeds

The communications connectivity and bandwidth available at the South Pole significantly limits the science that can be conducted in the Antarctic interior. The three satellites in operation list their current information for frequency band, daily contact window, and uplink in Table 3.5.

Satellite Link Information			
Satellite	Operating Frequency Range	Daily Contact Window	Uplink (Outbound)
DSCS-B7	Military X-Band	3.5 Hours	10 Mbps
TDRS-SPTR2	S-Band, Ku-Band	4 Hours	275 Mbps, 5 Mb/s
Skynet-4c	Military X-Band	5.8 Hours	1.5 Mbps

Table 3.5 Satellite Information

The South Pole Satellite systems current architecture configuration is seen below in Figure 3.6. with the three satellites, currently in operation.

Figure 3.6 Systems Architecture Description [32]

3.2.3 Operational Timeline

Satellite service is fragmented into small windows of time. From Table 3.5 illustrates the current daily contact window, with the average, no more than four hours daily between the three satellites. Many research projects are best performed when data-gathering protocols can be adjusted in near-real time. Severe bandwidth limitations encourage researchers to be on site to gather there data rather than at their home laboratories in the United States. The laboratories at the researchers' home site have access to multiple resources that are essential to further enhance the scientist research. These barriers to remote access work against reducing costs by minimizing the number of people on ice [9]. Along with changes in satellite service means changes in the way scientific data and personnel interact with their colleagues [10]. The proposed conceptual Carrier-

Pigeon UAS would supplement the existing scientific data transfer protocol to allow researchers to maintain a consistent reporting procedure. Below in Figure 3.7 is an operational satellite schedule for a fourteen-day time period from April 24, 2017 to May 6, 2017 at the South Pole station. The SPTR has multiple windows because of the multiple satellites that are visible in its systems architecture.

Figure 3.7 South Pole Satellite Schedule [33]

Figure 3.8 illustrates mapping the elevation angle of the three satellites on the y-axis with a daily twenty-four-hour timeline on the y-axis. The DSCS with the smallest elevation angle has the smallest window of daily visibility. Versus the SPTR and TDRS system with the greatest elevation angle and the longest daily visibility window of 5.8 hours.

Figure 3.8 South Pole Satellite Elevation Angles [36]

Current satellite coverage only allows up to 13.3 hours of upload hours per day. This is not enough satellite time to feasibility transmit all daily requirements of data capacity.

Requirements and Constraints derived from Chapter 3.2:

- 1. Satellite coverage not adequate for data transfer due to LEO limitations.**
- 2. Coordination with central collection procedure for daily data compiled for various research labs at South Pole Station.**

3.3 Satellite Influence on Carrier Pigeon UAS

The current satellite architecture, satellite transfer speeds, and satellite operational windows highlight the need for a supplemental form of data transfer. The satellite data transfer challenge is the number one driver for a technical feasibility case of the need for the Carrier Pigeon UAS for the United States Antarctica Program. The satellite architecture at the South Pole also influences the overall design of the Carrier Pigeon aircraft in the selection of the avionics in the system. The avionics will need to be considered heavily in the conceptual design phase of the Carrier Pigeon UAS. Navigation equipment with SATCOM, HF, and iridium capability to navigate the preplanned route. SATCOM, HF, and iridium redundancy in both avionics and

ancillary systems of UAS are critical to comply with airspace management from Department of Interior OAS.

Chapter 4

ROUTE OPTIONS

Unmanned aircraft must fly mission profiles that enable them to use their payloads effectively in time and space. Segments can include ingress to the mission area, loiter, and egress back to the recovery site [8]. Unmanned aircraft performance ranges from designs that break endurance or altitude records to lackluster designs. When performance pushes the state of the art, meeting the requirements becomes much more challenging. In meeting the performance requirements, a considerable amount of time must be taken to investigate all possible proposed mission profiles. In this proposed mission profile, the Carrier-Pigeon UAS must launch, climb to cruise, cruise, descend and then reach the desired location of high connectivity for delivery of the research data payload. The Carrier Pigeon will not return to South Pole Station. Flight missions are one-way to location of high connectivity. Return mission requirements would not meet personnel, aircraft performance from unforeseeable variable weather, and extreme weather recovery capabilities at South Pole Station. A determined number of aircraft will be pre-positioned at South Pole during austral Summer to make flights during winter when manned aircraft are unable to land at South Pole Skiway. An analysis to determine what validates a location of high connectivity, candidate route options for potential mission locations, and a sample mission profile for a route will be conducted. Analysis on these aspects will allow route and mission profile feasibility conclusions to be evaluated.

4.1 Location Range

High endurance UAS applications have been under development for several decades. Countless different mission sets such as; multi-day telecommunication support, military ISR employment, and airborne science just to name a few. The mission profile for the Carrier-Pigeon UAS requires the system not only to have high endurance, but to be able to fly long range – about 3,000 nautical miles. Although there are locations that are closer to fly for suitable maintenance

support, such as McMurdo Station or Scott Base. Both only being around 900 nautical miles from the South Pole Station. The payload that the Carrier Pigeon will carry is physical data storage of scientific files. This scientific data needs to deliver to a location that will have adequate resources for connectivity and scientific research facilities to ensure ease of data transfer to scientist home laboratory. Currently, McMurdo station, Palmer Station and USAP vessels on the continent of Antarctica do not have to continuous communication connectivity to upload the data. In order to fulfill the system's mission, the UAS must fly off the continent of Antarctica and will not make a return mission. The Carrier Pigeon mission is a one-way route off the continent with no return flight mission.

Below in Figure 4.1 are the four candidate locations determined based upon, distance from the South Pole Station, overall connectivity capability to specific research institutions for data transfer, infrastructure for operations and maintenance support of system. The connectivity capability ranking was conducted through trade studies of current communication infrastructure at locations. A look at data rates for research centers and universities were the primary use for assessment of rank. The trade studies also took a look at airport size and runway length. Although the Carrier-Pigeon UAS will most likely be run-independent with net or sky-hook for retrieval. The run way length is direct correlation for support infrastructure for maintenance and connectivity. Runway independence will be discussed in further detail later.

Candidate Location	Distance from South Pole (NM)	Connectivity Capability	Recovery Infrastructure
Christchurch, New Zealand	2792	High	High
Ushuaia, Argentina	2115	Low	Medium
Punta Arenas, Chile	2215	High	High
Hobart, Australia	2836	High	High

Table 4.1 Candidate Locations

4.2 Locations of High Connectivity

4.2.1 Christchurch, New Zealand

Christchurch, New Zealand is currently the home to a number of national programs for Antarctica research to include the United States, Italy, and South Korea. The International Antarctic Center provides both base facilities, a museum, and visitor center focused on current Antarctic activities. The United States Navy and United States Air National Guard use Christchurch Airport as the main supply route to McMurdo and Scott bases in Antarctica [10]. A study in 2013 found the economic impact of Antarctica-related activities was \$103 million for the Canterbury community and \$162 million for New Zealand [11].

The Antarctica office has even put together a business case for future plans for a National Antarctic Research and science hub, to be built on Christchurch airport land. It would provide a research facility with four large modular laboratories that could be leased to local and international scientist. The labs would have specialist capabilities such as extreme cold freezers, ultra-dry environments and aquariums. Samples of rock, soil, or marine life could be brought back from Antarctica for research to be carried out here in a bio-secure environment, meaning normal quarantine regulations would not need to be followed.

The University of Canterbury has the Gateway to Antarctica Center for Antarctica Studies and Research in Christchurch. The center plays a leading role in international and national Antarctic research projects. These projects include engineering in extreme environments, Antarctica's role in climate change, connections between Antarctica and New Zealand and human influences in and on Antarctica. They offer three postgraduate programs. The research is focused on three interdisciplinary topics that are of strategic importance; Atmosphere-Climate Cryosphere, Antarctic Ecosystems, and Antarctic Southern Ocean Governance [12]. Christchurch's headquarters for USAP supply chain, research facilities with network connectivity both professionally and academically make this location prime for a candidate of the system.

4.2.2 Ushuaia, Argentina

Ushuaia, Argentina is the capital city of the Argentinean province of Terra del Fuego and is commonly referred to as the southernmost city in the world. Ushuaia is by far the most popular gateway for Antarctic tourism, capturing almost 90% of the 35,000 tourists who travel there each year. Even though it is referred to as the southernmost city in the world there are no established bases for national Antarctic science programs. Although tourism is high the infrastructure to support scientific programs and data upload is limited. The lack of capable facilities with network connectivity and research programs ranks Ushuaia last in candidate locations [31].

4.2.3 Punta Arenas, Chile

Punta Arenas was the key site to early Antarctic scientific expeditions. One of the most important is the failed Imperial Trans-Antarctic Expedition by Sir Ernest Shackleton. Punta Arenas is the site to national Antarctic programs of more than 20 countries. The highest of any of the so-called “gateway” cities to Antarctica. Numerous commercial charter flights with Falcon 7X being currently conducted. Commercial aviation charters, numerous national Antarctic programs, and the one of the shortest-range requirement at 2215 NM provide strong argument for candidate route selection for Carrier Pigeon UAS [31].

