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High Altitude Airship Station-Keeping Analysis

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HIGH ALTITUDE AIRSHIP STATION-KEEPING ANALYSIS

THESIS

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AFIT/GAE/ENY/06-J07

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THESIS

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Douglas P. Kondrack

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Abstract

Lighter-than-air vehicles were once widely utilized by most major militaries. The airship's extended range and flight endurance made them the optimal vehicle for surveillance and reconnaissance. These flight characteristics have created new interest in using lighter-than-air vehicles as high altitude surveillance and communications platforms. Future Department of Defense plans include high altitude airships that will operate at near space altitudes and take advantage of the low wind region in the upper atmosphere located at approximately 24 km. A high altitude airship could provide 24-hour coverage of a target area if operated in this low wind region. This study investigated the station-keeping abilities of two such high altitude airships: a large/fast design (AS #1) and a smaller/slower design (AS #2). The two baseline airship designs were subjected to the same simulated yearlong station-keeping mission using realistic upper atmospheric wind data over the designated target of Baghdad. Actual wind data was generated by the Navy's Fleet Numerical METOC Detachment and used to model the movements of both baseline airships. Their station-keeping capacity was determined by the duration of time each vehicle spent inside the targets coverage radius (552 km). The AS #1 design remained inside the operational radius for 87.67% of the year and the AS #2 design was only operational for 39.45% of the year. Neither airship maintained its station for the entire yearlong mission. This study concluded that advancements are required in propulsion or power production to decrease the size of the airship designs and increase the vehicles maximum velocity in order to counter the upper atmospheric winds.

HIGH ALTITUDE AIRSHIP STATION-KEEPING ANALYSIS

1 Introduction

1.1 Motivation

Throughout the history of warfare, advancements in technology have evolved the methods by which wars are fought; yet the fundamental strategies implemented by successful military leaders have remained constant. One of these strategies that is as relevant today as it was many years ago is that victory favors the force that dominates the high ground. An elevated position, whether it is a hill on a battlefield or total air superiority over a target, grants the controlling force greater visibility and space awareness of the battle. Modern militaries have progressed from high altitude aircraft, such as the SR-71, to geostationary orbiting satellites in order to obtain the observational advantages of controlling an elevated position.

Though satellites have remained the current standard in elevated surveillance and communication relays, the cost of implementing these low earth-orbiting vehicles is staggering [1]. Furthermore, orbital mechanics restricts a single satellite from maintaining continuous coverage over a specified ground target resulting in hours of non-operation. A multiple satellite constellation can be deployed to increase the target coverage time, however the developmental and implementation costs of operating multiple satellites are increased proportionally to the required number of vehicles [2]. These drawbacks have inspired engineers to develop more cost effective surveillance vehicles that can provide instantaneous and continuous coverage over any target on the planet. Unmanned autonomous vehicles, such as the Global Hawk and Predator, have been used successfully in supplementing the surveillance gap left by LEO satellites, but these aircraft are limited by their on station endurance and service ceiling.

In regards to the shortcomings of current surveillance platforms, military strategists have desired a single vehicle that can provide continuous coverage over any specified target. A recent concept proposed to fulfill this requirement is to combine lighter-than-air vehicle and UAV technologies to create a high altitude airship capable of reaching near space altitudes, and provide continuous on-station coverage [3]. Lighter-than-air vehicles have been proven successful in long flight endurance missions and recent innovations in technology and materials have made it possible for such vehicles to obtain near space altitudes. Though the technology exists to deploy a high altitude surveillance airship, varying strong upper atmospheric winds may overwhelm the crafts propulsion system and displace the vehicle from its station. These winds produce extreme drag forces on the airship due to the large surface area of the vehicle's lifting gas envelope, and it may not be possible for the airship to generate enough thrust to counter these forces. Therefore, an analysis of the station-keeping capacity of candidate high altitude airship designs must be conducted to determine if this concept is currently feasible in actual atmospheric conditions.

1.2 Background

Today, the most common role for lighter-than-air vehicles is as an advertisement platform. But the endurance capabilities of the airship have renewed the Department of Defense's interest in contracting the development of a high altitude airship. The Lockheed Martin Corporation is in the process of developing the MDA High Altitude

Airship prototype to demonstrate the feasibility of loitering a surveillance or communications platform at near space altitudes [5]. The HAA is projected to reach an altitude of 65,000 ft, maintain its station for one month, and counter winds of 35 knots [6]. These performance parameters are required by the Department of Defense but the exact speed and service ceiling of the HAA has varied through the development process. If successful, this radical concept could revolutionize military reconnaissance and surveillance capabilities. However, since the performance parameter values of the HAA have changed many times it is necessary to investigate the adequacy of the defined top speed and service ceiling of a high altitude airship.

1.3 Research Objectives/Questions

A number of studies have been conducted on the cost and general performance benefits of using high altitude airships as continuous on-station vehicles. Studies estimate that these lighter-than-air vehicles are substantially cheaper to operate than satellites and provide much greater endurance than current UAVs [1]. However, it has not been demonstrated that these extremely large vehicles have the ability to resist strong upper atmospheric winds. The objective for this research analysis is to verify that a predetermined baseline airship design is capable of continuous on-station operation over a specified target with respect to actual bi-daily upper-atmospheric wind conditions. The detailed research questions for the analysis are summarized in Table 1. The first two questions stated in the table are preliminary objectives that need to be addressed before the station-keeping analysis can begin. The vehicle designs used in the analysis will be calculated using an existing tool developed by Captain R. Moomey [1]. The baseline airships will then be scaled against past and present designs to compare the vehicles length and lifting gas volume.

Table 1: Research Questions

Preliminary Question	What size airship is required to lift a sensor payload and propulsion system to near space altitudes?
Preliminary Question	How do the baseline airship designs used in the analysis compare to past and present airships?
1	What is the station-keeping capacity of a high altitude airship over the course of a yearlong mission?
2	What maximum velocity must a high altitude airship generate in order to counter upper atmospheric winds at a specified target?
3	Is it advantageous to design a high altitude airship for one particular operational altitude?
4	Is the high altitude airship loitering mission a viable concept in terms of airship size and station-keeping ability?

1.4 Methodology Overview

The research will be performed as follows. The station-keeping performance of high altitude airships will be determined using two baseline airship designs developed for a maximum altitude of 24 km and maximum velocities of 11 m/s and 19.7 m/s. The size of the baseline airship is computed with respect to its operational altitude and the size of its propulsion system. Therefore the 11 m/s airship will be considerably smaller compared to the 19.7 m/s design. These two baseline airships will be subjected to a yearlong station-keeping mission over a specific target with identical mission parameters. Wind data at the operational altitude will be used to model the two vehicle’s movements over the course of the yearlong mission. The resulting location of the vehicle at 0000 hours and 1200 hours on each day of the mission will be calculated and used to determine both of the airship's total distance from the target at each time step. This distance will be compared to an operational radius centered at the target location to establish if the target is within the airships' coverage capacity.

1.5 Assumptions/Limitations

The analysis outlined above will be limited by the wind predicting system used to model the movements of the two baseline designs. Due to the extreme operational altitude of 24 kilometers, few data sources are available that can capture wind conditions at this location in the upper atmosphere. Therefore, the best and only program capable of generating the required wind data has only the capacity of calculating wind speed and direction at two times during a given day (0000 hours and 1200 hours). With such limited data available, it is assumed that the wind velocity will remain constant over the course of this twelve-hour period. It is also assumed that both baseline airships will maintain the 24 km operational altitude for the entire yearlong mission. The airships will not have the ability to alter their altitude in order to find regions of lower wind velocity. The yearlong mission will be divided by season into four investigations: winter, spring, summer, and fall. The airship in question will begin each season at the operational height and directly over the specified target. During the yearlong mission the airship will alter its bearing in response to the varying wind direction. It is assumed that the turning time of the vehicle is significantly smaller than the twelve-hour constant wind time step; therefore the turning time is not accounted for in the analysis and the change in the airships bearing will occur instantaneously.

1.6 Implications

If the baseline airship designs prove to be capable of continuous station keeping over the specified target, the results will validate the proposed high altitude airship conceptual designs. High altitude airships could be implemented as continuous communications and surveillance platforms providing unparalleled endurance and on-station operation. The analysis will also compare the sizes of the two baseline airships and determine if the scale of the designs are obtainable from an engineering perspective. If the size of the airship is unrealistic, or if the vehicle proves to be unsuccessful in countering the upper atmospheric winds, the analysis could show that current high altitude airship designs are impractical for a loitering mission.

1.7 Thesis Overview

The following chapters provide detailed airship background and descriptions of the station-keeping analysis. Chapter two covers basic lighter-than-air vehicle terminology, the evolution and demise of airship operations in the United States military, and relevant upper atmospheric climatological background. Chapter three discusses the procedure used in determining the station-keeping capacity of the two baseline airship designs. Specifically, this section includes: the yearlong mission description, details of the baseline airship designs, mission operational radius and displacement calculations, airship size comparisons, and an overview of the weather models that were utilized. Chapter four presents the data obtained from the station-keeping analysis, and Chapter five interprets this data in order to answer the before stated research questions.

2 Literature Review

2.1 Chapter Overview

Lighter-than-air vehicles played a prominent role in military aviation at the beginning of the 20th century. With fixed-wing aviation in its infancy, rigid and non-rigid airships were the best performing aircraft of the time. Airships were utilized in military and civilian operations because of their unparalleled performance: large lift capacity, extended range, and exceptional flight endurance. This chapter examines the buildup and demise of United States military airship operations, and discusses the possible future of lighter-than-air vehicles in a high altitude communication and surveillance role. These future high altitude airships must be able to station keep over a given target for long periods of time by countering upper atmospheric winds that can reach speeds of up to 100 miles per hour. Fortunately there exists a region in the stratosphere where wind speeds are reasonably low, and this optimal operation altitude for airships will be presented in the following discussion.

2.2 Historic US airship applications

The United States use of lighter-than-air vehicles was most intensive after World War I and during the course of World War II [7]. Military strategists became interested in the airship's unique performance capabilities such as the ability to lift relatively large loads, substantially longer flight endurance, and greater combat range compared to the fixed-wing aircraft of the time. Other advantages associated with the operation of lighter-than-air vehicles were their ability to vertically take off and land without the need of large airstrips. This allowed the airships to operate out of any site clear of large obstructions such as trees or tall buildings.

Beyond the airships performance benefits, military commanders and government officials were drawn to these enormous flying machines. The sheer size of the airship combined with its quiet and elegant movements captivated observers. Soon, these large vehicles became a symbol of national pride and technological superiority. The most well known example of this was Germany's development of the 804 foot Hindenburg in 1936 (Figure 1) [4]. Though the giant Hindenburg tragically exploded on May 6th, 1937, it was extremely successful in its worldwide propaganda tour until the fateful accident.

Figure 1: Hindenburg Accident at Lakehurst, New Jersey [4]

With the many advantages of implementing lighter-than-air vehicles came just as many disadvantages. The large size of the airship made it very susceptible to enemy detection and extremely vulnerable to attack. Once an airship was engaged the likelihood of the vehicle surviving was very small due to the highly combustible hydrogen that filled the gas envelope. Airships that used helium as an alternative to hydrogen decreased the danger of combustion, but in-turn increased the size of the airship due to the fact that helium was a less efficient lifting gas. By WWII the airship's vulnerabilities became more apparent when compared to newer fixed-wing aircraft. Its limited maneuverability and slower speed stood out more starkly. Other drawbacks to airship operations were the dangers associated with launching and landing lighter-than-air vehicles, and the necessity of large hanger facilities to store them in. The large surface area of the gas envelope, combined with small winds, created enormous drag forces on the airship that made ground handling hazardous and nearly suicidal during very windy days. Once the airship was safely on the ground, large hangers were needed to protect the gas envelope fabric from damage and degradation by the elements. These disadvantages drove up the cost of operating airships, but their unique performance capabilities made them valuable in certain military applications [7].

2.2.1 Three Principle Airship Designs

It is important to understand the three basic designs of an airship. Lighter-than-air vehicles are classified by three fundamental design concepts: rigid, semi-rigid, and non-rigid. The particular design of the airship can limit the vehicles performance, structural integrity, or mission capacity.

2.2.1.1 Rigid Airships

Rigid airships, or dirigibles, have an internal metal frame that provides structural support for the aircraft's gas envelope (Figure 2). The increased strength of the internal frame gives the airship the ability to dramatically increase its size, in turn allowing for a larger gas envelope, larger lift capability, and an increased service ceiling [4].

Consequently, the larger the airship and metal frame, the more lift must be generated to sustain the desired flight conditions due the mass of the metal structure. This leads to an iterative design problem balancing the airship's size and mass with the desired flight performance. The largest airships ever built had rigid designs and they include the German Zeppelins and their American counterparts: ZRS4 USS Akron and ZRS5 USS Macon.

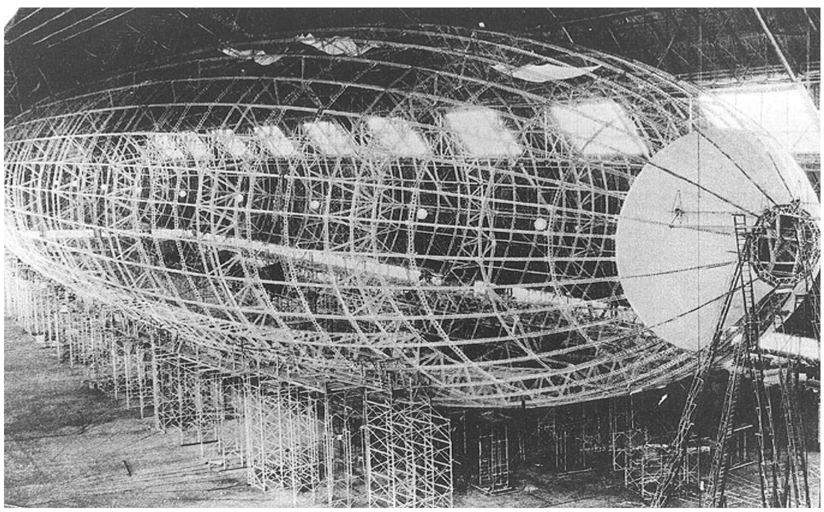

Figure 2: Internal Metal Frame of Rigid Airship [7]

2.2.1.2 Non-rigid Airships

As the name implies, non-rigid airship design is the counter to the rigid concept. The craft does not have an internal metal frame for support, and the structural integrity of the gas envelope is dependent on the tensile strength of the gas envelope fabric. This limits the size of the airship but decreases its mass. Internal air compartments called ballonets control the airships altitude. These gas volumes inflate or deflate to adjust the buoyancy force acting on the balloon by the surrounding atmosphere. Non-rigid airships, or blimps, are the most common lighter-than-air vehicles in operation today. The most well known non-rigid airship, the Goodyear blimp, is pictured in Figure 3 with its internal ballonets [8].

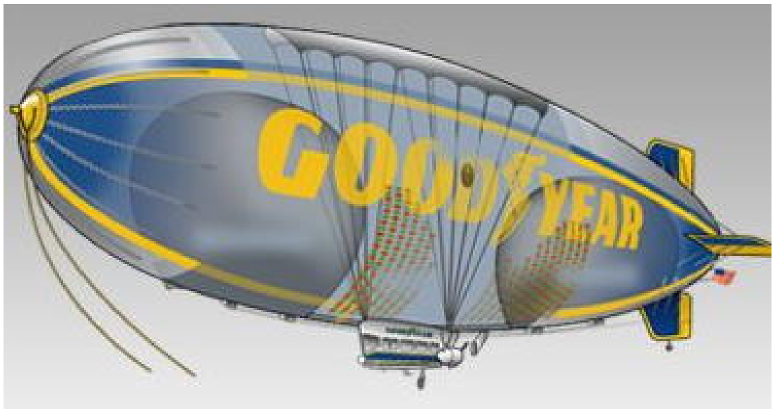

Figure 3: Goodyear Blimp with Ballonets [8]

2.2.1.3 Semi-rigid Airships

Semi-rigid airships are a hybrid between rigid and non-rigid. This design does not have a complete internal metal frame like the rigid concept, but the airship does have a rigid keel running from nose to tail at the base of the gas envelope. This metal keel offers structural support for the craft, and provides hard points for the attachment of heavy equipment, such as engines. Semi-rigid airships were not the most common lighter-than-air vehicles used by the United States. However, many European and a few South American countries implemented the design. The most accomplished semi-rigid airship was the Italian made Norge (Figure 4). The Norge made the first manned-flight over the North Pole on May 12th, 1926 [7].