4.2.4 Hobart, Australia

Hobart, Australia is the most complete infrastructure of any of the “gateway” cities to Antarctica. Hobart hosts the largest critical mass of Antarctic scientist and scholars anywhere in the world with world-class research and education institutions. The University of Tasmania (Institute for Marine and Antarctic Studies) IMAS has been the world leader in university studies. In the early 1990’s, the local government created the Tasmanian Polar Network which represents considerable Antarctic and Southern Ocean business and science sector. Hobart has a strategic logistical, economic, and scientific gateway status primarily for the French and Chinese Antarctic

programs. Hobart is the longest-range requirement of all candidate locations at 2836 NM. The extended range may cause the system developer in the conceptual design considerable optimization challenges [31].

4.3 Candidate Routes

Below is Figure 4.2 the four candidate routes are illustrate on the map of Antarctica. Since the South Pole Station is at 9,301 ft. the mission profile for each the candidate route will relatively stay unchanged because of take-off location. The Carrier-Pigeon UAS will always take off from the South Pole Station and fly the same pre-programed route to its proscribed candidate location. Since the South Pole Station is at such an altitude to start the UAS will fly at a cruise altitude of 16,000 ft. in order to bypass all potential terrain features on the Antarctica continent. Key terrain features that because special interest is Mt. Vinson in West Antarctica, the Transantarctic Mountains that divide East and West Antarctica, and Dome A. These areas are key terrain because they all rise above 13,000 ft.

Figure 4.2 Candidate Location Routes

In order to better understand the physical terrain discussed earlier in chapter 2 an example stage I- (climb and cruise) mission profile of the Carrier Pigeon is below in Figure 4.3 to Christchurch.

Cross Section through A to B

Figure 4.3 Candidate Route to Christchurch

In order for the Carrier-Pigeon UAS to conduct a mission fly to Christchurch the aircraft must fly over western Antarctica from the Ross Ice Shelf. There has been no defined climb rate or ceiling specific at this time. But looking at historical UAS of this size a 150 ft./min climb rate (conservative assumption) is a good place to start along with a cruise altitude of 16,000 ft. with a ceiling of 19,000 ft.

Requirements and Constraints derived from Chapter 4.1:

1. Rank of candidate locations based on four categories:

- Established interest in US Antarctic Program South Pole Station (US Base).
- Infrastructure able to handle recovery of UAS (airport).
- Connectivity to NSF network to upload data storage fastest.

- University Antarctic research focus

- Candidate route range to location

2. Candidate routes ranked as follows based on above hierarchy:

1. Christchurch, NZ

2. Punta Arenas, Chile

3. Hobart, AU

4. Ushuaia, Argentina

Chapter 5

VEHICLE OPTIONS

Most vehicle options and sizing are derived from historical aircraft. In this chapter, we develop system requirements for the Carrier-Pigeon UAS, analyze comparable candidate UAS platforms, and begin to develop a range of limits for performance numbers from aircraft design equations. The development of building a framework of low bound and high bound limitations for design specific numbers will further answer the question of whether or not a sound physical solution is feasible for data transfer UAS from the South Pole Station.

5.1 UAS Systems Requirements

In order to design an aircraft, it is necessary that a set of system requirements for the aircraft be derived. Systems level requirements which lead to mission specifications come about in different ways, depending on the customer. Many aircraft never make it beyond the initial design phase. In fact, most don't. If it becomes evident during the research program, that the problem cannot be solved in a reasonable time frame or at a reasonable cost, the subject design can be dropped or modified [17]. Development of requirements to answer the question if the problem can be solved with the design is one of the fundamental basis for this research. Below in Figure 5.1 is an initial set of requirements derived from conclusions of analysis that will have the greatest impact of the Carrier-Pigeon design and feasibility assessment. These requirements do not make up the entirety of the system requirements.

System Requirements	
UAS Requirement	Rationale
System will be capable to operate during Antarctic winter season	During this time passage and cargo flights in and out of South Pole are halted to limiting weather conditions. Continuous capability to extract data during this time period is critical to NSF mission requirements for scientific research.
System will execute mission plan from South Pole to determined location of high connectivity	System will ensure range equation is satisfied for mission to location of high connectivity with non-stop flight and non-refuel during mission execution.
System will be capable of transportation in cargo to South Pole via largest aircraft in USAP fleet (LC-130)	System will have the capability to be pre-staged at Amundsen Scott South Pole Station prior to employment. This will allow UAS capability to have required hardware on ground prior to winter when aircraft cargo is unable to reach South Pole Station.
System will be able to fly at a cruise altitude of 16,000 ft.	Amundsen-Scott South Pole station is situated at 9,301 ft. UAS will need to ability to take off and reach a cruise altitude of 16,000 ft.
System will be capable of being employed minimally manned (2-3 personnel)	Due to the decrease personnel during winter (40 personnel) the UAS must be able to be employed without a heavy burden on the operation force at Amundsen-Scott station.
System will have a payload capacity to carry at minimum 20TB of physical hard drive	The minimum data transfer must exceed current weekly data transfer by a factor of 10x better to ensure that the program cost is offset for new system development for customer.
System will have a Ground Control Station established at South-Pole Station	This will ensure that flight missions and all information is consolidated at a central location to be processed and ensure that UAS is operational.

Table 5.1 Systems Requirements

5.2 Comparable Candidate UAS

While the number of UAS in operation is growing, the field is fairly small considering the mission requirements for the Carrier-Pigeon requirements. Similar UAS were selected with a fairly wide range spectrum for initial sizing comparison. This long range, high endurance, extreme cold weather UAS will be comparable to tactical military, long range, and commercial maritime survey UAS. Figure 5.1 shows the comparable aircraft for range, size, and endurance.

Comparable Candidate UAS									
UAV Platform	Engine Type	Cruise Speed	Empty (lbs.)	MTOW	Range (nm)	Endurance	Length	Wingspan	Unit Cost
Scan Eagle 2	2 stroke	60 kts	35.3	58	800	24+	5.6 ft	10.2 ft	800,000
Aerosonde	2 stroke	39 kts	60	80	75	14	5.8 ft	11.9 ft	420,000+
Integrator	2 stroke	55 kts	80	135	58	24+	8.2 ft	16 ft	5,400,000
Shadow	Wankel	70 kts	186	375	59	9	11.2 ft	14 ft	15,500,000
Primoco UAV	4 stroke	75 kts	220	330	809	10	11.9 ft	15.9 ft	70,000
RQ-2 Pioneer	2 stroke	110 kts	392	452	100	6+	14	16.9	850,000
GNAT	2 stroke	105 kts	560	1140	?	48	16.5	35.4	4,003,000
Hermes 450	Wankel	70 kts	992	1212	162	30	20 ft	34.5 ft	2,000,000
MQ-5A Hunter	2X Mercedes	89 kts	1603	1950	67	21	22.99 ft	34.67	15,000,000+

Table 5.2 Comparable UAS with Unit Cost

The eight-comparable aircraft in Figure 5.2 are a representative range of UAS that may have existing performance characteristics that could be altered in order to meet Carrier-Pigeon mission requirements; with the heavy emphasis on the systems, increased endurance, increased range, and decreased payload weight. The aircraft empty weights in Figure 5.2 range from 35.3 lb. to 1603 lb. The cost per unit of aircraft ranges from \$70,000 to upward of 15,000,000. Although unit cost represents a huge variation range, even the most expensive per unit aircraft cost is many orders of magnitude lower than the \$700 million dollars to launch another satellite into low earth orbit satellite.

At the heaviest maximum take-off weight is the Northrop Grumman MQ-5 Hunter at 1950 lb. with a fuel capacity of 79.3 gallons. The Hunter is employed for military ISR operations and has a significantly larger payload, range, and time-on-station capabilities than other

unmanned platforms for the military. As the comparable aircraft weights increase though, so does the physical size of the aircraft, causing more constraint on the shipping capability of the UAS in the USAP fleet of LC-130's during Summer resupply missions. Due to shipping constraints on a pallet on an LC-130 the UAS will have to have modularity. The UAS will be capable of disassembly at several breakpoints in order to be shipped on a standard 163L Air Force pallet with dimensions of 108" X 96" X 96". Shipping requirements will be discussed further in Chapter 6. The Scan Eagle and the Hunter represent the spectrum of maximum take-off weight for both the heaviest and lightest range of UAS that would potentially meet the system requirements of the Carrier Pigeon UAS. The Tier I vehicles meet the systems modularity and shipping requirements, but fall short in range and endurance requirements for the derived Carrier Pigeon mission profile. While the Tier II vehicles meet range and endurance requirements, but fall short in modularity and shipping requirements. The Carrier Pigeon system feasibility lies in between the bounds Tier I and Tier II aircraft.

The Boeing-Insitu Scan Eagle was identified as a baseline for performance design to the Carrier-Pigeon UAS. The design parameters of the Scan Eagle will be analyzed, compared, and reverse engineered to output lower and upper limits the Carrier Pigeon initial performance parameters must meet for feasibility. The Scan Eagle has a published range of 800 nautical miles, but in 1998 piloted a transatlantic mission of 2,000 nautical miles using only two gallons of fuel during the 26-hour crossing. After being launched from the top of a car, it navigated autonomously across the Atlantic using onboard global positioning satellite navigation system following a pre-programmed flight path [18]. Although that falls short of the 3,000-nautical mile range needed for the Carrier Pigeon. The Scan Eagle has an endurance of more than 18+ hours, a ceiling of 19,500 ft., maximum take-off weight of 58 lb., a length of 5.6 ft., and a wingspan of 10.2 ft. It has a unique purpose-built modular propulsion system that is powered by heavy fuels. The heavy fuels design allowed the Scan Eagle capability to run on the military's JP-8 and diesel fuel in deployed

theater operations, where Jet-A is not as abundant. The Scan Eagle is made specifically for the ruggedized military application in austere environments. The Scan Eagle platform served as the perfect baseline candidate aircraft to develop parameters for the Carrier-Pigeon. But the ScanEagle could not be a direct solution to Carrier Pigeon because it does not meet the range requirement of over 2,000 nautical miles to the four candidate locations [20].

5.3 Aircraft Sizing

General arrangement of aircraft is on the basis of estimations and predictions of:

Structural Efficiency: $\frac{W_E}{W_{TO}}$

Aerodynamic Efficiency: L/D

Propulsive Efficiency: BSFC

The aerodynamic efficiency, propulsion efficiency, and structural efficiency are often performed for initial sizing on candidate aircraft configurations. The Scan Eagle will be our candidate aircraft configuration that will be used to build and make assumptions for the derivation of the Carrier-Pigeon performance parameters [20].

The structural efficiency of an aircraft is explained and derived to show how predictions will be made for the Carrier-Pigeon based from the Scan Eagle example. The estimation of the weight of a conceptual aircraft is a critical part of the design process. There are many ways and levels to weight analysis. Everything from sophisticated methods with detailed statistical equations for various components to crude component build up. This research will focus on the latter, with crude weight estimation and build-up in order to answer whether there can be an aircraft design feasible to continue on to further conceptual analysis and development. The focus on determining the basic aircraft description parameters begins with the following parameters:

Takeoff Weight (W_{TO})

Empty Weight (W_E)

Fuel Weight (W_F)

Payload Weight ($W_{payload}$)

The basic parameters and estimations combine together in the below equation for weight build up.

$$W_{TO} = W_E + W_{Pay} + W_F$$

From these requirements from the design mission the development of estimates and predictions can begin to form. This process is iterative and must cycle through values for each of the prescribe parameters. The parameters must be validated individually to ensure that they are correct and can be obtained. But also, the parameters must be validated on how they affect the overall performance when input to get the mission requirements – with our focus on range and endurance [30].

5.4 Scan Eagle Weight Estimation Example

Below are the Scan Eagle basic weight parameters to build a baseline for computing an estimated weight approximation for the Carrier Pigeon UAS and to ensure our calculations are correct for flight endurance, mass fuel fractions, range. Critical to note, in sizing UAS, the payload weight is sometimes incorporated into the takeoff weight and empty weight. Carrier Pigeon calculations follow this guideline and not the classical weight estimation [29].

Takeoff Weight (W_{TO}) = 58 lb.

Empty Weight (W_E) = 35.5 lb.

Fuel Weight (W_F) = 11.5 lb.

Payload Weight ($W_{payload}$) = 11 lb.

5.5 Flight Endurance

Because this study is focused on the technical feasibility of the Carrier-Pigeon UAS early conceptual design methods are applied that make crude weight estimation, performance estimation, and propulsion type selection. Full conceptual design utilizes more complex weight estimation methods that account for detailed systems information. These simple weight estimations are suitable for determining the “corner of the universe” of possible designs in which the design of interest resides. Because range and endurance are generally the most important design parameters for aircraft design, most efforts try to maximize one or the other. The flight endurance equation with assumptions for aerodynamic efficiency will be explored. A representative range of an aerodynamic efficiency between 12 and 20 was selected from research from trade studies, comparable design books, and experienced engineers that have worked in the design field. The Carrier-Pigeon UAS will look at the design parameters that will develop what the potential feasible solution to this system will initially look like.

This weight analysis seeks to define the potential takeoff gross weight. Weights can be calculated through functions and procedures that are dependent upon the takeoff gross weight. No single approach, is possible for unmanned aircraft design [15]. Range and endurance equations for turboprops or reciprocating engines driving propellers are applicable to any liquid-fueled propulsion system where the power generator converts the fuel’s chemical energy into propeller shaft power. Battery-powered electric propulsion was researched to see the likely feasibility of an electric propulsion system. Battery-powered electric propulsion did not meet the initial assessment of long endurance and extreme cold weather conditions found for mission requirements at the South Pole Station. Lithium polymer and Lithium ion batteries have an order of magnitude smaller than that of gasoline in mass specific power energy. Therefore, the current

battery technology would not meet system requirements due to extreme cold weather operability and power density.

The UAS loses weight as it expands the fuel mass after combustion as exhaust. For example, these equations can be applied to a hydrazine fueled engine that drives propeller. The range and endurance equations below are also rearranged to solve for fuel mass fraction. Below is the calculation for a range of a propeller aircraft at constant angle of attack is:

$$R = \frac{L}{D} * \eta_p * \ln\left(\frac{1}{1 - MF_{Fuel}}\right)$$

Where R is the range, L/D is the aircraft lift-to-drag ratio, η_p is the propeller efficiency, and BSFC is the power generator brake specific fuel consumption. Solving this equation for fuel mass fraction results in:

$$MF_{Fuel} = 1 - e^{\left(\frac{-R * BSFC}{\frac{L}{D} * \eta_p}\right)}$$

Endurance for a propeller aircraft with a constant angle of attack and constant velocity is:

$$E = \left(\frac{L}{V * D} * \eta_p\right) * \ln\left(\frac{1}{1 - MF_{Fuel}}\right)$$

Something that must be heavily considered in calculations for range and endurance is to be especially careful with fps (British) units. Each equation must identify the units of the data used to be sure that all units cancel, leaving the units of the desired answer. Be wary of equations involving horsepower. Anytime the constant “550” appears in an equation, the other units must be converted to feet, pounds, and seconds (one bhp = 550 ft-lb/s). Another potential source of confusion is the specific fuel consumption C, which is usually given in units of $hours^{-1}$. This must be divided by 3600 to yield $seconds^{-1}$ [1].

The range requirement needed to be designed to was determined to be 3000 nautical miles. 3000 nautical requirements were derived from the candidate routes seen in chapter 4 with potential for reserve. In order to ensure the feasibility of a sound physical solution the farthest location of high connectivity is considered the range requirement. The longest location of high connectivity is Hobart, Australia at 2,836 nautical miles from the South Pole Station. This would allow any other location to be considered if the system developer decided to change the mission location to any of the other candidates. 3,000 nautical miles also accounts for at worst case scenario for the longest range a 5% range reserve or extended flight due to the extreme mission. 3,000 nautical miles was the accepted design range during iterations of sizing for empty weight fractions and L/D ratios.

5.5.1 L/D Ratio

The range of lift over drag ratios for the Carrier Pigeon UAS was developed from various trade studies conducted similar aircraft of this size and maximum weight take off. The range ratio of L/D was selected from 12 to 20. 12 likely to be easily achieved and 20 very hard to achieve. The desired design L/D from carpet plots and trade studies of similar aircraft is 16. In order to ensure the worst-case scenario for feasibility of design. L/D value of 12 was utilized during all calculations. The sizing matrix for carpet plots for the Carrier Pigeon UAS reflects the desired ranges of L/D from 12 to 20.

5.5.2 Propeller Efficiency, η_p

One of the single biggest variables affecting the efficiency of the propulsion system is the choice of propeller. Even the Wright brothers cited good propeller design as one of the key developments that enabled them to fly their first aircraft successfully. There are a ton of manufacturers that produce propellers and their accuracy varies considerably. Their design philosophy, geometry, materials, and manufacturing all impact efficiency. Peak efficiencies vary for such propellers from 43% to 65% for two-bladed propellers of similar diameter, even when

operating at the correct advance ratio for the chosen pitch. Propeller thrust also varies significantly with variations in advance ratio. As the airspeed seen by the propeller changes, if the rotational speed does not, the various aerodynamic sections of the propeller see different angles of attack. Therefore, a fixed-pitched propeller will have to compromise between thrust during takeoff and while at cruise speed and at maximum airspeed [19]. The Carrier-Pigeon UAS will utilize a fixed pusher propeller two blade configuration. Two blade pusher propeller configuration was determined from the selected candidate engines that utilize the same configuration in both the Scan Eagle and Aerosonde discussed in section 5.5. Comparison two-blade pusher propeller configuration propeller efficiency yield a conservative estimate of .8 depicted above in Figure 5.5. This η_p depends on a various number of factors such as manufacturing and materials selection. A representative range found in research from similar medium UAS in trade studies output ranges from an η_p of .7 to .9. A high confidence that a two-blade fixed pusher propeller can achieve .8 propeller efficiency was determined and were used in range calculations.

5.5.3 Propulsion Systems and Brake Specific Fuel Consumption

All aircraft require powerful, lightweight, efficient propulsion. For medium and small unmanned aircraft systems, this almost always means some form of propeller-based system. As it is difficult to engineer variable-pitch propellers on the scales required, fixed pitch systems are generally used. Most of the time in the commercial small to medium unmanned aircraft systems bespoke built engines are not commonly developed. Usually the incurred costs of developing bespoke prime movers means that the designer of small and medium UAV's is generally faced with rather difficult compromises in selecting the appropriate propulsion system from components already available on the market. But for the Carrier-Pigeon development a bespoke engine will most likely have to be developed in order to maximized its performance for the required long range high endurance mission. Development of a bespoke engine will be many

orders of cost lower than the alternative of incurred cost of launching another satellite into low earth orbit.