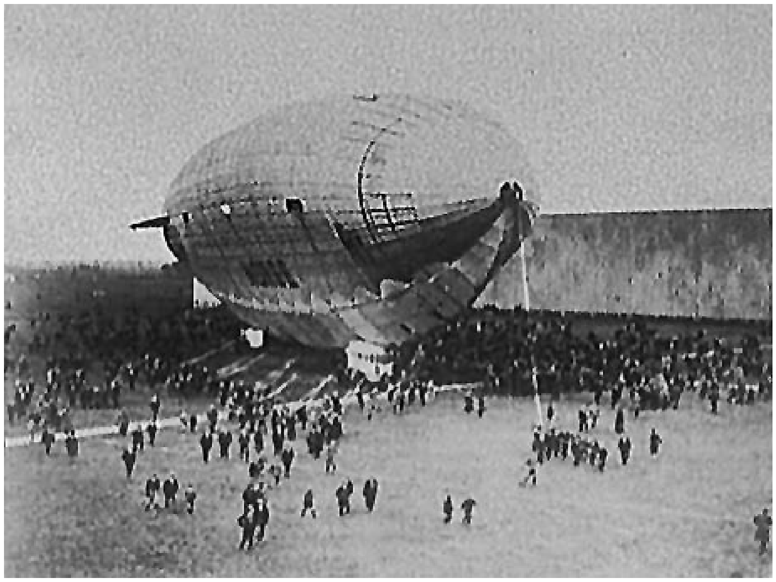

Figure 4: The semi-rigid Norge Airship [7]

2.2.2 US Military Airships

The only two services in the United States Military that operated lighter-than-air vehicles were the Navy and Army; the Air Force had not yet been created. Discarding the numerous small observation balloons used by the US Army, the majority of airship operations were conducted by the US Navy. The Army Air service experimented with non-rigid and semi-rigid airships until June of 1937 when the Army's airship division was cancelled, and the remaining resources transferred to the Navy. Consequently, nearly all military lighter-than-air vehicle operations were conducted by the US Navy's rigid and non-rigid airships.

2.2.2.1 Rigid US Navy Airships

The largest airships operated by the US Navy were its four Z-type dirigibles.

2.2.2.1.1 USS Shenandoah

The first rigid airship built in the United States was the USS Shenandoah designated type ZR1 (Figure 5). The Shenandoah was built at the Lakehurst Naval Air Station in New Jersey and was basically a copy of the German Zeppelin. Construction of the airship began in April 1922 and the ZR1 was officially launched in August 1923 [4]. The original design of the Shenandoah called for hydrogen to be used as the lifting gas. However a number of airship accidents had been caused by hydrogen combustion, such as the British built ZR2 and the US Army's Roma, and this forced engineers to substitute helium for safety concerns. The Shenandoah airship stretched 680 feet in length and was powered by six external propeller engines. The Shenandoah had a crew compliment of 29 men with an additional ground handling crew of over 400 men required to launch and receive the large craft. The airship operated as a test vehicle that helped the US Navy to improve future airship development, operations, and public support. The USS Shenandoah's military service was tragically cut short on September 3rd, 1925 when violent atmospheric changes stressed the airships internal frame to the point of failure. The failure of the internal frame resulted in the aircraft being ripped into two sections and eventually crashing in southeastern Ohio. Nineteen crewmen perished and the accident raised concerns about the ability of lighter-than-air vehicles to withstand unpredictable weather conditions.

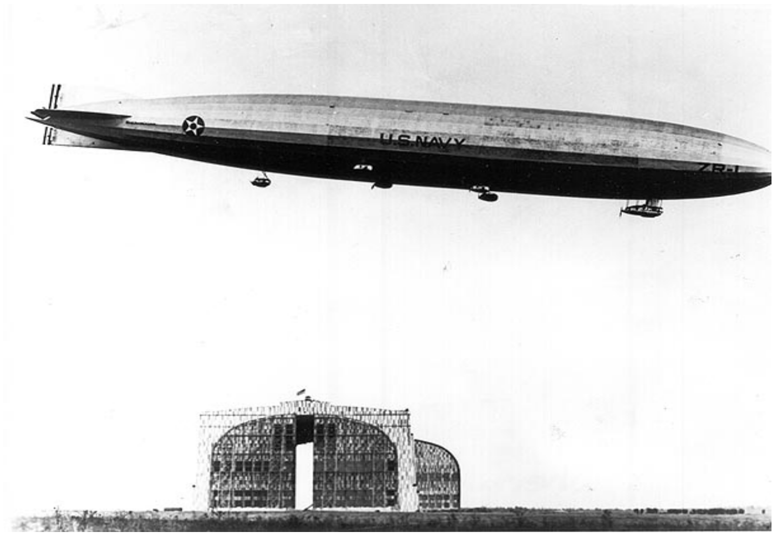

Figure 5: USS Shenandoah [4]

2.2.2.1.2 R-38

The R-38 was supposed to be the United States Navy's second rigid airship, designated ZR2 (Figure 6). The manufacturer, R. A. W. Bedford, located in the United Kingdom constructed the R-38. The airship was commissioned by the US government in the latter years of the First World War, and had the potential of being the largest dirigible in the world. In addition to the R-38's impressive performance, the craft was outfitted with offensive and defensive weapons (Table 2). After construction was completed on June 7th, 1921, the airship was to be delivered to the US Navy on its fourth trial flight from Howden, England to Norfolk, Virginia [9]. The R-38 arrived at Norfolk in late August of 1921 only to be redirected back to Howden because of extremely dense fog coverage over the Naval Air Station. On August 24, the airship was conducting a series of tight turns when the internal frame broke apart at the middle of the ship. The hydrogen lifting gas combusted and the airship plummeted to the earth killing 44 men. The R-38 never served in the US Navy but influenced airship designers to pursue safer lifting gases such as helium.

Figure 6: R-38 Airship [4]

Table 2: R-38 design specifications and Armaments [4]

Length	695 ft	Bombs	4x 520 lb
Diameter	85.5 ft		8x 230 lb
Speed	71 mph	Guns	1x pdr gun on top of ship
Engines	6 x 350 hp		12x machine guns
Volume		2, 724,000 cft	

2.2.2.1.3 USS Los Angeles

The longest-living US Navy rigid airship was the USS Los Angeles designated ZR3. The Los Angeles was built in 1924 by the Luftschiffbau Zepplin Company located in Germany, and was transferred to the United States as apart of war reparations demanded by the Allies. The airship was the largest flying machine of the time with a gas envelope of 2,470,000 cubic feet, and a crew compliment of 40 to 50 sailors [4]. The

Los Angeles never operated in combat but rather performed as a test platform for training men and experimenting with new airship technologies. Researchers successfully developed better ground handling equipment and demonstrated the ability to launch and receive aircraft from a dirigible (Figure 7). The Los Angeles was the longest operated rigid airship in history, with 4,398 flight hours logged, and a total distance traveled of 172,400 nautical miles [4]. The most successful rigid airship the United States ever operated; it was decommissioned on June 30th, 1932 because of economic influences.

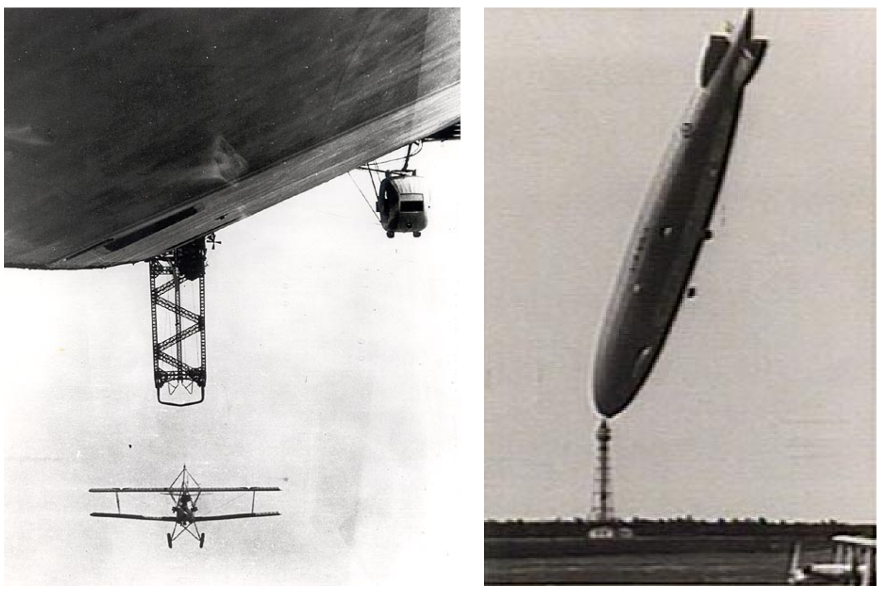

Figure 7: ZR3 Hook-on Test and Low-mast Mooring [4]

2.2.2.1.4 USS Akron

Due to the success of the USS Los Angles, the United States Navy called for the production of two more rigid airships manufactured by the Goodyear-Zepplin Company [10]. The first of the two was the USS Akron, designated ZRS4 (Figure 8). The Akron was revolutionary in design and its capabilities (Table 3). The internal frame was strengthened because of lessons learned from the USS Shenandoah and the R-38 crashes; furthermore the ZRS4 was capable of launching and receiving five fixed-wing aircraft. The five F9C Sparrow hawks provided defense against attacking aircraft, and extended the scouting range of the airship. The Akron was commissioned on November 2nd, 1931, and served until April 3rd, 1933, when the airship tragically crashed off the coast of New Jersey due to a violent storm [10]. Seventy-three men were lost in the disaster, and lost with them was support for future operation of lighter-than-air vehicles.

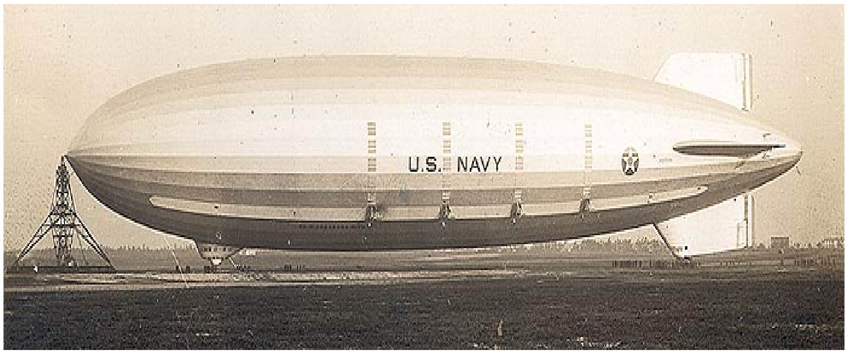

Figure 8: USS Akron at Lakehurst NAS [10]

Table 3: USS Akron Design specifications [10]

Length	785 ft	Support Planes	5 x F9C
Diameter	132.9 ft	Hanger Dimensions	75 ft x 60 ft x 16 ft
Engines	8 x 560 hp	Max Speed	73 kts. (37.5 m/s)
Volume	6, 850,000 cft (193,970 m^3)	Service Ceiling	5,852 m (19,200 ft)

2.2.2.1.5 USS Macon

The USS Macon, designated ZRS5, was the last rigid airship commissioned by the United States military (Figure 9). Identical in design to her sister ship, the USS Akron, the USS Macon was christened on March 13th, 1933, and served for twenty three months. With the loss of the Akron, the USS Macon was rushed into operation even though dangerous structural deficiencies in the internal frame had been discovered. The airship logged 54 flights and 1,798 flight hours while attempting to revitalize support for the dirigible service [4]. With no attention given to its structural flaws, the USS Macon was bound for disaster and on February 12th, 1935, the craft's upper fin collapsed forcing the crew to abandon ship off the coast of California. Two men were killed and the incident resulted in the death of the United States military's rigid airship program.

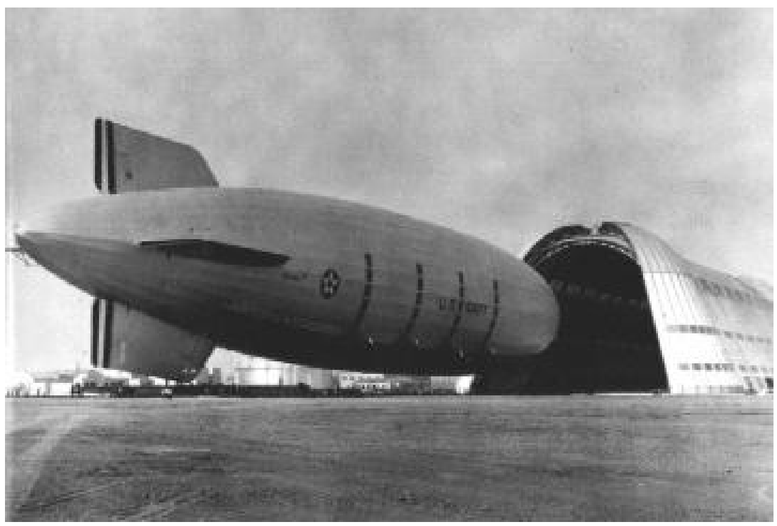

Figure 9: USS Macon Emerging From Hanger [4]

2.2.2.2   Non-rigid US Navy Airships

The United States Navy's non-rigid airships were significantly smaller in size compared to its massive dirigibles. As mentioned previously in this chapter, the size of the non-rigid ships is decreased significantly because of the lack of an internal metal frame. The rigid design concept was abandoned due to the inability of the metal structure to withstand varying strong winds. In the non-rigid airships, decreased gas envelope volume due to the limiting tensile strength of the gas envelope fabric restricted the non-rigid airship from lifting large payloads and achieving high altitudes easily attained by the rigid airships. Yet the flexible gas envelope of the non-rigid ships allowed the vehicle's shape to deform and absorb the wind forces without catastrophic failure that was common to the rigid airships. Smaller payload capacity limited the vehicle's mission capabilities, nevertheless the US Navy's non-rigid airships proved to be the most successful lighter-than-air vehicles used in combat operations.

The first US Navy non-rigid airship was built in 1917, and manufacturing continued until 1958 [9]. During this time interval, twelve different designs were designated A through M, and the final Naval crafts built were labeled ZPG. The most noteworthy non-rigid airships of these designations are the K, M, and ZPG class blimps.

2.2.2.2.1 Type K Non-rigid

The non-rigid airship with letter designation K was the workhorse of US airship operations (Figure 10). Developed by the Goodyear Company, the first type K blimp was brought into service in 1931, and they continued their service through WWII. Initial specifications of the airship called for an internal volume of 320,000 cubic feet, but due to the airships success many K type blimps were modified to extend their service life with the largest having a gas envelope volume of 547,000 cubic feet [4]. The K type blimps were eventually phased out of operation by more modern non-rigid airships and decreasing support of lighter-than-air vehicles. The safe and reliable K blimps were one of the longest serving and successful airships of the US Navy.