There are no concrete solutions for what is the best approach in selecting an engine. For long-endurance aircraft, gasoline-fueled internal combustion engines with multiple cylinders, via multi-cylinder engines, multiple engines, or both [19]. For sizing and assessing propulsion systems a representative set of engines has been researched and hand selected based from two similar aircraft, that have similar endurance and range. This engine selection will provide a foundation to build on into the conceptual design phase for understanding the size, type, brake specific fuel consumption, and power to weight ratios needed in order to compete with mission requirements. The Insitu Scan Eagle, Textron Aerosonde, and Viking 400 are equipped with engines that allow for high performance and mission readiness that meet within the long range and high endurance for the Carrier Pigeon mission. We will take a look further into understanding these engines to make comparison conclusions on whether or not a bespoke engine will need to be built or if modifications to one of these current engines would meet requirements.

The Textron Aerosonde is propelled by the Lycoming EL-005 Engine. One of the smallest aircraft engines that Lycoming builds. It was specifically designed for heavy fuel applications for Department of Defense with compact dimensions of 14.10" X 7.0" X 14.50". The Lycoming EL-005 is a two-stroke Otto cycle spark-ignited engine that is optimized for jet fuels and uses digital electronics controls. It is air-cooled that is loop scavenged with reed valve technology to control the fuel-air mixture admitted to the cylinder. It is equipped with air assist electronic fuel injection, an electronically controlled throttle and an integrated permanent magnet alternator. As a heavy-fuel compatible engine, the EL-005 gives aircraft the flexibility to operate around the world with commonly-accessible fuel types [26].

The 3W 180 SRE-Hybrid engine is a wankel hybrid cycle engine with compact design. The 4-stroke rotary engine is very light and offers an outstanding power-to-weight ratio. Because

of its high power to weight ratio it allows for higher payload weight in field operations. With the hybrid boost power, an additional 15 KW depend on store capacity. The additional power volume is simplifying lift off or acceleration. The engine can run with gas or heavy fuel. A standard manifold is offered or a high-pressure injection manifold. The cooling of the engine is guaranteed by water cooling of the housing and oil cooling of the rotor [28].

The Zanzottera 498H is an opposed two-cylinder box two stroke engine with an output of 44HP fuel injected into the intake manifold and is propulsion for the Viking 400 and Aerostar. The Zanzottera has specific fuel consumption of better than .57 lb./hr./hp and empty weight of 41 lb. [27].

In order for a range of 3000 nautical miles to be achieved, a baseline case to reverse engineer the potential individual performance parameters needed be input into the breguet range equation. Since the Scan Eagle had made the 2,000-nautical mile transatlantic journey the decision was made to look into the Scan Eagle's design parameters. Since Insitu manufacturers an ITAR (International Traffic in Arms) free Scan Eagle for Maritime surveillance for tuna fishermen, performance parameters were readily available and published for the rotary wankel engine.

The calculated Brake Specific Fuel Consumption for the two described candidate engines are:

$$Lycoming\ EL - 005\ BSFC = \frac{1.7 \frac{lb}{hr}}{3\ hp} = .56$$

$$3W - 180SE = \frac{.55 \frac{lb}{hr}}{2.57\ hp} = .21$$

$$Zanzottera\ 498H = .57\ (list\ on\ spec\ sheet)$$

Engine Manufacturer	Engine Type	Power	SFC (lb/hr/hp)	Dimensions (Inches)	Weight (lb.)
Lycoming	2 Stroke	5 HP @ 5,000 RPM	0.56	7 X 14.5 X 14.1	13.8
3W	Wankel	27.5 HP @ 6000 RPM	0.21	6.5 X 7.4 X 8.74	14.99
Zanzottera	2 Stroke	44 HP @ 6500 RPM	0.57	17.7 X 18.6 X 30.5	41

Table 5.6 Engine Comparison

5.5.4 Payload Weight

Payload weight matters in aircraft design. In aerospace engineering, double the payload and it doubles the aircraft size. A study of the commercially viable solutions for how much 10 TB of storage weighs is represented below in Table 5.7. This table shows both a breakdown of internal and external hard drives. The Carrier Pigeon UAS design is looking to offer the ability to place the hard drive in a ruggedized payload compartment. In Table 5.7 the hard drives represented are all off the shelf, with their descriptive weights and data storage capacity. Since they are commercially viable options, they offer the worst-case scenario for the mission payload weight. In order to determine payload weight feasibility, an analysis to get the payload weight as close to exact as possible is needed. Erroring on the side of heavier allows for a safety factor. If the program was developed to build the Carrier-Pigeon UAS most likely a specific hard drive would be designed to decrease the payload weight, but off the shelf components is a good place to start for weight estimation. 20 TB of storage capacity was determined by researching the data demands on a daily basis at the South Pole Station of an estimate of 2 TB per day. To reach the desired payload of 3 lb. two 10 TB external hard drives would meet the data storage transfer requirement. The Carrier Pigeon UAS architecture primary mission is to supplement data transfer during the winter months in Antarctica. The winter months in Antarctica usually range from a sixteen-week cycle. For continuous coverage, a Carrier Pigeon UAS can launch on an operating window of every ten days from the South Pole. The 20 TB hard drives would cover 2 TB per day

of required data. Twelve Carrier Pigeon UAS platforms would need to be shipped to the South Pole station during the summer. This would allow a Carrier Pigeon to launch every ten days for the duration of the winter. The Carrier Pigeon architecture will be discussed in further detail in chapter 6. The 20 TB external hard drives payload are a representative of possible storage capacity. Hard drive storage capacity is increasing and weight is exponentially decreasing daily. Although SD cards are commercially available at maximum storage capacity of 512 GB format and weighing about .35 ounces. In order to achieve the system requirement of 20TB of storage, 40 SD cards would need to be within the payload. The total weight for the 40 SD cards would be .875 lb. About two pounds less than the two external hard drives. The decision was made to represent the payload in external hard drive weight to represent the worst-case scenario for maximum payload. Below in Figure 5.8 shows the trade study conducted on external and internal hard drive weight comparisons.

Manufacturer	Type	Storage Capacity	Weight (lb.)	Cost (USD \$)
Seagate IronWolf NAS SATA	Internal	10 TB	1.5	284.99
Seagate BarraCuda Pro 7200	Internal	10 TB	1.4	344.99
Seagate Enterprise Capacity HDD	Internal	10 TB	1.43	319.95
Seagate Backup Plus Hub	External	10 TB	2.34	269.99
G-Technology G-Drive USB 3.0	External	10 TB	2.4	299.99
Fantom Drives	External	10 TB	1.4	297.97

Table 5.7 External Hard Drive Weights

Since 1980 the decline of hard drive cost per gigabyte has decreased an exponential amount. Nearly 13,000 times cheaper than the first consumer hard disk drive in 1980. The first hard drive disk in 1980, the IBM 350 with 5 MB of data weighed 2,000 pounds. The average hard drive cost per gigabyte in 1980 was \$437,500 and the average hard drive cost per gigabyte in 2016 was \$0.019. Space per unit cost has doubled nearly every 14 months. Not only has the space per unit cost decreased but the weight per gigabyte has decreased on a similar pace, as shown above. Below in Figure 5.8 shows the representative exponential decrease of data storage density

over time. This decrease in storage density will allow for a payload to carry enough respective scientific data to warrant physical transfer from the South Pole Station to Christchurch.

Figure 5.8 Data Storage Density

5.6 Sizing Matrix

A presentation format for aircraft sizing is called the carpet-plot. The carpet plot superimposes the maximum take-off weights versus specific fuel consumption, versus lift over drag ratios. To avoid clutter, the horizontal axis has been shifted to the left an arbitrary distance. This shifting of the axis is crucial to the development of the carpet-plot format. Using all the above calculations for range, endurance, and mass fuel fractions a carpet plot of the Scan Eagle was developed to bracket the potential L/D that was used for design, validate brake specific fuel consumption, and back out conservative estimates of propeller efficiency. Below in Figure 5.9 is the carpet plot constructed from Scan Eagle design parameters for validation of code. The carpet plot shows the maximum take-off weight of the Scan Eagle at 58lb.

Figure 5.9 Scan Eagle Carpet Plot

The below carpet plots were developed from calculating the desired range for the Carrier Pigeon UAS with a representation of three empty weight fractions for comparison for candidate solution sizing for UAS system. The three empty weight fractions are: .55, .60, and .65.

Figure 5.10 Carpet Plot of .55 Empty Weight Fraction

Figure 5.11 Carpet Plot of .6 Empty Weight Fraction

Figure 5.12 Carpet Plot of .65 Empty Weight Fraction

The above carpet plots show that the Carrier Pigeon UAS design range mass fraction that meets the range requirement of 3000 nautical miles, payload weight of 3 lb., and propeller efficiency is between .55 and .65. A great deal of analysis was conducted on the optimal inputs to meet mission requirements. The range and endurance outputs change drastically with various inputs. The optimal mass fuel fraction with an L/D of 12 and propeller efficiency of .8 was .55.

Leaning toward the optimal takeoff weight of 78 lb. and empty weight of 43 lb. The takeoff weight includes the 3-lb. payload.