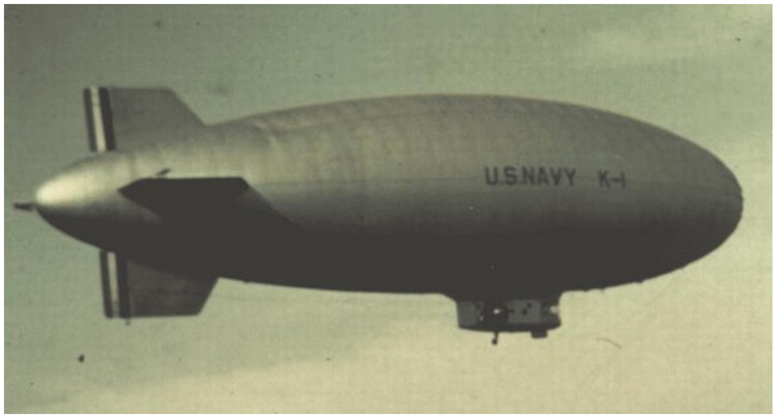

Figure 10: US Navy K-1 Non-rigid Airship [4]

2.2.2.2.2 Type M Non-rigid

The success of the type K blimps in WWII influenced the US military to develop a larger non-rigid with greater endurance. Goodyear responded with the type M airship, following its type L design, which was primarily used as a training platform. The type M had a larger gas volume of 625,000 cubic feet (17,698 cubic meters) and on September 11th, 1943, the US government contracted the first M blimps (Figure 11). Along side its predecessor, the type K, the type M airship operated successfully in the latter years of WWII and beyond. The endurance of this class of airship was demonstrated on October 27, 1946, when the M-1 flew nonstop for 170.3 hours [4]. The type M was eventually phased out by the ZPG class and the continuing abandonment of lighter-than-air vehicle operations.

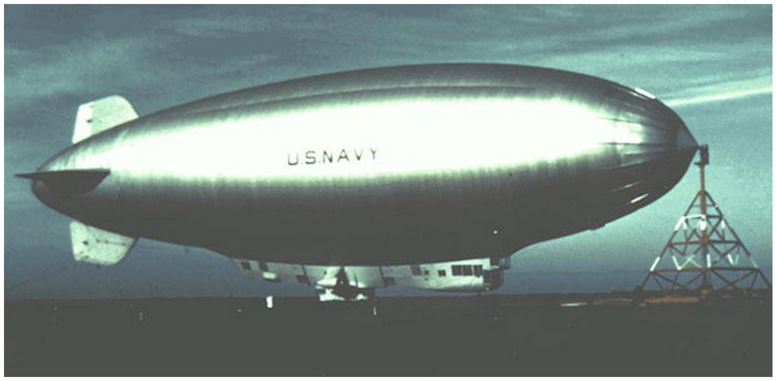

Figure 11: US Navy M-1 Non-rigid Airship [4]

2.2.2.2.3 Type ZPG Non-rigid

The last airship class to serve in the US military was the ZPG non-rigid airship (Figure 12). All type ZPG blimps were built or modified by the Goodyear Company, and the first ZPG operated by the US Navy was the ZPG-2. Twelve ZPG-2 airships were constructed to replace the aging type M blimps. The larger ZPG-2 had a gas volume of 975,000 cubic feet (27,608 cubic meters) that increased the blimps range and endurance. The ZPG-2 demonstrated its endurance capabilities by being the first US airship to cross over the artic circle, and with another continuous flight of 264.2 hours without refueling [4].

Five ZPG-2 airships were converted into ZPG-2W blimps. The ZPG-2W was a product of the Cold War. They were designed to provide an Airborne Early Warning system by detecting incoming Russian aircraft. A large radar dome was placed on top of the gas envelope along with a radar antenna mounted below the control car.

The last airship to operate in the US Navy was the ZPG-3W. The ZPG-3W was also designed as an Airborne Early Warning platform. It was designed with a large search radar mounted inside the gas envelope and a height finding antenna located on top of the airship. This lighter-than-air vehicle was the largest non-rigid airship ever built with a length of 403 feet (135 meters) and a gas volume of 1,465,000 cubic feet (41,484 cubic meters). Four ZPG-3W non-rigid airships were built, and the last flight of this class of airship (also the last military flight) was conducted in 1961 [9].

Figure 12: US Navy ZPG Non-rigid Airship [4]

2.2.3 US Military Airship Operations

Lighter-than-air vehicles were not used in combat operations until World War II and then only non-rigid airships were utilized. The enormous and very costly rigid airships operated by the US military only served in peacetime operations after WWI and before WWII. The massive rigid airships had many offensive and defensive combat capabilities, but they were never proven in wartime. Ultimately, the rigid airship was used as a test and development platform, and as a propaganda tool to demonstrate United States military power. Military commanders had high expectations for the rigid airship fleet, but the numerous accidents involving dirigibles convinced policy makers to implement and develop only non-rigid airships for the future.

When the United States entered WWII, they were the only country with a military airship division. The primary airships used in WWII operations were the non-rigid types K and M. These were the first US military lighter-than-air vehicles utilized in combat. The type K and M airships were vulnerable to high-speed enemy aircraft, but their endurance and station-keeping abilities made them perfect for escorting supply convoys. The blimp's maximum speed was sufficient enough to keep pace with the slow moving supply ships, and the airship's elevated view point allowed crews to spot enemy U-boats outside the U-boat's attacking range. Hundreds of these non-rigid airships were used in anti-submarine warfare roles without a single airship being lost to enemy action. Throughout World War II, the US Navy's airship fleet escorted approximately 89,000 merchant ships without a single supply ship being lost to a U-boat attack [10]. This achievement was unparallel by any other aircraft; however the type K and M airships eventually lost funding. This money was allocated to developing better and faster fixed-wing aircraft during the Cold War.

An attempt to continue lighter-than-air vehicle military operations was made by the development of the ZPG non-rigid airship. As mentioned in the previous section, these airships were transformed into Airborne Early Warning platforms for Cold War purposes. The blimps proved useful, but they were never produced on a large scale. Support for lighter-than-air vehicles faded, and the ZPG non-rigid airships were the last blimps used in US military operations.

2.3 Future Airship Development

Interest in using lighter-than-air vehicles for military purposes has been revitalized in the past few years. Technical innovations in material strength, combined with advancements in unmanned aircraft capabilities, have created new opportunities for airship operations. Designers have been drawn back to lighter-than-air vehicles because of their unique performance characteristics, such as the ability to station keep over a target for long periods of time. The Department of Defense has tasked engineers at Lockheed Martin to purpose a high altitude airship (HAA) for various communication and surveillance missions that would operate at near space altitudes and possibly replace the need for orbiting satellites [5].

2.3.1 Lockheed Martin's High Altitude Airship

The United States Missile Defense Agency has awarded a $40 million contract to Lockheed Martin to deliver a HAA prototype by the year 2006. This new non-rigid airship will have the capability of achieving altitudes greater than 60,000 feet, be able to station keep for up to one month, and supply enough power to operate various payload equipment for military use (Figure 13) [6]. The prototype will be the largest non-rigid airship ever built, with a gas envelope nearly five times larger than the US Navy's ZPG-3W (Table 4). The large gas volume is necessary for the HAA to reach near space altitudes with its required payload and propulsion systems. The extremely high altitudes mandated by the contract are achievable only by the development of strong, efficient, and lightweight propulsion systems and gas envelope fabrics. Examples of these components are thin-film photovoltaic solar cells, commercially available fuel cells, and lightweight/high-strength gas volume fabrics. These advancements in airship design and performance will demonstrate new mission capabilities for lighter-than-air vehicles.

Figure 13: Lockheed Martin High Altitude Airship [5]

Table 4: Design Specifications for HAA [6]

Length	500 ft (153 m)
Diameter	160 ft (49 m)
Gas Volume	5,200,000 cft (147,212 m^3)
Required Speed	35 knots (18 m/s)

2.3.1.1 High Altitude Airship Mission

The airship is designed to satisfy a multiple mission objectives while in geostationary orbit: short and long-range missile warning, surveillance, target acquisition, and weather monitoring [5]. The near space operation altitude allows for coverage over a large footprint area on the surface of the Earth, and even greater air surveillance capabilities (Figure 14). High Altitude Airships will allow military commanders to deploy communication or surveillance platforms continuously over any target of interest located anywhere on Earth. The airships will also operate at a fraction of the cost of current low Earth orbit satellites that do not even have the capability to continuously cover a single target area.

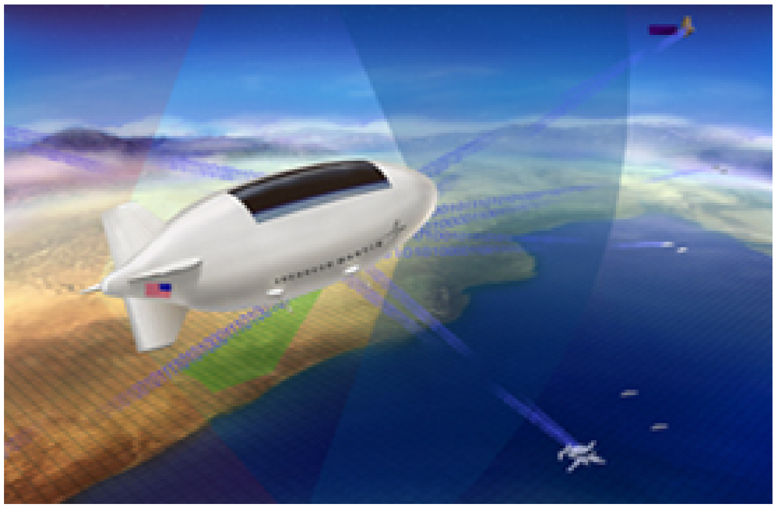

Figure 14: HAA Surveillance and Communication Mission

2.4 High Altitude Wind

The greatest opponent to High Altitude Airship station-keeping is the craft's ability to resist strong and varying upper atmospheric winds. The magnitude and direction of these winds vary with altitude, location, and season. If the wind velocity is greater than the velocity produced by the airship's propulsion system, the blimp will be displaced from its target area rendering the platform's communication and surveillance equipment useless. To ensure continuous on-station operation, the airship must fly at the altitude(s) with the lowest wind speed. Fortunately, there is section in the stratosphere around an altitude of 24 km (78,739 ft) where reduced temperature gradients, and converging east/west winds, yield low average wind speeds. This optimal operation altitude for the airship has been labeled the stratonull [11]. If High Altitude Airships are going to operate successfully, this location in the upper atmosphere must be utilized. To understand the stratonull, a basic understanding of varying atmospheric temperatures and wind directions must be attained.

2.4.1 Temperature Gradient With Respect to Altitude

The atmosphere is divided into five sections: the troposphere, stratosphere, mesosphere, thermosphere, and exosphere (Figure 15). Of these five regions the most pertinent to operating High Altitude Airships, and the location of the stratonull, is the stratosphere [12]. Starting at the Earths surface, the first section of the atmosphere is called the troposphere. This layer extends from the surface to an altitude of about 10 km. Ultraviolet rays that are not absorbed in the ozone layer radiantly heat the Earth's surface, which then convectively heats the atmosphere at ground level. The temperature decreases as altitude increases in the troposphere because the elevated air is removed from the Earth's surface. Separating the troposphere and the stratosphere is the tropopause.

Starting at the tropopause, up through the stratosphere, an isothermal section of the atmosphere extending from 10 km to about 20 km can be seen from Figure 15. The temperature of the air stops decreasing in this section and begins to increase at a height of about 20 km. The Earth's ozone layer causes this phenomenon. Ozone is the common name for the molecule that contains three oxygen atoms. These molecules absorb the majority of harmful ultraviolet rays that are incident from the sun. The absorption is due to the ideal size of the O_3 molecule. The incoming ultraviolet waves interact with the ozone in resonance absorptions that separate an oxygen atom from the molecule and release heat through kinetic energy given to the separated particles. The concentration of the Earth's ozone layer is maximized in the stratosphere and then diminishes as altitude increases [12]. At the top of the stratosphere, the stratopause, ultraviolet rays are no longer being absorbed. This leads to another isothermal region at about 50 km, followed by a significant decrease in temperature through the mesosphere.

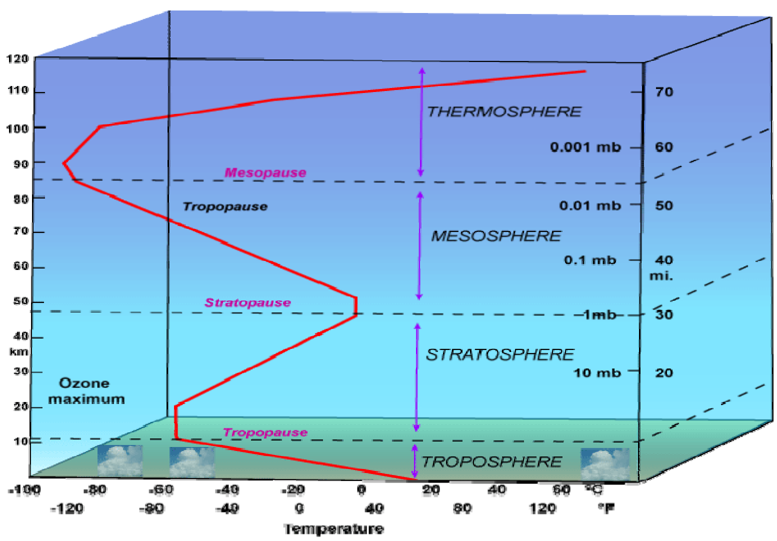

Figure 15: Atmospheric Temperature With Increasing Altitude [13]

The region of interest to High Altitude Airship operation is the section of atmosphere where the temperature increases between 20 and 25 km. First and foremost, operations above these altitudes are not currently feasible from a design point of view. The density of the air decreases exponentially with increasing altitude, and above 25 km the density is too low for practical airship operation (Figure 16) [1]. Buoyancy forces acting on the craft's gas envelope generate lift for an airship. If the gas inside the envelope is less dense than the surrounding atmosphere, the airship will rise and visa versa. To achieve enough lift for flight there must be small enough mass per volume inside the gas envelope. Above 25 km the airship's gas envelope would be enormous and unattainable for engineers to construct and operate.

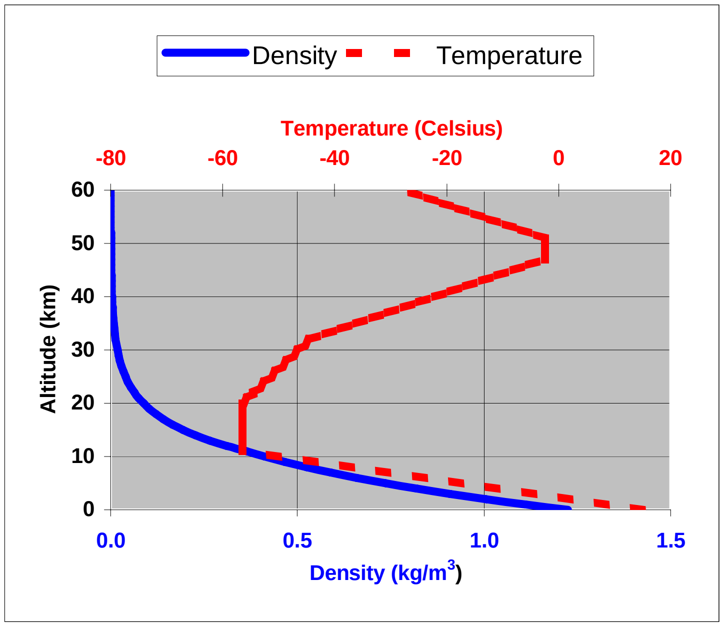

Figure 16: Decreasing Density as Altitude Increases [1]

Altitudes between 20 km and 25 km are attainable with current airship technologies, and more importantly span the region of the stratonull. The stratonull is approximately located at 24 km, which is just above the isothermal region in the stratosphere as shown in Figure 15 [11]. The corresponding pressure height to this 24 km altitude is approximately 30 mb. The 30 mb pressure height is dependent on the temperature of the air and changes with season, but the annual average altitude of the 30 mb level is approximately 24 km. Around this altitude, the isothermal temperature of about –55 degrees Celsius is increased. This is due to the ultraviolet rays being absorbed by the ozone, which results in heating the air. The location of the stratonull occurs here because the temperature difference (temperature gradient) between the surrounding altitudes is at a minimum. For example, from Figure 15 the average temperature at 23 km is –54 degrees Celsius which is very close to the average temperature at 24 km: –53 degrees Celsius.