5.6.1 Wing Planform Geometry

Wing planform geometry is the basic geometry used to begin the layout of the aircraft. The required reference wing area S_{Ref} can be determined only after the takeoff gross weight is determined. Since the Carrier Pigeon take-off weight has been determined from the carpet plot sizing and empty weight fraction of .55 an initial calculation of the wing area can be output. The wing area, S_{Ref} can be determined from the rearranging the C_L equation and solving for S_{Ref} .

$$C_L = \frac{W}{\frac{1}{2} * \rho * V^2 * S_{Ref}}$$

C_L can be rearranged and solved for S_{Ref} in the below equation. Since we know that the Carrier Pigeon will have to have a cruise altitude of up to 20,000 ft. in order to clear the transatlantic mountains discussed in chapter 3, the ρ of 20,000 ft. is $12.67 (10^{-4} slugs/ft^3)$ in referencing the standard atmosphere air properties table. A representative cruise velocity of $84.39 ft^2$ is assumed from the Scan Eagle specified cruise speed and a weight of 78 lb. from our .55 empty weight fraction of Carrier Pigeon carpet plot sizing.

$$S_{Ref} = \frac{W}{\frac{1}{2} * \rho * V^2 * C_L}$$

The values output an S_{Ref} of $23.7 ft^2$. The estimation of S_{Ref} can be utilized to validate rough approximation calculation of the planform area. The S_{Ref} and trapezoidal wing planform area should match one another. The Carrier Pigeon UAS will assumed to have a trapezoidal wing planform area modeled after a scaled-up version of the Scan Eagle. Something to note, the reference wing area is fictitious, and extends through the fuselage to the aircraft centerline [15]. The trapezoidal wing planform area is calculated by simple geometry:

$$Planform = .5 * (C_{tip} + C_{root}) * B_{span}$$

$$Planform = .5 * (2.2 + 3.9) * 7.8$$

Below in Figure 5.9 is a representative sketch of the Carrier Pigeon UAS with C_{tip} , C_{root} , and B_{span} configured in a trapezoidal layout. The taper of the representative sketch is derived from basic wing theory considerations and overall systems considerations for both launch and recovery. Since the Carrier Pigeon UAS will launch via a pneumatic catapult and be recovered by a cable hook system - a concept discussed further in this chapter - achieving adequate lift at low speeds during landing and takeoff are not a critical sizing factor. The wings of the aircraft do not need to be much larger than needed because the angles of attack needed at low speed do not need to be accommodated since the UAS will launched and recovered at considerable speed [19].

When deciding on initial considerations for planform shape the trade-off between aspect ratio and weight are important. Fundamentally a high aspect ratio wing, will be more aerodynamically efficient than a low aspect ratio one because of the reduction in induced drag. And a high lift over drag wing is necessary for the configuration. From the carpet plots a lift over drag ratio range between 12-20. But since a wing is essentially a cantilever beam, the greater the aspect ratio, the larger the bending moments and the heavier it is likely to be for the planform area. The needed ability for the Carrier Pigeon UAS to have modularity at several break points is why a very high aspect ratio wing is least likely to be considered. This is because of the structural loads that will be encountered and more potential for failure as number of break points for modularity for shipping the system increases. Thus, the Carrier Pigeon wings are shorter and the taper of the wings is even more important to control induced drag [19]. The Carrier Pigeon has a swept flying wing configuration based on the Scan Eagle's layout. The flying swept wing causes for some design considerations that the systems developer in further conceptual design will have to determine are worth the undertaking. These considerations are the pitching moment that comes with no tail and an optimized study to select an airfoil to generate high lift coefficients. Now this

design will still have to incorporate modularity with break points in mind, most likely at the c_{root} of the wing connecting to the fuselage. Further development of this will have to be incorporated in follow development in conceptual design phase. Taking the initial planform calculations, launch and recovery configuration, and comparison to ScanEagle swept flying wing the below initial napkin sketch design allows a future systems developer to begin to determine what a possible feasible solution to what the Carrier Pigeon UAS could look like is seen in Figure 5.14.

Figure 5.13 Carrier Pigeon UAS Planform

5.7 Avionics

The avionics in an unmanned aircraft are all but the easiest part of design for an aircraft and can become some of the most complex part of feasibility and design. Avionics must be designed to be compatible with the physical environment in which they operate. UAS physical environment can be demanding for electronics. The shock, vibration, and acceleration can be more stressing than what is experienced in ground-based electronics. Especially if a catch recovery is planned for the system. The avionics must be capable of operating within a defined

temperature range. Enclosures are usually provided to protect electronic boards from the local surrounding mounting location [15].

At the most basic level the electrical power needed by the avionics is from a redundant system of battery packs. The power supply feeds the primary receiver, navigation sensors, and control surface servos. The power supply also needs to have sufficient capacity to deal with servo torques that are needed in flight. Since the avionics supply is so critical to the safety of the aircraft, it is common to have multiple batteries with some form of fail over system to switch between them. As a system developer, the assessment of what flight time any battery goes from 100% to 50% capacity in typical flying conditions so that an estimate can be made of battery supply condition directly to the time in flight of aircraft is needed. Since the Carrier Pigeon UAS is on the order of 18-21 hours of flight for candidate routes to Christchurch understanding battery consumption and operating temperature range for electronics is critical to avionics. Also, what must be taken into account is if the batteries do not offer sufficient endurance for the UAS, some form of a generator fixed to the main propulsion engine or dedicated power generation system must be considered. Especially for redundancy in cold weather conditions and for a safety factor [19]. Gasoline powered engine systems with attached generators are commercially available and a viable option for the Carrier Pigeon system.

Almost all UAs systems rely on flaps or control surfaces for pitch, roll, and yaw control. Servos are readily available in a wide range of shapes, sizes, and torques. Servo torque usually varies with servo weight. If high-torque and power, metal-gearred servos are used, large control surfaces can be reliably controlled by each one. Below in Figure 5.10 is a representative table of examples for servo size and weights. Although at this stage an estimated BOM (bill of materials) will not be constructed, but a basic understanding of the specified servo characteristics that will need to be research further is presented.

Servo Properties					
Type	Make	Depth (mm)	Width (mm)	Height (mm)	Weight (g)
Metal	Hitec	30	46	60	100
Metal SHT	MKS	22	40	40	79
Metal HT	Savox	22	40	40	67
Metal	Hitec	22	40	40	58
Metal	MG	22	40	40	57
Plastic	Futuba	20	40	35	45
Metal	MKS	10	30	35	34
Metal	Blue Bird	10	30	35	33

Table 5.14 Servo Properties

5.8 Navigation Sensors

The GPS has been revolutionary in the effectiveness of UAS's. Prior to the introduction of GPS, the latitude-longitude positioning had to be accomplished primarily by inertial and magnetic means. The UAS state data are estimated through inputs from many sensors. These can include inertial sensors, GPS's, magnetic compasses, and air data sensors. The various sensors can measure similar parameters but with different update rate, drift, resolution, and accuracy [15]. The Carrier Pigeon UAS will have a pre-programmed flight mission and will fly the same mission to Christchurch, New Zealand every time. The GPS sensors that will be used can provide the update rates at a relatively low bound because the flight path will be already pre-programmed and will not need any in flight updates. Since the main challenge of data transfer for location of the South Pole Station is satellite windows utilizing iridium satellite on a low update rate to ensure navigation will need to be investigated more to ensure mission success.

5.9 Launch

The Carrier Pigeon UAS design will be runway independent since the Antarctica South Pole Station does not operate the Jack F. Paulus Skiway aircraft runway during the winter months. The Skiway runway is a 12,000-ft. long runway made specifically for the LC-130's that land during the summer months at the South Pole station. The Carrier Pigeon UAS will be designed to have a trailer mounted air compressed launcher. Through basic calculations a

modified launch speed can be calculated for a 78-lb. aircraft. The launch speed can be developed to determine if two already operational launcher systems could be possible solutions if adapted to fit the Carrier Pigeon weight, environment, and personnel requirements.

Initial assumptions made to determine the launch speed are:

- launcher will provide 60% of the power needed to achieve flight
- 40-knots launch speed specification derived from the ScanEagle maximum speed of 80-knots
- launch distance of 22 ft. for launcher track

$$(v_2)^2 - (v_1)^2 = 2 * a * \Delta x$$

$$a = 31.5 \text{ m/s}^2$$

$$F_{tot} = m * a$$

$$F_{tot} = 1072 \text{ N}$$

$$F_{launcher} = 0.6 * F_{tot}$$

$$F_{launcher} = 643.2 \text{ N}$$

$$F_{launcher} = m * a'$$

$$a' = 18.9 \text{ m/s}^2$$

$$(v'_2)^2 - (v'_1)^2 = 2 * a' * \Delta x$$

$$v'_2 = 15.9 \text{ m/s}$$

The launch speed of the Carrier Pigeon at 78 lb. was determined to be 15.9 m/s. This calculation is a rough estimation but can provide a good specification for comparison to other current launchers. Two potential possible launcher solutions are the Robonic OHTO and the Scan Eagle Mark 4 launcher. Both launchers are a trailer mounted launcher that conquers rugged terrain, high altitudes and extreme temperatures.