To understand the benefit of this low thermal gradient, it is important to understand how wind is created. In a simplified case, wind is governed by thermodynamic principles, and temperature is the driving force. Wind (air), just like any moving fluid, will always flow from a more energetic state to a lower energetic state when no work is being input. In temperature terms, wind will blow from a warmer region to a cooler region. In pressure terms, wind will blow from a high-pressure region to a low-pressure region. When the temperature gradient between the warm region and cold region is large, the air will move faster to achieve equilibrium. In the situation involving the stratonull, the minimal thermal gradient between 20 km and 24 km creates a region in the upper atmosphere where the wind magnitude is small compared to the above and below altitudes [14]. This phenomenon can be related to the day-to-day occurrence of calm winds in the morning and stronger winds in the afternoon, assuming there are no storm systems. Before sunrise the Earth's surface is cool and constant because of the lack of sunlight during the night. This can be related to the cool isothermal region between 10 km and 20 km on Figure 15. After the sunrise, the Earth begins absorbing the ultraviolet rays from the sun, and the temperature of the surface starts to rise. This can also be seen on Figure 15 as the gradual rise in temperature at 20 km. Throughout the morning the temperature difference is minimal, hence calm winds. In the Afternoon the Earth's surface has absorbed much more heat and the temperature gradient is much larger, therefore stronger winds are produced.

2.4.2 East Wind and West Wind Crossover

The stratonull phenomenon can also be observed by identifying the regions in the atmosphere where opposing winds interact. For example, if a 10 m/s wind is blowing directly west at 60 degrees north latitude and a 10 m/s wind is blowing directly east at 50 degrees north latitude, there must be a location between 60 and 50 degrees latitude where the fluid flow speed equals zero because of the opposing currents. Finding these regions in the atmosphere is difficult, but by studying global and seasonal wind velocities estimates can be made.

The three-cell model shown in Figure 17 defines a simplified global wind structure [15]. It is assumed that the figure shows a perfectly spherical Earth spinning on its axis with the sun directly over the equator. As discussed in the previous section, wind is generated by temperature gradients and in this model the sun is predominately heating the air at the equator. The warm air rises at the equator and drifts either north or south towards cooler regions. These flows are called Hadley cells. At approximately 30 degrees latitude, the cooled air descends and moves back toward the equator, but these winds do not move directly north and south. The Earth's rotation deflects the air that is causing the wind to blow from the northeast or southeast back towards the equator. This phenomenon is due to the Coriolis forces caused by the Earth's rotation that create predominately easterly surface winds in the lower latitudes [15]. Not all the air at 30 degrees latitude proceeds back toward the equator. Above 30 degrees north latitude and below 30 degrees south latitude there exists a westerly flow caused by airflow from a high-pressure region at 30 degrees latitude towards a low-pressure polar front at 60 degrees latitude. These winds deflect toward the east and generate prevailing westerly surface winds. This simple model depicts both westerly and easterly winds occurring on the earth's surface. Consequently they are occurring in the upper atmosphere because of the Hadley cells and the conservation of momentum of the moving air. The regions of interaction between these opposing winds will create an area of low wind velocity that has been defined as the stratonull [11].

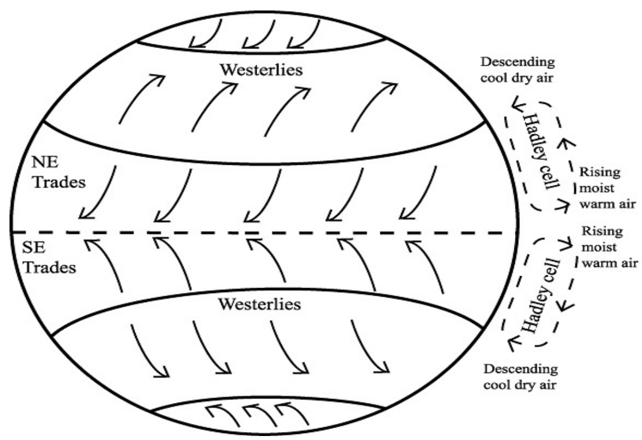

Figure 17: Three-Cell Model of Global Winds [15]

The three-cell model is good for illustrating the generation of easterly and westerly winds, but realistic winds are not as simple. Winds are highly dependant on location, season, and altitude. At an altitude of 24 km, winds are predominately westerly in the winter from the low latitudes to the poles, and they are predominately easterly during the summer, concentrated around the equator and extending toward the poles as well. A good illustration of the dependence of wind direction on altitude and season is shown in Figure 18 [14]. The figure represents the average wind direction and magnitude for the summer and winter hemispheres during the time of the solstices when the winds are strongest. The winds depicted are only zonal winds, east or west winds, as opposed to meridional winds, north or south winds. The reason being is because the meridional winds are generally small in magnitude, and hence contributes little to the high altitude airship station-keeping problem. A "W" and pink shading denotes westerly winds and easterly winds are labeled with an "E" and given yellowish shading. The variation in shading indicates the magnitude of the wind increasing in intervals of 10 m/s. The lowest velocity regions are bordered with a bold black line and the highest velocity regions have the darkest shading. For example, during the summertime the strongest easterly winds are estimated to be at an altitude of 60 km and located at 35 degrees latitude.

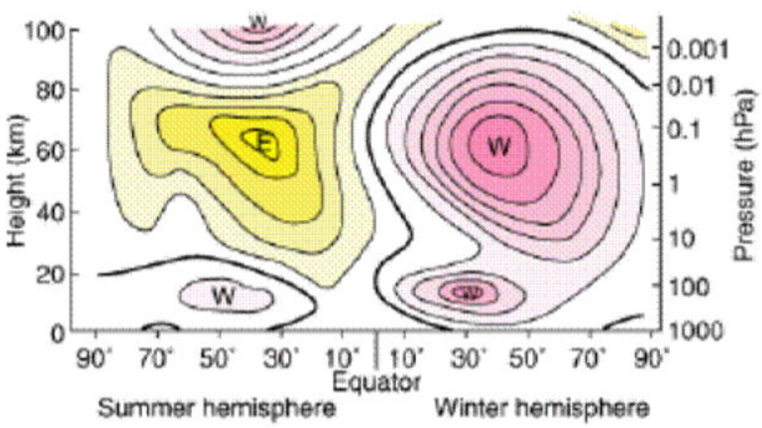

Figure 18: Summer and Winter Hemisphere Climatologies [14]

The crossover region between easterly and westerly winds is apparent in the figure. A barrier between the summer easterlies and winter westerlies occurs at the equator, and extends from the surface of the earth to an altitude of approximately 80 km. This low wind region would be optimal for station-keeping high altitude airships, but its location would be restricted to targets on or near the equator. If total global coverage is required, the stratonull must be utilized. The stratonull is apparent in the summer hemisphere at around 24 km and spans most of the hemisphere from the equator to the pole. The altitude of this low wind region is not constant at 24 km throughout the hemisphere, and changes in the airships altitude might be required for optimal station-keeping. In the winter hemisphere there is no low wind velocity region that spans the entire hemisphere. This implies that high altitude airships operating away from the equator during wintertime must be able to counter westerly winds to maintain their locations.

It is important to remember that Figure 18 represents average wind velocities during the time of the solstices. Over the course of an entire year, the locations of the low wind regions may vary in latitude and altitude, but the previous figure is a good starting point when locating the stratonull. For an example from actual wind data, Figure 19 depicts a calculation of wind speed and direction at a pressure height of 30 mb (about 24 km altitude) on February 25th, 2004 [16]. The wind's direction and magnitude are shown using wind barbs. The number of tick marks on the tail of the barb, with one tick mark representing 10 knots, gives the speed of the wind. The direction of the wind is shown by the orientation of the barbs vector. On this particular day, it is winter in the northern hemisphere and summer in the southern hemisphere. The south is experiencing mostly easterly winds, and the north is experiencing mostly westerly winds. The crossover region between the two hemispheres resulting in low winds can be seen around the equator and up to 25 degrees north latitude. The stratonull region in the summer hemisphere is located at approximately 60 degrees south latitude and extends around most of the globe. This data matches well with the average predictions in Figure 18, and supports the possibility of station-keeping high altitude airships for long periods of time. The biggest challenge will be to accurately and precisely predict where these low wind regions occur. If the airship is accidentally positioned in a region experiencing high winds, the craft will be blown off target and possibly be unable to recover.

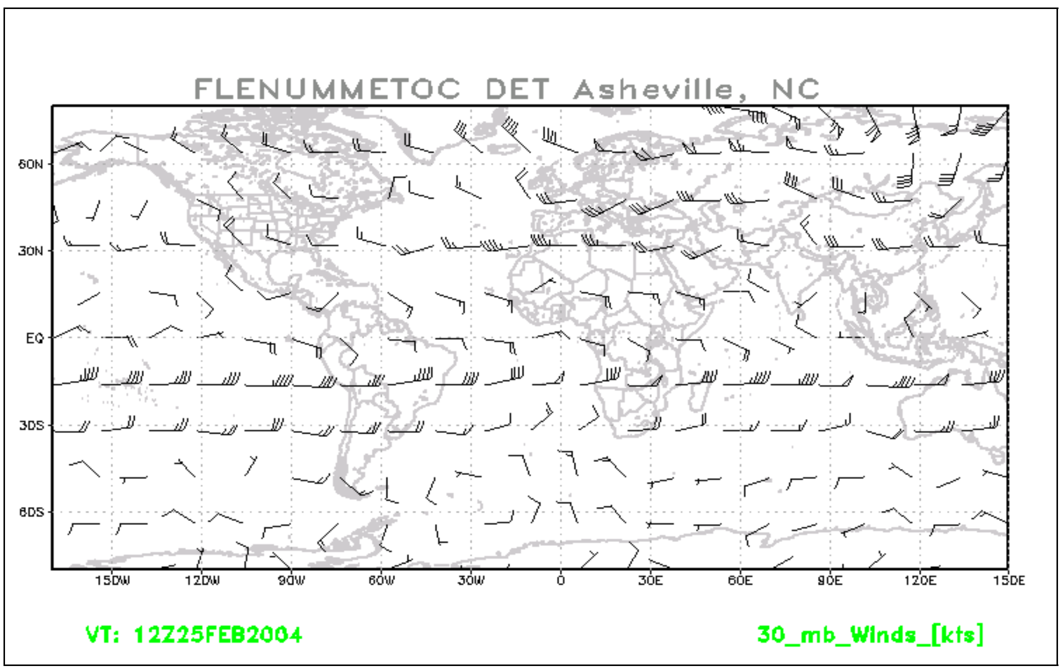

Figure 19: Wind Magnitude and Direction at 30 mb on 25 February 2004 [16]

2.5 Chapter Summary

Lighter-than-air vehicles played a significant role in the early years of United States military aviation. The enormous rigid airships were a symbol of national pride and technological achievement. Dirigibles were eventually phased out due to a number of catastrophic mishaps and replaced by safer helium filled non-rigid airships. The United States military had much success operating blimps during WWII, but the Navy's airship department lost support from policy makers because of Cold War ambitions of building better and faster fixed-wing fighter and bomber aircraft. Attempts were made to revitalize the use of airships with the creation of the ZPG blimps, but the program was eventually cancelled. New interest in operating high altitude airships for communication and observation missions has been spawned. High altitude airships could station-keep for long periods of time in the low wind regions of the upper atmosphere. This region has been defined as the stratonull, and it is the optimal operation space for the high altitude airship. To date however, detailed mission analysis for candidate designs has not been conducted using actual wind data, nor have such demonstrations been flown. To validate some of the preliminary design concepts, a station-keeping analysis will be conducted. The next chapter will explain the process used to examine the performance of two high altitude airships operating in the upper atmosphere over the course of one year.

3 Methodology

3.1 Chapter Overview

The following chapter examines the procedures and calculations used for the station-keeping analysis. A high altitude airship mission was chosen for the analysis for two baseline airship designs. The first design will be sized to have a maximum velocity of 19.7 m/s and the second 11 m/s. These values are based on the annual mean and standard deviation of wind velocity over the designated target and were obtained from the Air Force Combat Climatology Center. Both airships must satisfy HAA mission parameters, defined in the design criteria section of this chapter, such as sensor payload and an operational altitude of 24 km. Once the airship sizing is completed, wind and climate data were obtained from the Navy's Fleet Numerical Detachment to model the airships' movements and power used over the course of the defined station-keeping mission. The station-keeping results for both baseline airship designs will be compared and evaluated by mission performance, as defined in the following sections.

3.2 Airship Mission Description

The mission used for the analysis is modeled after the proposed high altitude airship mission. The airship is assumed to be a communication or surveillance platform with a primary mission to station-keep over a specified target for the duration of one year. The year chosen for the mission was 2005 and it was divided into the four seasons: winter, spring, summer, and fall. The airship will start each season above the target in order to compare the station-keeping ability of the airship with respect to the season. The exact dates used for the mission are: December 21st, 2004 to March 19th, 2005 for winter, March 20th, 2005 to June 20th, 2005 for spring, June 21st, 2005 to September 21st, 2005 for summer, and September 22nd, 2005 to December 20th, 2005 for fall.

For this particular analysis, the target for station-keeping operations was designated as Baghdad, Iraq, located at 33.3 degrees north latitude and 44.45 degrees east longitude. Baghdad was chosen because the majority of military operations are currently being conducted at this location, and the United States forces could benefit significantly from a communication and surveillance platform continuously stationed above their position. The airship will only be operational if it stays within a certain distance of the target. An estimated coverage area must be calculated to define the maximum distance the airship can drift from downtown Baghdad.

3.2.1 Ground Footprint

The ground footprint of the airship is the predicted area projected on the surface of the earth that is within the coverage capacity of the sensor equipment. It is assumed that the sensor equipment can be oriented in any direction and angle, allowing for maximum coverage. Therefore, the airship's sensors can operate as long as the line of sight between the vehicle and target is not obstructed. It is also assumed that the surface of the earth below the airship is flat with no mountains or elevated structures blocking the line of sight. The line of sight footprint can be calculated using the altitude of the airship and the radius of the earth.

The defined operational altitude for the mission is set at 24 km (78,740 feet) for this study, and is assumed that the airship will maintain this elevation throughout the entire mission duration (24 km is the estimated location of the stratonull). The radius of the earth is approximately 6378 km and for the footprint calculation it is assumed that the earth is a uniform sphere with this radius. Figure 20 will assist in the calculation.