The Mark 4 launcher is powered by an onboard diesel generator and air compressor. The Mark 4 launcher is designed for a two-man setup and operation that takes only 10 minutes. The Mark 4 launcher is 22 ft. in length, 7.25 ft. in width, and 8 ft. in height fully deployed, weighs 4,200 lb., and launches the Scan Eagle at 25 m/s [29]. A scaled up version of the Mark 4 launcher could be developed to launch the 78 lb. Carrier Pigeon UAS to begin the flight mission to location of high connectivity. Further analysis of design performance measures would have to be calculated to determine the launch speed for the Carrier Pigeon UAS.

The second launcher in consideration is the Robonic OHTO is a 53 ft. in length, 6.8 ft. in width, and 6.4 ft. in height fully deployed. The launcher weighs 7760 lb. sets up in less than 10 mins, with a launch angle between 8-12°. Although the launcher will have to be engineered to be able to handle temperatures of -60°C due to the South Pole austral winter. Robonic builds pneumatic launchers that are designed specifically for tactical UAS in extreme environments. They can specifically design a flexible launcher that has interface adapters and different ground architectures that will allow reduced personnel and sustainment costs. The Robonic has the ability to design the OHTO to have an exit velocity of up to 55 m/s with a UAS weight of 660 lb.

Wind velocity at the south pole station is derived from chapter 2 wind profiles and seen at an average of 10 m/s. Both the Mark 4 launcher and Robonic launcher will be able to handle a 10 m/s wind. Winds higher than 10 m/s will require the system to suspend launch until favorable conditions.

5.10 Recovery

The Carrier Pigeon UAS recovery system can be deployed and stationary at any location. Preferably the system recovery would be designed after the Scan Eagle SkyHook [48]. The SkyHook eliminates the need for runways and nets with the small-footprint design. The system readily adapts to shifting winds and other recovery environments. The system uses real time kinematic GPS for consistently accurate approach and capture. Since the location of recovery will

have adequate GPS this is a feasible option. This system is easily setup and stowed in less than 20 minutes with two operators. The Carrier Pigeon SkyHook recovery system could be setup at any of the candidate route locations airports. For example, Christchurch New Zealand International airport is situated only 8 miles northwest of the city center and would be easily accessed to the USAP personnel to recover the incoming aircraft upon capture.

Chapter 6

COMMAND, CONTROL, AND HOW TO SUPPORT

Unmanned aircraft sizing is dependent upon system-level trades that involve ground elements. The ground infrastructure also depends on the aircraft size, onboard systems, and mission capabilities. The aircraft is but one element of which the unmanned aircraft system is comprised of. System architectural decisions and component selection can have varying degrees of impact on the aircraft, ground elements, and operational utility [15].

6.1 Systems Architecture

A fundamental output of system concept definition is the system architecture. System architecture is the composition and organization of system elements and communications networks. The systems architecture entails the allocation of tasks among hardware and software in various system locations. System architecture questions include [15]:

What type of ground station are required?

- Carrier Pigeon ground control station (GCS) will be equipped for one personnel computer station. GCS will be modular in a shipping container with adequate insulation and heat to accommodate stage I mission.

Will the control stations be integrated with other systems?

- GCS will be integrated into South Pole Station operations and USAP facility in Christchurch. Mission hand off of aircraft will occur from South Pole Station to Christchurch executed in McMurdo Sector in accordance with USAP Interagency Air Operations Manual [21]

What support equipment is necessary, and how does this fit within the logistics and footprint requirements?

- Consumables, repair parts, and fuel will be necessary to meet mission requirements. Supply of equipment will be resupply with aircraft shipment operations.

6.2 UAS Supply Routes and Timeline

There are two ways to get the Carrier Pigeon aircraft to the South Pole Station. First, the UAS could be shipped to McMurdo Station and taken on the South Pole Traverse. The South Pole Traverse is a 995-mile long compacted snow road that links the two locations together. It was constructed by leveling snow and filling in crevasses. Caterpillar and Case Corp. tractors pull specialized sleds to deliver fuel and cargo in a 40 day one way trip. Below in Figure 6.1 shows the South Pole Traverse route and in Figure 6.2 shows cargo and fuel bladders on giant slides.

Figure 6.1 South Pole Traverse

Figure 6.2 Fuel Bladders and Cargo along Traverse [42]

The second way to supply the Carrier Pigeon UAS to the South Pole station is on an airlift from the 109th Airlift wings LC-130's. Below is the airlift contract support timeline for flight operations for 2017. The support contract below illustrates a representative process that the Carrier Pigeon UAS would have undergone to make the journey to the South Pole Station. Coordinated submission to move eighteen aircraft would have to occur no earlier than July 12th and no later than November 8th - the earlier the better. Multiple flights with the system piecemealed due to resupply priority would most likely occur in order for all twelve aircraft to be delivered. The Carrier Pigeon UAS would most likely be categorized as "Mission Essential" resupply and would fall behind three other resupply priority categories seen in Figure 6.2. The supply of the Carrier Pigeon UAS to South Pole via airlift is extremely high due to the amount of flights and supply priority. Although, unknown bad weather could hinder airlift operations, this could be mitigated with careful planning and coordination by the systems client with support contract personnel.

Continental Area Acquisition Schedule Version 6			Antarctic Support Contract Continental Area Acquisition Schedule for FY18				TL-FRM-0049 February 2017
	Maximo Purchase Request Submitted By Date	Required Delivery Date To PT Hueneme	McMurdo--Julian Required On Site Date (ROS)	McMurdo-- Required On Site Date (ROS)	South Pole-- Julian Required On Site (ROS) Date	South Pole-- Required On Site (ROS) Date	NOTES
Start of MCM Heavy Airlift	12-Jul-17	23-Aug-17	7280	7-Oct-17	N/A	N/A	1-9
	19-Jul-17	30-Aug-17	7287	14-Oct-17	N/A	N/A	1-9
	26-Jul-17	6-Sep-17	7294	21-Oct-17	N/A	N/A	1-9
South Pole opens	02-Aug-17	13-Sep-17	7301	28-Oct-17	7301	28-Oct-17	1-4, 6-9
	09-Aug-17	20-Sep-17	7308	4-Nov-17	7308	4-Nov-17	1-4, 6-9
	16-Aug-17	27-Sep-17	7315	11-Nov-17	7315	11-Nov-17	1-4, 6-9
	23-Aug-17	4-Oct-17	7322	18-Nov-17	7322	18-Nov-17	1-4, 6-9
	30-Aug-17	11-Oct-17	7329	25-Nov-17	7329	25-Nov-17	1-4, 6-9
	06-Sep-17	18-Oct-17	7336	2-Dec-17	7336	2-Dec-17	1-4, 6-9
Heavy Airlift Gap Period During this period all cargo will be vetted and prioritized for movement between Christchurch and McMurdo.	13-Sep-17	25-Oct-17	7343	9-Dec-17	7343	9-Dec-17	1-4, 6-9
	20-Sep-17	1-Nov-17	7350	16-Dec-17	7350	16-Dec-17	1-4, 6-9
	27-Sep-17	8-Nov-17	7357	23-Dec-17	7357	23-Dec-17	1-4, 6-9
	04-Oct-17	15-Nov-17	7364	30-Dec-17	7364	30-Dec-17	1-4, 6-9
	11-Oct-17	22-Nov-17	8006	6-Jan-18	8006	6-Jan-18	1-4, 6-9
	18-Oct-17	29-Nov-17	8013	13-Jan-18	8013	13-Jan-18	1-4, 6-9
	25-Oct-17	6-Dec-17	8020	20-Jan-18	8020	20-Jan-18	1-4, 6-9
	01-Nov-17	13-Dec-17	8027	27-Jan-18	8027	27-Jan-18	1-4, 6-9
	08-Nov-17	20-Dec-17	8034	3-Feb-18	8034	3-Feb-18	1-4, 6-9
	15-Nov-17	27-Dec-17	8041	10-Feb-18	8041	10-Feb-18	1-4, 6-9
Start of South Pole winter	22-Nov-17	3-Jan-18	8048	17-Feb-18	8048	17-Feb-18	1-4, 6-9
Final Summer airlift to McMurdo	29-Nov-17	10-Jan-18	8055	24-Feb-18	N/A	N/A	1-9
REQUIRED ON SITE BY PRIORITY							
Resupply Vessel	19-Oct-17	30-Nov-17	8121	27-Jan-18	Priority 1		1, 10, 14, 15, 16
Life/Health/Safety Critical	19-Oct-17	30-Nov-17	8121	27-Jan-18	Priority 1		1, 10, 14, 15, 16
MCM Food Requests	19-Oct-17	30-Nov-17	8121	27-Jan-18	Priority 2		1, 11, 14, 15, 16
Mission Critical	19-Oct-17	30-Nov-17	8122	27-Jan-18	Priority 3		1, 12, 14, 15, 16
Mission Essential	19-Oct-17	30-Nov-17	8123	27-Jan-18	Priority 4		1, 13, 14, 15, 16
Mission Important	19-Oct-17	30-Nov-17	8124	27-Jan-18	Priority 4		1, 13, 14, 15, 16
MCM VSL Project Requests	Project Dependent	30-Nov-17	8124	27-Jan-18	Priority 4		1, 13, 14, 15, 16
South Pole Post-Vessel COMAIR/SUR RDDs At Port Hueneme:			COMAIR	30-Jan-17	COMSUR	11-Jan-18	16
McMurdo Post-Vessel COMAIR/SUR RDDs At Port Hueneme:			COMAIR	5-Feb-17	COMSUR	18-Jan-18	16

Figure 6.3 Support Contract for Airlift [43]

6.3 Transportability

In heavy airlift operations, the LC-130 Hercules is the primary means of supply for both equipment and supplies to the South Pole Station. The designed gross weight is 155,000 pounds for the LC-130. The LC-130 heavy airlift supply option is critical to the design requirements in order to be able to ship multiple Carrier Pigeon Systems to the South Pole during one flight in the summer months. Cargo on an LC-130 are secured to 463L pallets inside the fuselage of the aircraft. The usable dimension of 463L pallet is 108 by 88 inches with tie downs as seen below in Figure 6.4. The max capacity of 463L 7,500 lb. per pallet. Empty each pallet weighs 290 lb. or 355 lb. with two side nets and a top net [43]. They make around about a 100 or so flights during the summer to the South Pole Station to stock up on fuel, supplies, and personnel for the winter over. In order to get eighteen Carrier Pigeon aircraft down to the South Pole Station for winter season on an LC-130 would only have to take one and half flights to stack two UAS per pallet on an LC-130 capable of fitting six pallets. Likelihood of this operational supply load is low due to

contract support, but considering this option makes the business case for system feasibility stronger.

Figure 6.4 LC-130 Cargo Diagram

6.4 Personnel Allocation

Since the establishment of the South Pole Station in 1957 there have only been 1551 people that have wintered over. In 2018, there are only 40 winter-over personnel at the South Pole Station. 7 women and 33 men. This happens to be the smallest crowd since 1998. The largest crowd ever to winter over was in 2005 with a total of 86 people [45]. Since there are so few people at the South Pole station most personnel complete multiple duties and tasks to help the mission continue at the South Pole. For example, the South Pole cook is also a certified EMT. Previous support contractors that provided personnel at the South Pole Station were Raytheon Polar Services Company (2000-2012) and Antarctic Support Associates (1990-2000). Now the support contract is fulfilled by Leidos Holdings who took over in 2016 from Lockheed Martin (2012-2016). The personnel that will conduct maintenance, transport, and launch of the Carrier

Pigeon UAS will most likely be contract personnel from the Leidos Holdings. Since these personnel resources are limited and require them to have multiple tasks, minimal personnel requirement need employ the Carrier Pigeon UAS for its mission is essential to the feasible for operational requirements during the winter at the South Pole Station. Assuming the largest empty weight fraction from the initial aircraft sizing based on the derived outputs, the UAS would have a weight of 78 lb. To safely lift a 78-lb. aircraft would require two personnel. This follows the guidelines established in OSHO requirements that personnel should not lift more than 55 lb. The Mark 4 launch would only require the same two personnel to employ the launch of the Carrier Pigeon UAS. Two personnel out of the 40 personnel on ground during winter-over is a feasible workload. Personnel would not solely operators and maintainers of the Carrier Pigeon but will be trained and certified on the system.

6.5 Maintainability

Critical to maintaining the Carrier Pigeon aircraft will also be to consider the environment and the personnel operating in that environment with the type of equipment they will need on in order to conduct routine preventative maintenance on the aircraft, pre-flight checks, fuel aircraft, and deploy launcher and mount aircraft to launcher. The USAP has a set of rules and guidelines that personnel must follow for worn equipment to ensure personnel readiness and safety. A key consideration in the Carrier Pigeon system architecture is evaluating the contractor personnel potential of fulfilling required duties to safely and accurately employ the UAS on mission. The minimum required clothing gear to be worn on flights and deep-field deployment past McMurdo station are found in USAP Extreme Cold Weather Clothing (ECW) [46]. The USAP clearly states in there USAP clothing issue and handbook that a clothing system is required that consists of long underwear, mid layers, insulation layer, cold weather gloves, and shell layer. Research into the ECW led to determination that aircraft maintenance, pre-flight procedures, and

aircraft deployment would not be hindered caused from the excess of proper personnel equipment during systems operation outside of the required proposed Carrier Pigeon facility.

6.6 Facilities

the Carrier Pigeon UAS will require the use of a facility at the South Pole Station. The required facility will need three 8' X 40' shipping container with internal heating against the extreme colder weather for equipment storage. The container will be able to house the twelve aircraft that will be shipped to the South Pole Station via the South Pole Traverse or on LC-130's. This container will also be used for system maintenance. Alongside the container a modular retractable enclosed shelter will need to be constructed to house the Mark 4 launcher. Both the shipping containers and the Mark 4 launcher must be position in an area where UAS employment is authorized. An area designated on the South Pole Station map as the operation zone to the north end of the NGV aircraft parking zone will be suitable for container and launch site and a proposed container layout design are displayed in Figure 6.5.

Figure 6.5 Proposed South Pole Station UAS Facility Site and Layout

Chapter 7

CONCLUSION

The feasibility of a Carrier Pigeon UAS that transfers physical data storage to a location of high connectivity from the South Pole Station was undertaken. The result of this research is that a sound systems solution for this specific mission is feasible and a detailed conceptual design phase should be carried out with follow on work.

This research feasibility study led to a sound business case that a physical aircraft can be developed not only in performance, but overall system requirement success, to support data transfer. It has been determined that an aircraft with a range of 3,000 nautical miles with empty weight fraction of .55, a propeller efficiency of .8, and brake specific fuel consumption of $.56 \frac{lb}{hr} / hp$ can be designed to meet the mission range, endurance, and profile. Furthermore, systems assessment identified Christchurch, New Zealand to serve as the primary location of high connectivity capable of supporting upload transfer of the required 20 TB of data per mission because of the confidence in scientific and recoverability infrastructure at the location. The analysis of the weather is favorable at the South Pole station for this systems deployment. The 10 m/s average wind speed at the South Pole confirms that a launcher system meets a 60% launch speed requirement of 15.9 m/s launch speed. Although, the extreme environment experienced during the South Pole Station winter would be a daunting task, but feasible for the deployment of the system if proper procedure - in personnel allocation, maintainability, and facility management were followed.

The feasibility requirement of a 3-lb. payload capacity for the design of the Carrier Pigeon UAS is confirmed from assessment of scientific data transfer demand of hardware equipment at the South Pole, weight estimation for aircraft performance, and current technology for data storage density.

The brake specific fuel consumption was obtained from calculations and investigation through trade studies of representative UAS engines of similar size. The overwhelming evidence from calculations and studies determined a modified or bespoke built engine can be designed to meet fuel consumption requirements. Furthermore, the research into the cost comparison of UAS programs of similar size is several of orders of magnitude lower than that of the \$700 million incurred cost of launching another low earth orbit satellite for the USAP to meet supplemental data transfer goals in the foreseeable future.

In conclusion, the transportability and modularity of the proposed system via either airlift or traverse hauled is feasible for the contract support of the USAP. The supply of twelve Carrier Pigeon UAS to the South Pole Station every austral winter for an aircraft to launch every 10-day window to supplement scientific data transfer is confirmed feasible. The 10-day operations rhythm would not over burden the operational reach of the winter over personnel at the South Pole Station. Therefore, this research is considered complete, but follow on detailed conceptual design will need to be initiated to undergo the arduous detailed design process for the Carrier Pigeon UAS to actually be developed.

BIBLIOGRAPHY

- [1] D. Raymer. *Aircraft Design: A Conceptual Approach*. American Institute of Aeronautics and Astronautics, 1992.
- [3] Cool Antarctica, Antarctica History. “A Timeline of the Exploration of Antarctic,” <https://www.coolantarctica.com> (accessed July 16, 2018).
- [4] Brandt, Richard., Hudson, Stephen. *A Look at the Surface-Based Temperature Inversion on the Antarctic Plateau*. Department of Atmospheric Sciences, University of Washington, Seattle. Washington, 2005.
- [5] Museum of Applied Arts & Sciences. *Radiosonde RS80 Atmospheric Measuring Instrument*. <https://collection.maas.museum/object/127457> (accessed August 5, 2018).
- [6] IceCube South Pole Neutrino Observatory. “IceCube Explained”. <https://icecube.wisc.edu/about/overview> (accessed June 5, 2017).
- [7] United States Antarctic Program. “South Pole Satellite FAQ’s”. <https://www.usap.gov/technology/contentHandler.cfm?id=1982> (accessed June 5, 2017).
- [8] Statista. *Average internet connection speed in the US from 2007 to 2017*. <https://www.statista.com/statistics/616210/average-internet-connection-speed-in-the-us/>. (accessed October 3, 2018).
- [9] NASA-NSF Astronomy/Astrophysics Advisory Committee Report. *Data Communications Supporting Astronomy/Astrophysics at South Pole Station*. May 11, 2006.