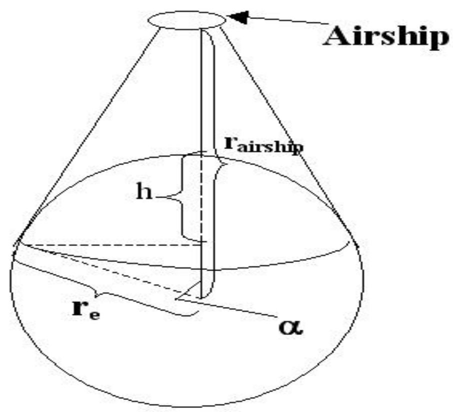

Figure 20: Line of Sight Coverage Area [2]

The figure shows the projected area of coverage on the earth's surface by an airship at a given altitude. The distance from the center of the earth to the airship is labeled $\mathbf{r_{airship}}$ and the radius of the earth is labeled $\mathbf{r_e}$**.** The maximum line of sight is drawn from the airship to the point tangent on the earth's surface. This line is perpendicular with $\mathbf{r_e}$, and the angle created between $\mathbf{r_e}$ and $\mathbf{r_{airship}}$ is labeled α. A line is also drawn from the tangent point to $\mathbf{r_{airship}}$ at a right angle to $\mathbf{r_{airship}}$, and the distance between this line and the earths surface is labeled **h**, which is the height of the circular cap [2]. The area of the circular cap defined by these parameters is the ground footprint area. The area of the circular cap is calculated by:

$$\text{Footprint Area} = 2\pi\, \mathbf{r_e}\, \mathbf{h} \tag{1}$$

To solve for the area, **h** must be defined using trigonometry and the known values of $\mathbf{r_e}$ and $\mathbf{r_{airship}}$. The following relationships can be seen from Figure 20:

$$\mathbf{r_{airship}} = \mathbf{r_e} + \text{Altitude of airship (24 km)} \tag{2}$$

$$\cos(\alpha) = (\mathbf{r_e} - \mathbf{h}) / \mathbf{r_e} \tag{3}$$

$$\mathbf{h} = \mathbf{r_e} - \mathbf{r_e} * \cos(\alpha) = \mathbf{r_e}\,(1 - \cos(\alpha)) \tag{4}$$

$$\alpha = \cos^{-1}(\mathbf{r_e} / \mathbf{r_{airship}}) \tag{5}$$

The footprint area can now be calculated by substituting equations (4) and (5) into equation (1). This relationship between footprint area and airship altitude is plotted in Figure 21:

$$\text{Footprint Area} = 2\pi\, \mathbf{r_e}^{\mathbf{2}}\,(1 - \cos\,(\cos^{-1}(\mathbf{r_e} / \mathbf{r_{airship}}))) \tag{6}$$

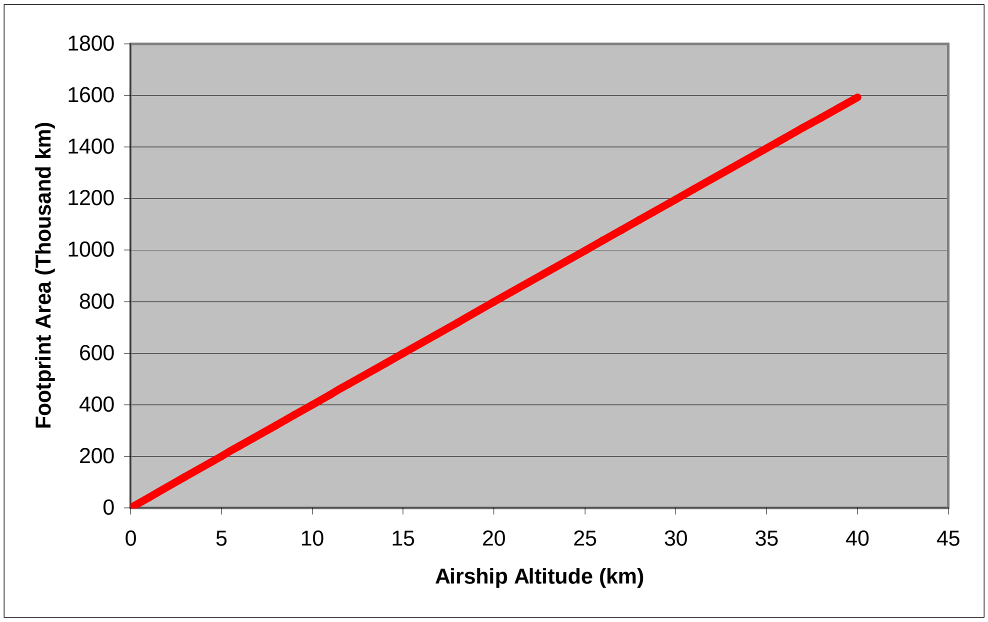

Figure 21: Increased Footprint Area with Increasing Altitude

Using a value of 6378 km for the radius of the earth, and at an airship altitude of 24 km, the calculated line of sight ground footprint is 958,174 km^2. With this circular area, an operational radius is computed to be 552 km. Therefore, the airship stationed at an altitude of 24 km can drift 552 km away from the target in any direction and still be in the line of sight with the target. The 552 km radius is superimposed over the target city (Baghdad) in Figure 22. For the station-keeping analysis, the airship will be considered operational if it is within this radius and non-operational if it drifts outside the radius.

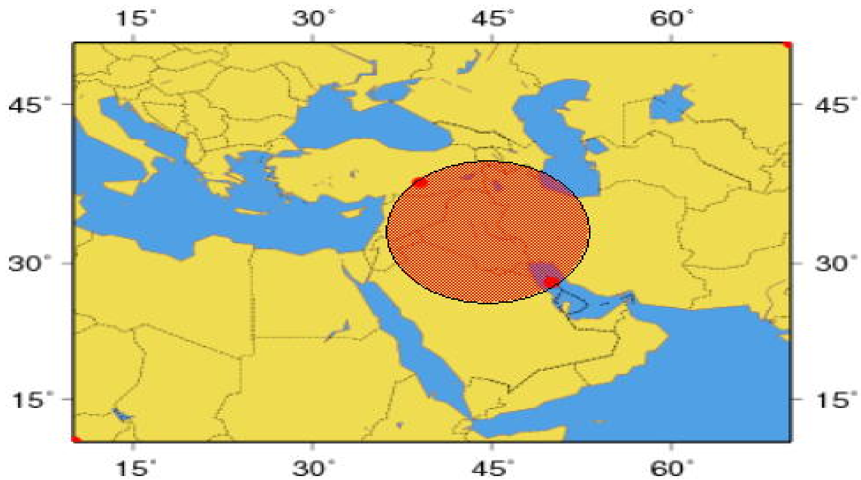

Figure 22: Operational Area for Baghdad Target at 24 km Altitude [17]

The operational radius and other mission assumptions for the station-keeping analysis are summarized in Table 5.

Table 5: Mission Assumptions Summary

Mission Duration:	1 year (Winter, Spring, Summer, Winter)
Mission Dates:	21 DEC 2004 to 20 DEC 2005
Airship Starting Position:	Above Target and at Operational Altitude
Operation Altitude:	24 km (78,740 feet)
Target:	Baghdad (33.3 N 44.45 E)
Operational Radius:	552 km (343 miles)

3.3 Baseline Airship Design

Two baseline airship designs were used in this station-keeping analysis. The model for developing these high altitude airships was created by Captain Eric Moomey, United States Air Force [1]. In depth explanations and complete calculations of the design can be found in Captain Moomey's thesis, "Technical Feasibility of Loitering

Lighter-Than-Air Near-Space Maneuvering vehicles." Both airship designs were built to satisfy a high altitude loiter mission at a constant altitude of 24 km (78,740 feet). This altitude is the predicted location of the low wind region in the earth's atmosphere: the stratonull. It is assumed that the airship will maintain this altitude throughout the entire mission in order to investigate the feasibility of designing a blimp for a specific elevation.

3.3.1 Design Criteria

The two baseline airships will utilize current state-of-the-art technologies and materials for their construction, propulsion, and power. Though the size of the two designs will vary, which will be discussed in more detail later in this chapter, both crafts will share the same basic design parameters (Table 6). The airships must be capable of lifting a typical sensor payload of 1000 kg to the operational altitude (24 km), while also providing enough lift for the crafts' structural mass, gas envelope, power supply, and propulsion plant. Power for the propulsion plant and the sensor payload will be generated by solar panels, specifically Copper-Indium-Gallium-diSelenide solar arrays (CIGS). These arrays are unable to function with the absence of sunlight; therefore it is necessary to include power storage devices on the craft to power the ships' operations during the estimated 12-hour daily eclipse timeframe. Li-ion batteries were chosen for power storage because of their high energy per mass ratio of 129 W*hr/kg [1]. Six electric propellers, with a blade diameter of three meters, will provide propulsion. Propellers are the optimum choice for the vehicle because they are efficient at low speeds and have the ability to move large volumes of air in the low-density conditions of the upper atmosphere. Helium is the designated lifting gas as opposed to hydrogen due to safety concerns about the combustibility of hydrogen. The fabric density of the gas envelope containing the helium is defined to be 300 g/m^2, a typical value of state-of-the-art fabric. The fineness ratio, length to diameter ratio, was taken from experiments conducted by the US Navy in 1927 [1]. These tests resulted in a fineness ratio of 4.62 that yielded the smallest drag coefficient on a lighter-than-air vehicle. Finally, the overall structural mass of the airship was estimated to be 20 percent of the total mass.

Table 6: Baseline Airship Design Parameters [1]

Payload Mass	1000 kg
Payload Power	5000 W
Power Generation	CIGS Flexible solar arrays
Power Storage	Li-ion Batteries
Daily Eclipse	12 hours
Propulsion	6 Electric Propellers
Propeller Diameter	3 meters
Lifting Gas	Helium
Fabric Density	300 g/m^2
Fineness Ratio	4.62
Structure Mass	20% of Total Mass

The size of the airship, particularly the size of the gas volume, is highly dependent on the operational altitude and maximum velocity specified by the designer. This makes the design model for a high altitude airship an iterative problem that might not converge to a solution for an airship operating above 30 km or for an airship with a maximum velocity of higher than 30m/s, because the required lifting gas volume would not be able to lift the propulsion system and the mass of the gas envelope fabric to such a high altitude. Same as all aircraft design, the biggest opponent to a successful model is the mass of the vehicle, and it is this parameter that drives the design of the airship. For example, if the service ceiling specified is raised to a higher altitude, then a greater volume of lifting gas is required to produce the lift. The larger lifting gas envelope significantly increases the mass of the airship, which is calculated using the fabric density multiplied by the amount of fabric. The increased amount of envelope fabric will require more lifting gas to offset the additional mass, and if the required gas volume is too large the airship may not be able to produce enough lift to obtain the desired operational altitude. The same problem arises when a higher airship velocity is required to counteract the atmospheric winds. Adding more power to the propulsion plant produces a higher velocity, and the increased power is generated by the addition of more solar arrays and more batteries. This creates more mass and a greater lifting capacity is required; hence a larger lifting gas envelope is required that will generate more mass, and so on. Figure 23 depicts this relationship by plotting the required lifting gas volume for a given operation altitude, and a maximum airship velocity to counteract the wind speed. This figure was generated by Captain Moomey.

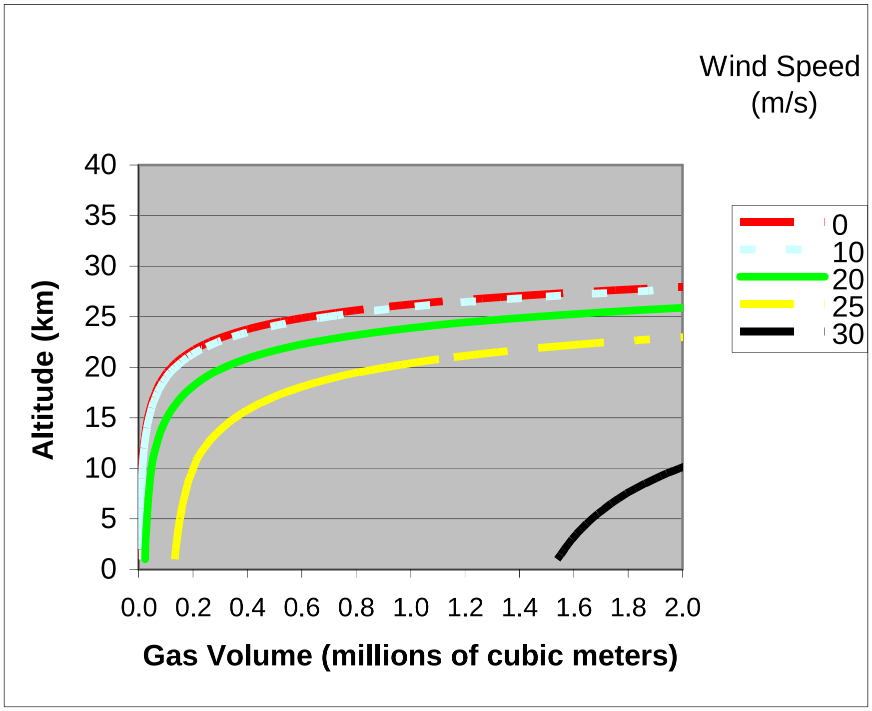

Figure 23: Gas Volume vs. Altitude for Velocity of 0 m/s to 30 m/s [1]

Two baseline airship designs were generated using Captain Moomey's model and the defined baseline airship design parameters. Both airships will operate at the same altitude (24 km), but each vehicle was given a different maximum velocity that varied the size of the airships and their station-keeping abilities. The chosen maximum velocity for the first airship was one standard deviation higher than the annual mean wind speed at the operational altitude and the specified target. The second airship's maximum velocity was chosen to be the annual mean wind speed at the operational altitude at the same target. As mentioned previously, the target for station-keeping operations was designated as Baghdad, Iraq, located at 33.3 degrees north latitude and 44.45 degrees east longitude.

The annual mean velocity and one standard deviation above the annual mean velocity was found using the Site Specific Upper Air Climatology program generated by the Air Force Combat Climatology Center [18]. This program will be discussed in detail later in the weather model section of this chapter. The higher velocity design was 38 knots (about 19.7 meters per second), and the annual mean was 21 knots (about 11 meters per second) (Figure 24). These two velocities and the given operational altitude of 24 km were used to size Airship #1 and Airship #2, and these airships are used in the station-keeping analysis.

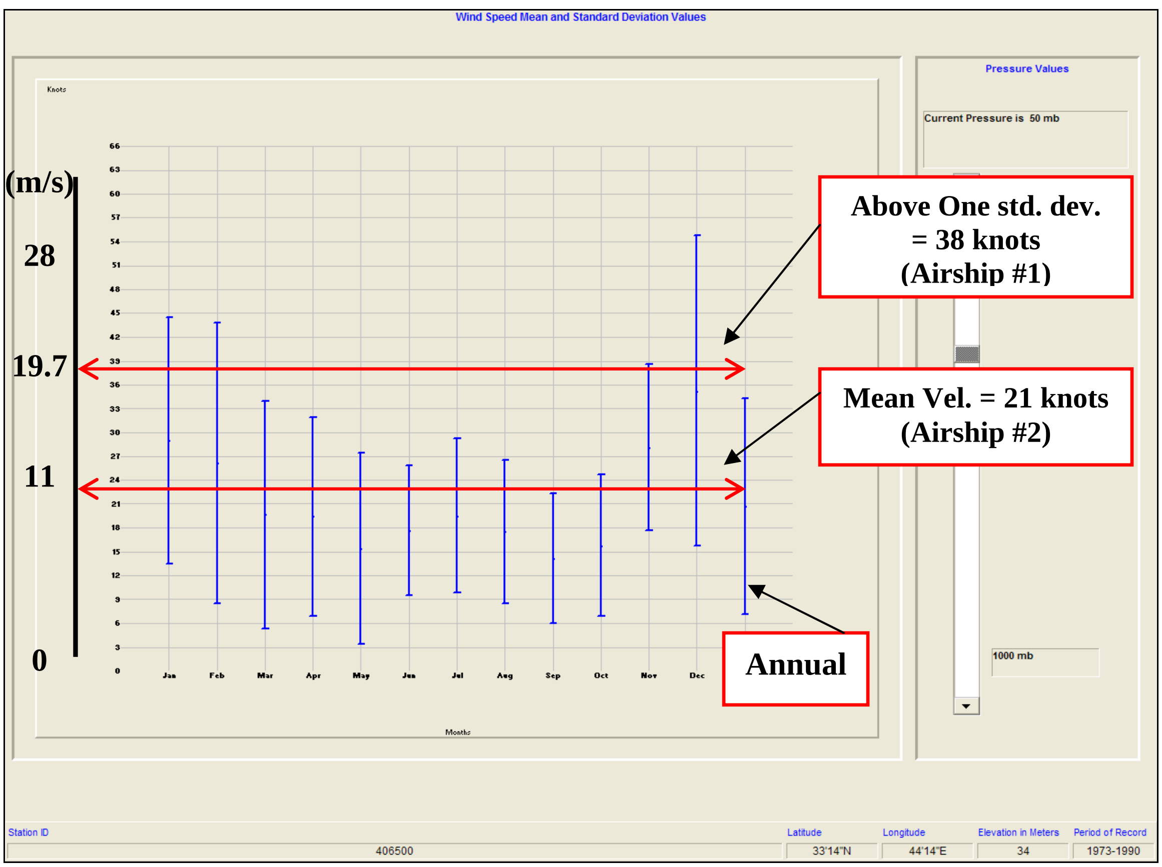

Figure 24: Wind Speed Mean and Standard Deviation over Baghdad at 50 mb [18]

3.3.2 Airship #1 (AS #1)

Airship #1 was sized for an operational altitude of 24 km and a defined maximum velocity at that altitude of 19.7 meters per second. These two parameters were placed in Captain Moomey's design model and the required gas volume was calculated to be $1.04*10^6$ m^3 of helium, with a total airship mass of 40,158 kg, and a maximum engine power of 35,412 Watts [1]. The airship's frontal area, maximum diameter, and length can be calculated using the given fineness ratio and the calculated gas envelope volume:

$$FinenessRatio = \frac{Length}{Diameter} \tag{7}$$

$$FrontalArea = \pi * \frac{Diameter^2}{4} \tag{8}$$

$$Diameter = \sqrt[3]{\frac{6*Volume}{\pi * FinenessRatio}} \tag{9}$$

Table 7 lists the size and performance design parameters for Airship #1. A drag coefficient of 0.028 was used for both airships. This value was derived experimentally for the average C_d of an airship with a fineness ratio of 4.62 [1]. The propeller area is the total area of all six propellers, each having a diameter of three meters. It is also stated that the vehicle's maximum velocity (V propeller) is 19.7465 meters per second, and this speed is achieved with a power generation plant and storage batteries capable of supplying a maximum power of 35,412 Watts.

Table 7: Design Values for Airship #1

C_d =	0.028	
Fine ratio =	4.62	
Airship Vol=	1.04E+06	m^3
V prop=	19.7465	m/s
Front Area=	4478.76	m^2
Diameter=	75.52	m
Length=	348.88	m
Ship Mass	40158	kg
Max Engine Power=	35412	W
Propeller Area=	42.4116	m^2

The dimensional values, such as length and ship mass, help to visualize the size of the airship and are used to compare the design against past and projected blimps. The performance values will be used to examine the airships ability to station-keep at the defined target, or propagate back toward the target if blown off course. By a quick inspection of Airship #1's dimensions, it can be said that this proposed design is very large and significantly bigger than any lighter-than-air vehicle ever built (Table 8). Airship #1 is well over twice as long as the largest non-rigid airship built (ZPG-3W) and Lockheed Martin's proposed HAA. The Gas envelope required to lift Airship #1's propulsion plant to the desired operational altitude is a staggering value of 1,041,000 cubic meters. That is approximately seven times larger than the HAA. It should be noted that the HAA has a proposed operational altitude of 60,000 ft, which is approximately 17,000 ft lower than the baseline airship design. This makes a major difference in the lifting gas volume size since the density of the atmosphere is much lower at 77,000 ft compared to 60,000 ft. A visual representation of the size of AS #1 compared to the ZPG-3W and HAA is shown in Figure 25. Four 100-yard long football fields are also included to give some scale to the airship's length. Though Airship #1 may exceed the current building capacity of airship engineers, it is assumed that for the station-keeping analysis AS #1 does exist and is capable of operating at the defined operational altitude and maximum velocity.

Table 8: Airship Length and Gas Volume Comparison

	Length (m)	Vol. (m^3)
ZPG-3W	135	41,484
HAA	153	147,212
AS #1	349	1,041,000
AS #2	274	503,000

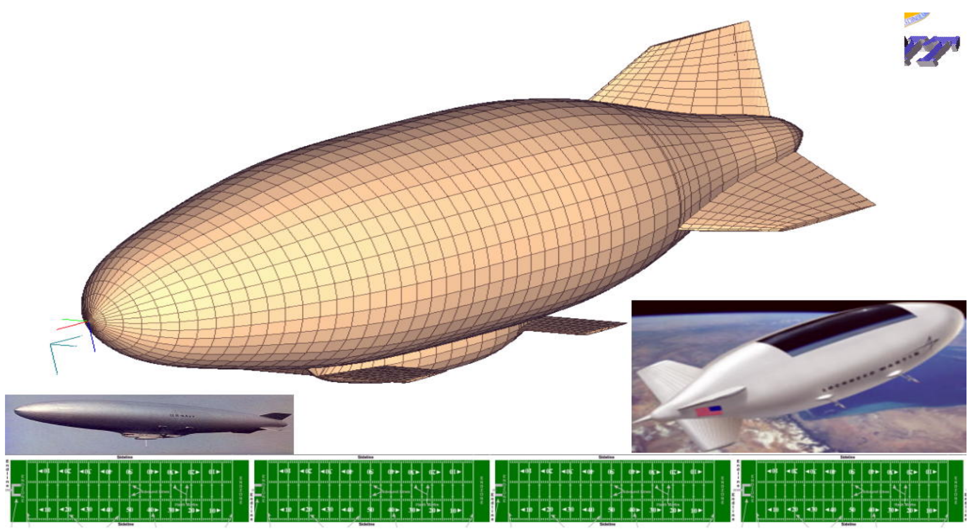

Figure 25: Airship #1 Size Compared to HAA and ZPG-3W

3.3.3 Airship #2 (AS #2)

Airship #2 was sized for an operational altitude of 24 km, and a defined maximum velocity at that altitude of 11 meters per second. The dimension and performance calculations for AS #2 were carried out in the same manner as described in the AS #1 section. Table 9 summarizes the relevant values needed for the analysis. Airship # 2 has a maximum velocity half that of airship #1, but the overall size of the airship is reduced considerably (Table 8). A visual representation of the size of AS #2 compared to the ZPG-3W and HAA is shown in Figure 26. Comparing the design to the HAA reveals that AS #2's length is 121 meters longer than the HAA and 355,788 m^3 larger in gas volume. This is still a significant size increase from the HAA, but the AS #2 design is much more achievable than the AS #1 design. Airships #1 and #2 are shown side by side in Figure 27 and the size difference is clearly apparent.

Table 9: Design Values for Airship #2

Cd =	0.028	
Fine ratio =	4.62	
Airship Vol=	5.03E+05	m^3
V prop=	11	m/s
Front Area=	2755.15	m^2
Diameter=	59.23	m
Length=	273.63	m
Ship Mass	19377	kg
Max Engine Power=	3246	W
Propeller Area=	42.4116	m^2

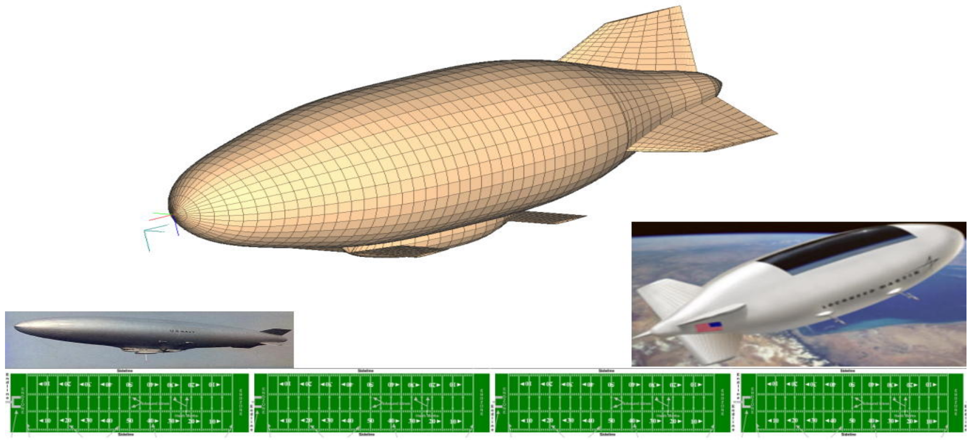

Figure 26: Airship #2 Size Compared to HAA and ZPG-3W

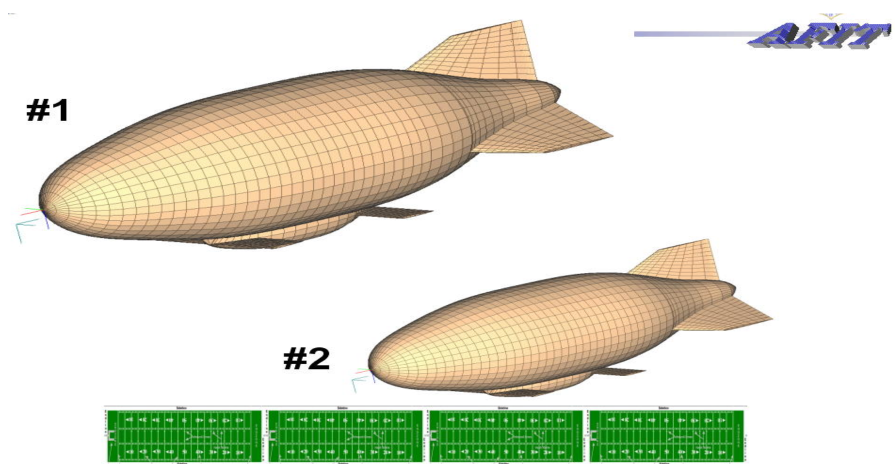

Figure 27: Airship #1 compared to Airship #2

AS #2's size is much more desirable from an engineering point of view, but the benefits of the smaller size are negated by its low maximum velocity (11 m/s). This critical performance limitation will significantly affect the airship's ability to counter upper atmospheric winds while attempting to station keep over the target area.

3.4 Weather Models

For understandable reasons, upper atmospheric climatology is not as readily available as surface climatology. Surface weather affects our day-to-day lives, and in-turn much more time has been spent on modeling the climatology near the earth's surface. Upper atmospheric conditions are only relevant to high altitude aircraft and spacecraft. Consequently the majority of information on upper atmospheric conditions is available through the military or the National Aeronautics and Space Administration.

For the station-keeping analysis, two sources of weather data were required. The first data set needed to include annual mean and standard deviation wind velocities at the operational altitude and over the specified target. These values were used for the initial sizing of the two airships. The second data source must include day-to-day wind magnitudes and directions at the location of the airship in order to model the vehicle's movements and station-keeping capacity.

3.4.1 Site Specific Upper Air Climatology (SSUAC)

The Site Specific Upper Air Climatology program is a product of the Air Force's Combat Climatology Center [18]. The AFCCC is an abundant source of various climatological data for multiple altitudes and at many locations around the world. The SSUAC program displays several climatological variables including: Skew-Ts; percent frequency of occurrence of wind directions for most mandatory levels; maximum and minimum values for temperature, dewpoint, relative and absolute humidity, density and wind speeds for several levels; and percentile graphs and mean deviation displays [18]. As mentioned in the Airship Design Criteria section of this chapter, the mean and standard deviation wind velocities that were used to size AS #1 and AS #2 were obtained using this program (Figure 24).

The SSUAC program can be downloaded from the AFCCC website with the proper security clearances. The AFCCC is a military entity and full access to the website can only be achieved with a ".mil" proxy or by obtaining a user name and password from the center's customer service agents. Once access is granted, the program can be downloaded by selecting the software tab on the site's homepage, followed by selecting the SSUAC program from the software download webpage. Instructions for downloading AFCCC programs are also available on the site. A data file for the particular location of interest must also be obtained from this webpage in order for the program to run properly. The AFCCC has SSUAC data files for 170 locations around the world, including Baghdad. The desired data file is downloaded and input into the SSUAC program to generate the various climatological plots for the given location (Figure 28). The program offers plots for temperature, dewpoint, humidity, density, and most importantly wind speed. These data values can be plotted for a given month or for the annual average.

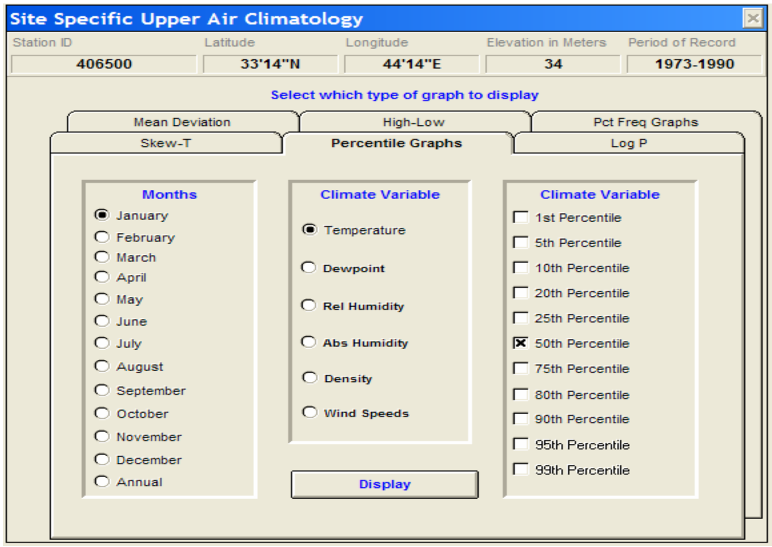

Figure 28: Site Specific Upper Air Climatology Data Selections for Baghdad [18]

The data obtained from the SSUAC program used in the station-keeping analysis was the annual mean and standard deviation wind velocity for Baghdad (Figure 24). As mentioned previously, these values were used to size the airships. It is important to note that the Baghdad climate data for the SSUAC program was acquired between 1973 and 1990, which is listed in the above figure in the period of record block. It is assumed that the wind data recorded over these 17 years is a good representation of the mean and standard deviation annual wind velocities. Another limitation with the SSUAC is that the wind velocity data was measured only up to a pressure height of 50 mb, and the equivalent pressure height for the operational altitude of 24 km is approximately 30 mb. With no other source of climatology data available at the defined target, the 50 mb wind values were assumed approximately equal to the 30 mb wind values. This is not a bad assumption because the 50 mb height is relatively close to the operational altitude of 24 km in the summer, and within a kilometer or two during the winter.

3.4.2 1.0 Degree Navy Operational Global Atmospheric Prediction System (NOGAPS)

The second weather model used for the station-keeping analysis was the 1.0 Degree Navy Operational Global Atmospheric Prediction System or NOGAPS. NOGAPS is a product of the United States Navy's Fleet Numerical METOC Detachment based in Asheville, North Carolina [16]. The Fleet Numerical Meteorology and Oceanography Detachment is a Department of Navy office within the Department of Defense that handles Navy, Marine Corps and other DOD agency climatological requirements [16]. NOGAPS is one of the only weather modeling systems that can calculate data for altitudes as high as the 10 mb level, and generate daily values at 0000 hours and 1200 hours Zulu time from 01/11/1997 to the present day and at any location on the earth. This model is ideal for examining the station-keeping ability of the two airships since NOGAPS can generate wind directions, magnitudes, and temperatures at the 30 mb pressure level and at the designated target for the duration of the mission.

The NOGAPS code is classified but basic information about the program is available. Primitive equations with hydrostatic approximations are used to calculate the data. The independent variables are: latitude, longitude, hybrid pressure coordinate, and sigma levels. Dependent variables calculated include: vorticity, divergence, virtual potential temperature, specific humidity, surface pressure, ground temperature, ground wetness and cloud fraction [16]. These values are computed over an integration domain of the entire globe and from the surface to the 1 mb pressure height.

Similar to the AFCCC, the Navy's Fleet Numerical METOC Detachment website can only be accessed with the proper security clearances. Access is gained if the user has a .mil proxy or by obtaining a user name and password from the customer service agents. The NOGAPS program is located under the atmospheric models section in the products division of the detachment's homepage. After selecting the 1.0-degree resolution NOGAPS program, a user input window is displayed in which the desired location, date(s), time(s), pressure level, and outputs are chosen (Figure 29).