- [10] Powell, Nick. *Keeping Connected: New Ground Station at South Pole to Help Maintain Communications*, Antarctic Sun, April 10, 2009.
<https://antarcticsun.usap.gov/features/contenthandler.cfm?id=1741>. (accessed June 2017).
- [11] Christchurch City Council. *Christchurch could become world-leading Antarctic research hub.*, May 31, 2016. <https://cccgovt.nz.cwp.govt.nz/news-and-events/news-search/show/647>. (accessed May 2017).
- [12] University of Canterbury: Gateway Antarctica. “Research”.
<https://www.canterbury.ac.nz/science/schools-and-departments/antarctica/gateway-research/>. (accessed September 6, 2018).
- [13] National Science Foundation. *United States Antarctica Program Science Workshop*. Aerospace Report No. TOR-2012(2228)-1, February 27th, 2012.
- [14] Carichner, Grant E., Nicolai Leland M. *Fundamentals of Aircraft and Airship Design: Volume I – Aircraft Design*, 2010. Chapter 14.
- [15] Gundlach, Jay. *Designing Unmanned Aircraft Systems: A Comprehensive Approach – Second Edition*, 2014. Chapters 4, 12, 19.
- [16] Drone Industry Insight. *Drone Energy Sources: Pushing the Boundaries of Electric Flight*, June 6, 2017. <https://www.droneii.com/drone-energy-sources>. (accessed September 10, 2018).
- [17] Roskam, Jan. *Airplane Design: Part I: Preliminary Sizing of Airplane*, 1997. Chapter 1.

- [18] FlightGlobal. *UAV Breaks Record with Transatlantic Crossing*.
<https://www.flightglobal.com/news/articles/uav-breaks-record-with-transatlantic-crossing-41541/>. (accessed August 3, 2018).
- [19] Keane, Andrew, Andras Sobester, and James Scanlan. *Small Unmanned Fixed-Wing Aircraft Design: A Practical Approach*. 2017.
- [20] Boeing. Insitu Scan Eagle Product Card. <https://www.insitu.com/information-delivery/unmanned-systems/scaneagle#4>. (accessed June 7, 2018).
- [21] National Science Foundation. Antarctic Infrastructure and Logistics: Division of Polar Programs. *US Antarctic Program Interagency Air Operations Manual*, September 16, 2016.
- [22] Australian Government. *Australian Antarctic Data Center: National Claims to Antarctic Territory*. <http://www.antarctica.gov.au/law-and-treaty/history/antarctic-territorial-claims>. (accessed April 20, 2018).
- [23] Goetzendorf-Grobowki, Tomasz, Rodzewicz, Mirosław. *Design of UAV for photogrammetric mission in Antarctic Area*. Warsaw University of Technology, September 2015.

- [24] Cassano, John. "Observations of the atmosphere and surface state over Terra Nova Bay, Antarctica, using unmanned aerial systems," *Earth System Science Data*.
<https://www.earth-syst-sci-data.net/8/115/2016/essd-8-115-2016.pdf>. (accessed August 15, 2018).
- [25] UAS Vision. *3W-Powered UAV for Flights in Antarctica*.
<https://www.uasvision.com/2016/07/11/3w-powered-uav-for-dlights-in-antarctica/>.
(accessed September 15, 2018).
- [26] Lycoming, Lycoming EL-005 engine product card.
<https://www.lycoming.com/engines/el-005>. (accessed August 20, 2018).
- [27] Zanzottera Technologies, Zanzottera 498H engine product card.
<http://www.zanzotteraengines.com/en/engines/498-hs.html>. (accessed August 28, 2018).
- [28] 3W International Multi-Fuel and Gas Engines, Wankel Rotary UAS Engine 3W-180 SRE Hybrid product card. <http://3w-international.com/wankel-rotary-uav-engine-3w-180-sre-hybrid/>. (accessed August 20, 2018).
- [29] Insitu, Insitu Mark 4 launcher product card.
https://www.insitu.com/images/uploads/pdfs/Launcher_Mark4_SE_ProductCard_PR041615.pdf. (accessed June 7, 2018).
- [30] A. Drake. AERO 433 Course Material.

- [31] Salazar, Juan and others, “Reimagining Antarctic Gateway Cities,” *Circles of Sustainability*. <http://www.circlesofsustainability.org/projects/antarctic-cities/>. (accessed April 4, 2018)
- [32] United States Antarctic Program. “Systems Architecture Description”.
https://www.usap.gov/technology/documents/Systems_Architecture_Description.pdf.
(accessed June 4, 2017).
- [33] United States Antarctic Program. “South Pole Satellite Schedule”.
<https://www.usap.gov/technology/documents/SPSAT%2020181201.pdf>. (accessed June 4, 2017).
- [34] Leone, Dan, “NASA Picks Up \$289M Option for TDRS-M,” *Space News* (2011).
<https://spacenews.com/nasa-picks-289m-option-tdrs-m/>. (accessed October 10, 2018).
- [35] Van Lipzig, N. P. M., J. Turner, S. R. Colwell, and M. R. Van Den Broeke, “Short Communication: The Near-Surface Wind Field Over the Antarctic Continent,”
International Journal of Climatology (2004).
- [36] United States Antarctic Program. “Satellites Elevation Angle Graphic”.
<https://www.usap.gov/technology/contentHandler.cfm?id=1982>. (accessed June 4, 2017).
- [37] Parish, Thomas R., Waight, Kenneth T. *The Forcing of Antarctic Katabatic Winds*.
Department of Atmospheric Science, University of Wyoming, Laramie WY, 1986.

- [38] British Antarctic Survey. *Discovering Antarctica*.
<https://discoveringantarctica.org.uk/oceans-atmosphere-landscape/atmosphere-weather-and-climate/regional-climate-variation-and-weather/>. (accessed August 15, 2018).
- [39] British Antarctic Survey. *Natural Environment Research Council*. “Aircraft Capability”.
<https://www.bas.ac.uk/polar-operations/sites-and-facilities/aircraft/>. (accessed June 6, 2017).
- [40] Australian Antarctic Division. Australian Government. *Pioneering Aircraft Use*.
<http://www.antarctica.gov.au/about-antarctica/history/transportation/aviation>. (accessed July 21, 2018).
- [41] United States Antarctic Program. “The Antarctic Treaty”.
<https://www.usap.gov/theAntarcticTreaty/index.cfm?m=2>. (accessed April 20, 2018).
- [42] Donenfeld, Jeffrey, “The South Pole Traverse Arrives,” Jeffrey Donenfeld Blog, January 16, 2013, <https://www.jeffreydonenfeld.com/blog/2013/01/the-south-pole-traverse-arrives/> (accessed July 2, 2018).
- [43] United States Antarctic Program. “Antarctic Support Contract”.
https://www.usap.gov/logistics/documents/TL-FRM-0049_FY18.pdf. (accessed September 12, 2017).
- [44] United States Army. Field Manual 55-17 Chapter 18 “463L Pallets and Shoring,”
<https://www.globalsecurity.org/military/library/policy/army/fm/55-17/ch18.htm>.
(accessed April 15, 2018).

- [45] South Pole Station. *Winter-Over Statistics*.
<http://www.southpolestation.com/trivia/wo.html>. (accessed August 20, 2018).
- [46] The National Science Foundation. Office of Polar Programs. *USAP Extreme Cold Weather Clothing Policy*, February 2017.
https://www.nsf.gov/geo/opp/documents/policy/AIL-POL_1000.06%20ECW%20Gear.pdf. (accessed October 13, 2018).
- [47] Robonic. Robonic OHTO pneumatic launcher product card. https://www.robonic.fi/wp-content/uploads/2018/09/Robonic-OHTO_brochure_A4_9-2018.pdf. (accessed June 7, 2018).
- [48] Insitu, Insitu SkyHook product card.
https://www.insitu.com/images/uploads/pdfs/Skyhook_Universal_ProductCard_PR041615.pdf. (accessed June 7, 2018).
- [49] Antarctic Connection. *Antarctic Weather*.
<http://antarcticconnection.com/information/antarctic-weather/?type=weather-index>.
(accessed September 22, 2018).
- [50] The Antarctic Mesoscale Prediction System. <http://www2.mmm.ucar.edu/rt/amps/>.
(accessed October 9, 2018).

Appendix A

MATLAB CODE

```

close all
clc

%% Breguet Range Equation Inputs

L_D = 12; %Lift to Drag ratio
N_p = .80; %Propeller Efficiency
BSFC = .55; %Brake Specific Fuel Consumption (lb./hp./hr.)
BSFC_s = BSFC/3600; %BSFC converted from lb./hr. to seconds
W_pay = 3; %Payload Weight (lb.)

We = 75;
Wfin = 43;
Wi = We+W_pay; %Weight Initial
Wf = Wfin+W_pay; %Weight Final
Wfuel = Wi-Wf; %Fuel Weight
V = 50; %True Airspeed kts

%% Breguet Range Equation Outputs

R_prop = ((550*N_p)/BSFC_s)*(L_D)*log(Wi/Wf); %Range for Propeller (550 converts hp. to
feet, lbs, secs

Nautical_Miles = R_prop/6076; %Nautical Miles

Mf = 1-exp(-Nautical_Miles*BSFC_s/(L_D*N_p)); %Mass Fuel Fraction

E = (L_D*N_p/V*BSFC)*log(1/(1-Mf)); %Endurance Equation

E_Hours = 3600/E; %Endurance in Hours

Wef = Wf/Wi; %Empty Weight Fraction

close all
clc

%% S_Ref Calculation

C_L= .7;
rho = .001267; %slugs/ft^3 @ 20,000 ft.
V = 84.39; %Velocity ft./s^2
W = 75; %lb. Weight of Aircraft

S_ref = W/(.5*(rho)*(V^2)*C_L);

S_ref_ft = 1/S_ref;

C_tip = 2.2;
C_root = 3.9;
B_span = 7.8;

Planform = .5*(C_tip+C_root)*B_span;

```

Appendix B
CANDIDATE ROUTE PROFILES

Cross Section through A to B

Cross Section through A to B