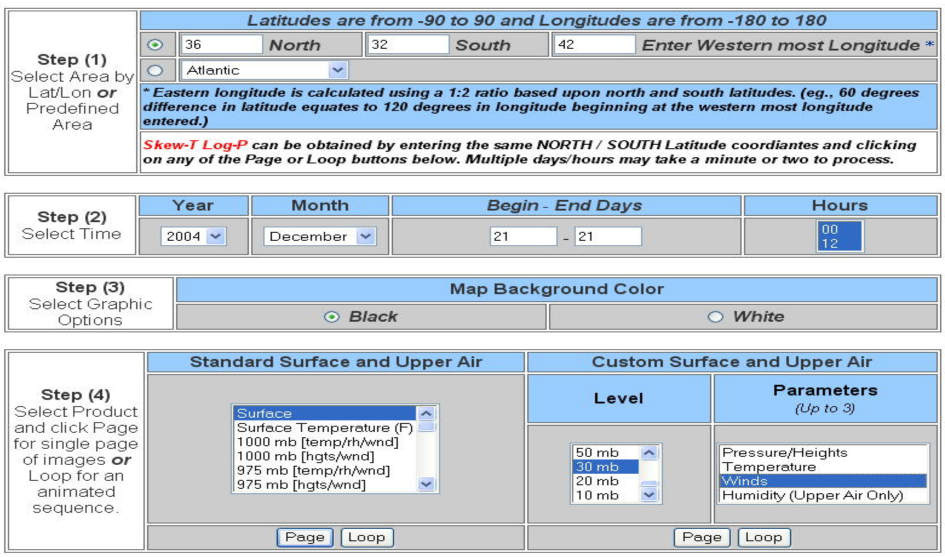

Figure 29: NOGAPS User Input Window [16]

The data required for the station-keeping analysis was the temperature, wind direction, and wind magnitude at the 24 km operational altitude. The pressure height corresponding to this altitude is approximately 30 mb and this level was used to generate the data. As the airship was displaced from the target location, the NOGAPS data was modified by altering the latitude and longitude inputs in the user window to correspond with the airship's movements. The desired date, latitude, and longitude were input into the program, and a plot of the location presented the wind results generated by NOGAPS with wind barbs defining the wind direction and speed. Figure 30 shows an example of the data results for Baghdad (33.3 degrees north latitude and 44.45 degrees east longitude) on the first day of the mission (21 DEC 2004) at the 30 mb pressure height.

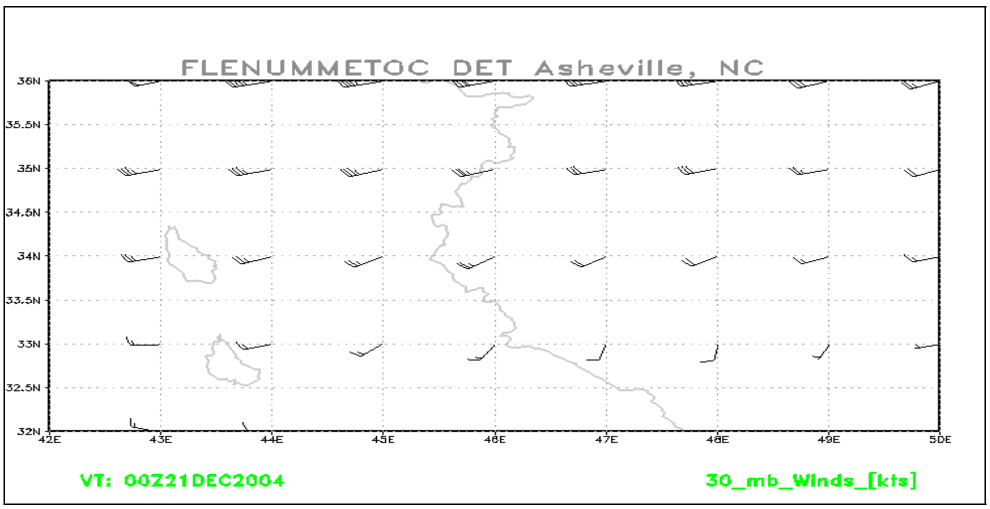

Figure 30: NOGAPS Results Plot Over Baghdad [16]

These plots were generated at 0000 hours and 1200 hours for each day of the yearlong mission. Examining the orientation of the wind barb vector and estimating the angle to the nearest five degrees yielded the wind direction. The angular axis was defined to be zero degrees directly east, 90 degrees directly north, 180 degrees directly west, and 270 degrees directly south. The wind magnitude is defined by the number of barbs on the tail of the wind vector: One barb represents 10 knots, a half a barb represents 5 knots, and a triangle represents 50 knots. A summation is taken of all the barbs on the velocity vector, and the total equals the wind speed in knots at the location of the wind barb (Figure 31).

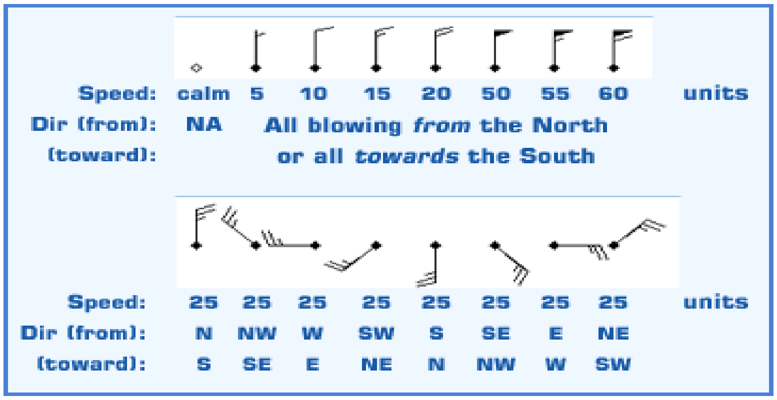

Figure 31: Wind Barb Descriptions and Examples [19]

The NOGAPS program was the best-suited data source for modeling the airships' movements because of its unique ability to generate wind values anywhere on the planet and for each day of the defined mission. It should be noted that exact wind values at a particular latitude and longitude must be interpreted from the result plots generated by the program. Since the station-keeping analysis is a broad examination of the effects of upper atmospheric winds on a high altitude airship, it is assumed that the estimated wind values are adequate enough to predict the movements of the airship during the yearlong mission. The wind data used in the station-keeping analysis was generated manually from the NOGAPS program and it would have been beneficial if the database could be queried automatically, but no such capability was found.

3.5 Station-keeping Mission Analysis

The overarching goal in the station-keeping analysis is to model the baseline airships' movements with respect to the upper atmospheric winds. The total percent power used by the airship during these movements was also calculated and it is proportional to the wind force acting on the vehicle. This calculated percentage was used to identify low and high wind periods during the yearlong mission. Airship #1 and Airship #2 were located over the target at an operational altitude of 24 km at the beginning of each season of the yearlong mission. The airships have an operational radius of 552 km, which was explained previously in the ground footprint section, and a maximum speed of 19.7 m/s for AS #1 and 11 m/s for AS #2. The wind and temperature data was generated using the NOGAPS program, and these values were used to model the airships movements. Data was obtained for each day of the designated season at 0000 hours and 1200 hours at the 30 mb pressure height and at the determined location of the airship. It was assumed that the data remained constant over the course of the 12-hour time period.

Temperature was the first value extracted from NOGAPS. With the temperature at the airships' location, the defined pressure of 30 mb, and the ideal gas constant, the density of the air can be calculated using the ideal gas law:

$$\rho = \frac{\Pr essure}{R * Temp} \tag{10}$$

Wind direction and magnitude values were then taken from the wind barbs generated by the NOGAPS result plots for the given time, day, and location. It is important to remember that the wind magnitude defined by the wind barbs is in knots and the airships were designed with maximum speeds given in meters per second, therefore a unit conversion from knots to meters per second is required. The wind magnitude will determine if the airship is capable of staying on station, if it will be blown off target, or if already displaced can the vehicle maneuver back toward the operational area. These three situations were defined by the abbreviations: **Loiter** or **Stay** in position, **Drift** away from target, and **Gain** distance back toward target, respectively. To determine which of the three situations is occurring; the wind magnitude is subtracted from the constant maximum airship speed to determine the difference. If the airship is located at the target and the wind magnitude is less than the vehicles maximum speed, the airship will maintain position and loiter. If the wind magnitude is greater than the ship's velocity, the airship will drift off target at a velocity equal to the difference between the airships maximum speed and the wind speed in the direction of the overpowering wind. Finally, if the airship is already displaced from the target but the vehicles speed is greater than the wind speed, the airship will gain distance back towards the target.

When the airship is moving, as in the **Drift** or **Gain** situations, the total displacement is calculated by using the speed difference between the wind and the airship during the 12-hour time interval:

$$\text{Total Displacement} = (V_{airship} - V_{wind}) * (12 \text{ hours}) \tag{11}$$

It is assumed that the airship will be at max power when resisting displacement by the wind and when propagating back toward the target. The direction of the displacement during a **Drift** situation is determined by the bearing of the wind. Trigonometric relationships are used to divide the displacement into an X and Y coordinate system with positive X defined as east, positive Y defined as north, and zero defined at the target location (this sign convention is used for all calculations):

$$X \text{ disp.} = \text{Total disp.} * \cos(\text{Wind bearing}) \qquad (12)$$

$$Y \text{ disp.} = \text{Total disp.} * \sin(\text{Wind bearing}) \qquad (13)$$

These X and Y components are used to determine the airships position after the 12-hour time step. The displacement after the 12 hours is added, or subtracted if the vehicle is gaining, to the airship's starting position before the time step and the final value is the airship's total X and Y displacement from the target. The radial distance is calculated using the Pythagorean theorem and if this distance is within the 552 km operational radius the airship is "on-station," and "off-station" when outside the 552 km radius.

In terms of latitude and longitude, the airship's location is calculated by converting the total X displacement in degrees of longitude, and converting the total Y displacement in degrees of latitude. These values are then added to the original position at the target (33.3 degrees north and 44.45 degrees east) to yield the vehicle's location in latitude and longitude, which is used to determine the next inputted position into the NOGAPS program. One degree of latitude approximately equals 111 km and remains relatively constant throughout the globe, but due to the spherical shape of the earth the value of one degree of longitude is highly dependent on the location (Table 10). As the airship propagates north or south, adjustments must be made to the longitude conversion that coincides with Table 10.

Table 10: Latitude and Longitude Conversions to Kilometers [20]

Length of 1 degree Latitude		
Latitude (deg.)	Miles	Kilometers
0	68.71	110.57
10	68.73	110.61
20	68.79	110.70
30	68.88	110.85
40	68.99	111.04
50	69.12	111.23
60	69.23	111.41
70	69.32	111.56
80	69.38	111.66
90	69.40	111.69

Length of 1 degree Longitude		
Latitude (deg.)	Miles	Kilometers
0	69.17	111.32
10	68.13	109.64
20	65.03	104.65
30	59.95	96.49
40	53.06	85.39
50	44.55	71.70
60	34.67	55.80
70	23.73	38.19
80	12.05	19.39
90	0.00	0.00

The direction of airship movement during a **Gain** situation is determined by the bearing toward the target. Computing the tangent angle with respect to the previous time step's final X and Y displacement components and adding 180 degrees to orient the angle directly toward the target calculates the crafts bearing:

$$Bearing = 180^\circ + \arctan\left(\frac{Y\_disp.}{X\_disp.}\right) \quad (14)$$

The airship travels along this vector at a speed equal to the difference between the wind velocity and the max airship velocity. If the possible **Gain** distance for the time interval is greater than the displacement distance from the target, the airship will throttle back and use a lower speed that will exactly position the vehicle over the target at the end of the 12-hour time step.

Along with calculating the airship's displacement and position, the power used by the propulsion system during each time interval was computed. The maximum power available to the propulsion system is a constant design parameter for each airship: 35,412 Watts for AS #1 and 3,246 Watts for AS #2. These values define the power required to propel the airship at the designated maximum velocity, which was chosen during the initial design process, and the maximum power available from the vehicles solar panels or batteries at any given time. The computed power utilized during each time interval was divided by the maximum power defined above to give the percent power used at each data point. The percent power is proportional to the wind force acting on the airship; therefore it represents the magnitude of the wind during each time step.

The power used by the airship is dependent on the situation. Obviously, if the vehicle is drifting away from the target, or gaining distance but not reaching the target after 12 hours, the propulsion system is using 100% of its power to propel the craft. During a loiter situation, full power may not be required to hold the airship in place if the wind speed is lower than the maximum vehicle speed. In this situation the power used is calculated by first computing the drag on the airship [21]:

$$\text{Drag} = \tfrac{1}{2}\, C_d\, \rho\, F_A\, V_{wind}^2 \qquad (15)$$

Where:

C_d = Drag Coefficient (0.028)

ρ = Density

F_A = Airship Frontal Area

V_{wind} = Velocity of the wind

The drag calculated is the required thrust the propulsion system must produce in order to loiter in position. With the thrust calculated, the next step in calculating the power required for a propeller propulsion system is to find the induced air velocity generated by the propeller blade. The induced velocity is a function of thrust, propeller diameter, density, and velocity of incoming flow [22]:

$$\Delta \upsilon = -\upsilon + \sqrt{\upsilon^2 + \frac{2T}{\rho A_P}} \qquad (16)$$

Where:

$\Delta \upsilon$ = Induced Velocity

υ = Velocity of incoming flow

T = Thrust

ρ = Density

A_P = Area of Propeller

The power required by the propulsion system to counteract a given wind velocity can now be calculated with the known values of wind speed, propeller diameter, and airship frontal area combined with the computed values of density, thrust, and induced velocity [23]:

$$P_{Engine} = T\left(\upsilon + \frac{\Delta\upsilon}{2}\right) \tag{17}$$

It should be noted that this station-keeping analysis is based on the optimum performance of the airship; therefore it is assumed that the propeller operates at 100% efficiency for all situations. The previous method is also used to calculate the power required during a **Gain** situation where the airship does not need full power to reach the target after the 12-hour interval, with one exception. Unlike the loiter situation, the velocity of the incoming flow is not the wind velocity, but the apparent velocity with respect to the wind and the calculated airship velocity needed to reach the target. Besides this variation in the incoming flow velocity, the procedure remains the same. By following these steps, the power required for each situation can be calculated along with the percent of total power used.

This algorithm was applied to every data point in the yearlong mission analysis (0000 hrs and 1200 hrs for each day) for both AS #1 and AS #2 to calculate the movements of the airships and the power used by the propulsion system with respect to the varying upper atmospheric wind conditions at the 30 mb pressure height. The airship's displacement was superimposed on scaled maps of the earth's surface to examine its movements and station-keeping abilities. Line graphs were produced using the airships radial distance from the target to observe the total time the vehicle stayed within the 552 km operational radius. Percent total power used during each time interval was also generated to study the variations in the power required by the propulsion system.

3.6 Chapter Summary

This chapter discussed the development of two baseline airship designs that were used in the station-keeping analysis. Both airships were subjected to the same station-keeping mission over the designated target, Baghdad. A line of sight operational radius (552 km) was calculated for both airships at 24 km along with dimensional values of frontal area, length, and diameter. AS #1 and AS #2 were compared to the HAA and ZPG-3W with respect to their length and gas volumes to help visualize the magnitude of the baseline airship designs. The weather models used for the sizing and station-keeping analysis, AFCCC and NOGAPS, were also discussed in detail. This data was used to model the airships movements and power required with respect to the varying wind conditions during the yearlong mission. The performance of both airships will be analyzed by comparing the time spent within the operational radius, keeping in mind the large variation in size between AS #1 and AS #2.

4 Analysis and Results

4.1 Chapter Overview

A yearlong station-keeping analysis was conducted for both the Airship #1 design and the Airship #2 design. Each vehicle used the same mission requirements and duration at a set pressure height of 30 mb. Wind data was obtained from the NOGAPS prediction system and used to model the movements of both airships during the analysis. Total percent powered used by the vehicles propulsion system was also calculated. The time spent outside the 552 km operational radius over the yearlong mission was determined for both airships and used to determine the station-keeping ability of AS #1 and AS #2. The results showed that the larger AS #1 design, with a higher maximum velocity, performed significantly better than the smaller and slower AS #2 design.

4.2 Airship #1 Station-keeping Mission Results

Airship #1 is by far the larger of the two blimps with respect to its length and gas volume. However, the drawbacks in its magnitude are made up for in the airships maximum speed of 19.7 m/s. This velocity is nearly double the maximum speed of the smaller AS #2. The analysis of AS #1's station-keeping abilities reflected the advantages of the vehicles higher top speed.

The airship initiated its mission at the target, Baghdad, and at a pressure height of 30 mb at the beginning of each of the four seasons in the yearlong mission. Wind data was extracted from the NOGAPS prediction program at each time and date over the defined 2005 mission. The airships displacement in kilometers was plotted over a map of the appropriate area given the maximum displacement during each season. The map includes major national borders, large bodies of water, and a highlighted red area corresponding to the 552 km operational radius. Total radial displacement with respect to the seasonal dates was also plotted on a line graph with the defined 552 km radius represented as a solid red line. This plot clearly shows the excursions from the operational radius taken by the airship during the season. To complement this line graph, the total percent power used during the same seasonal time steps is represented by a bar graph with a domain of 0% to 100% power used.

4.2.1 Winter

The winter wind magnitudes and direction followed closely to the general assumptions made in the previous chapter. Westerly winds dominated the entire season and the greatest wind speeds were also observed during this period of the yearlong mission. The strong westerly winds overpowered the vehicles propulsion system sending the blimp as far east as Kazakhstan (Figure 32). AS #1 made three departures from the operational area during the following dates: 1/8/2005 to 1/17/2005, 1/23/2005 to 2/4/2005, and 2/27/2005 to 3/2/2005 (Figure 33). The total time spent outside the 552 km radius for the winter was 24 days and the greatest radial displacement was 3,527 km on 1/13/2005. The total percent power used figure shows that max power was required during the drift situations, but there were time intervals of low wind speeds where minimal power was required to loiter the airship over the target (Figure 34).

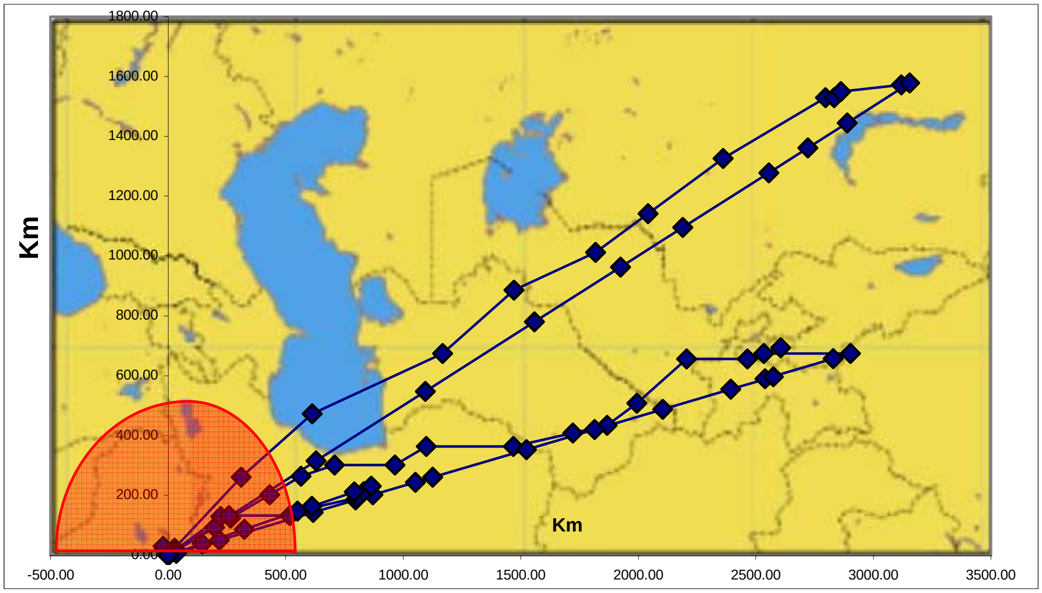

Figure 32: AS #1 Winter Displacement

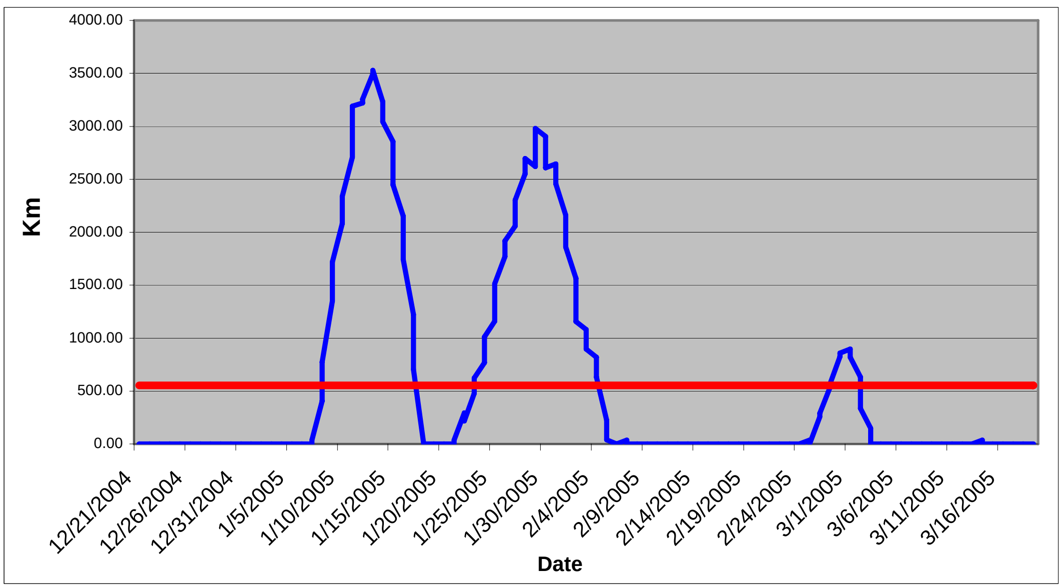

Figure 33: AS #1 Winter Total Distance from Target

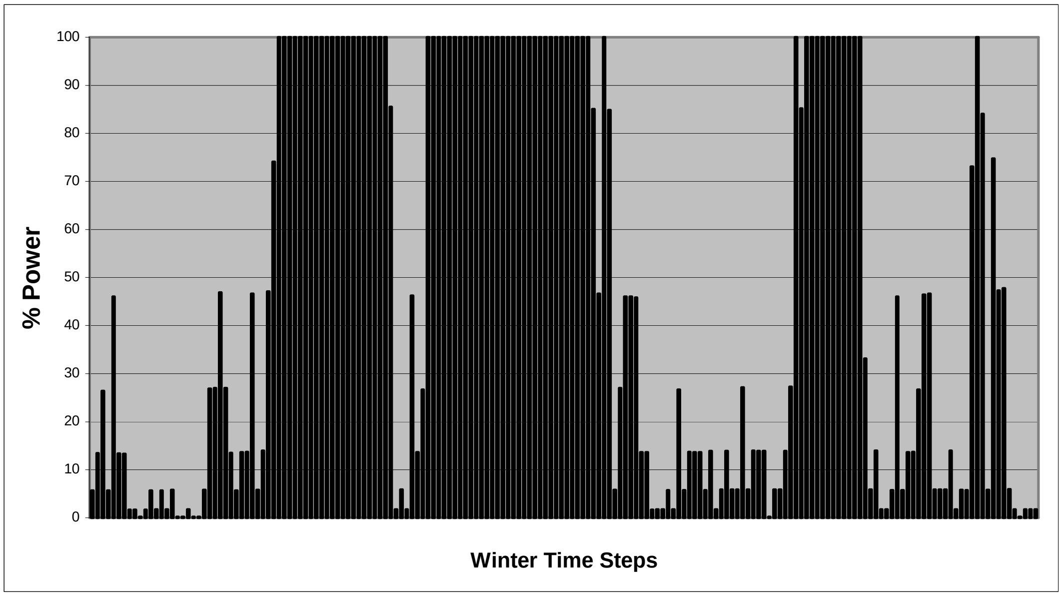

Figure 34: AS #1 Winter Total Percent Power Used

Though the airship was displaced from the target during the winter season, the propulsion system was able to maneuver the vehicle back to the target after each excursion from the operational area.

4.2.2 Spring

The spring period of the station-keeping mission generated better results than the winter, with respect to time spent outside the operational area. Strong Westerly winds were again observed at the beginning of the season and are thought to be residual winter wind conditions overlapping the spring. These winds sent AS #1 eastward to Kazakhstan, similar to the winter displacements (Figure 35). Unlike the winter analysis AS #1 only had one excursion from the operational area from 3/27/2005 to 4/6/2005 for a total of 10 days without coverage (Figure 36). The vehicle did have a larger maximum radial distance from the target, 3,896 km, but the propulsion plant was able to return the vehicle to the target relatively quickly once the wind magnitude decreased as the season progressed. Maximum power was only required during the displacement and the power used to loiter after the vehicle returned to its station reached a maximum of about 45% during only one time step (Figure 37).

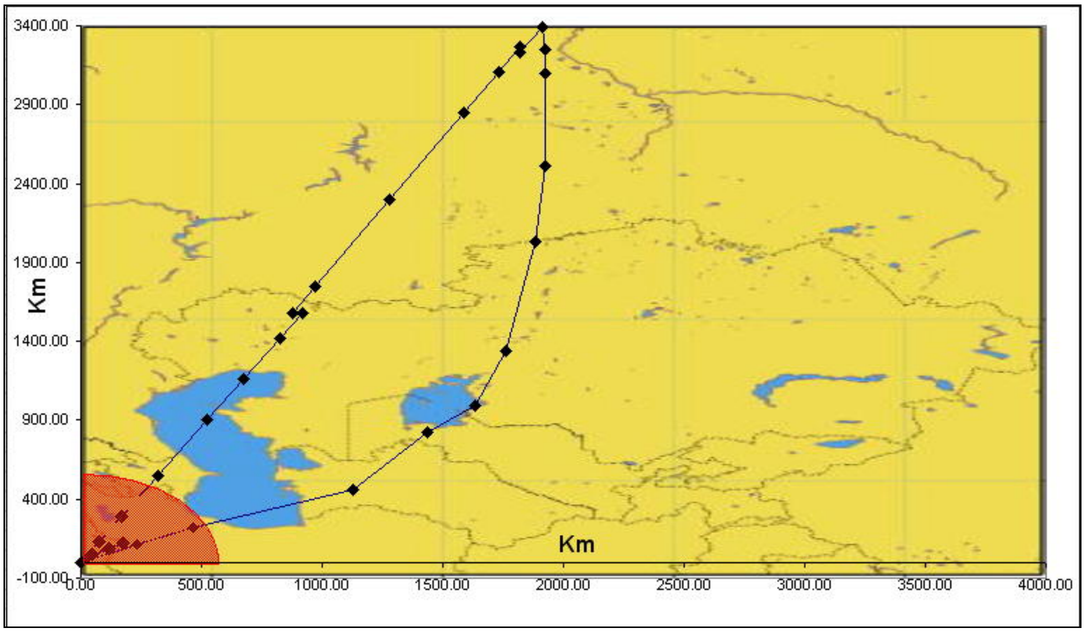

Figure 35: AS #1 Spring Displacement

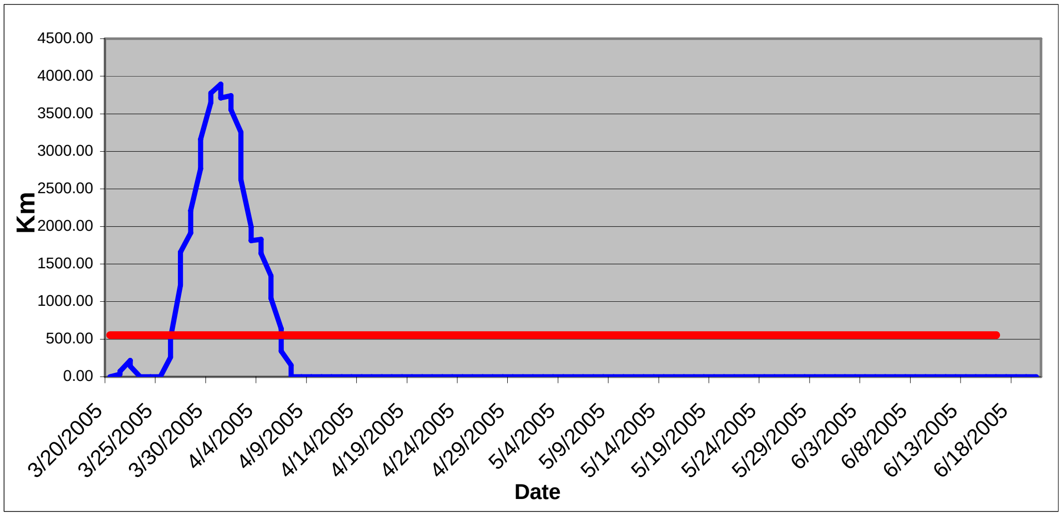

Figure 36: AS #1 Spring Total Distance from Target

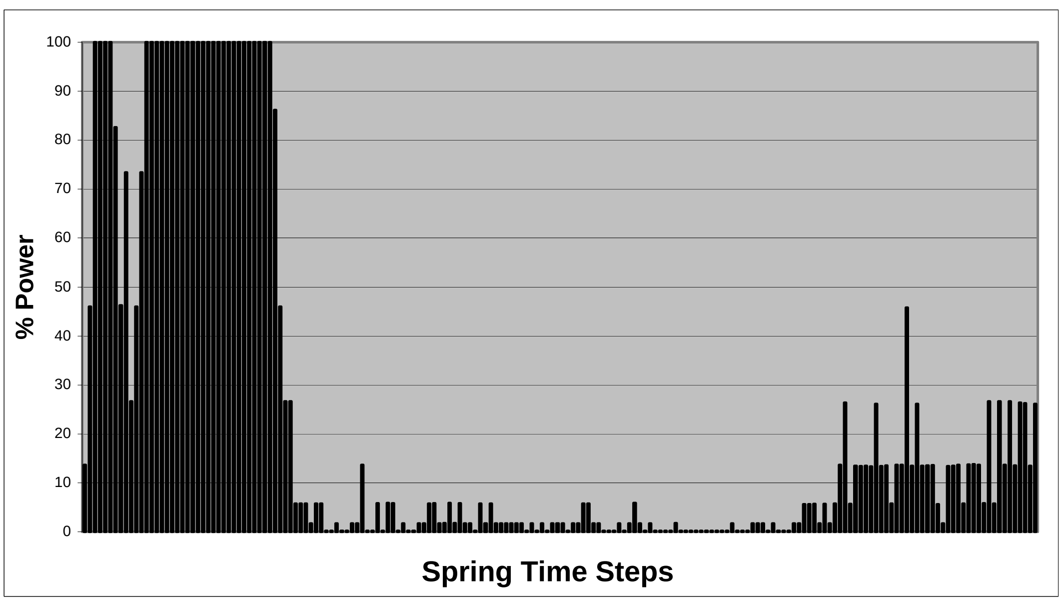

Figure 37: AS #1 Spring Total Percent Power Used

AS #1 performed well in the spring where lower winds allowed for undemanding station-keeping during the majority of the season. Wind velocities were predicted to be much lower in the spring and fall compared to the winter and summer because of smaller temperature gradients during this transitional period between the winter and summer maximums. This is reflected by the small amount of total power used in the latter two thirds of the season.

4.2.3 Summer

The summer season was somewhat uneventful from a station-keeping point of view. One important observation was the change in wind direction from westerly to easterly, which follows the predicted pattern discussed in the previous chapter. Therefore, the only displacements of the airship were to the west (Figure 38). These movements were of negligible concern because AS #1 remained inside the operational radius for the entire duration of the season and was only displaced a maximum distance of 180 km, well within the 552 km radius (Figure 39). However, the total percent power required by the airships propulsion system was significantly higher than the latter two thirds of the spring analysis (Figure 40).

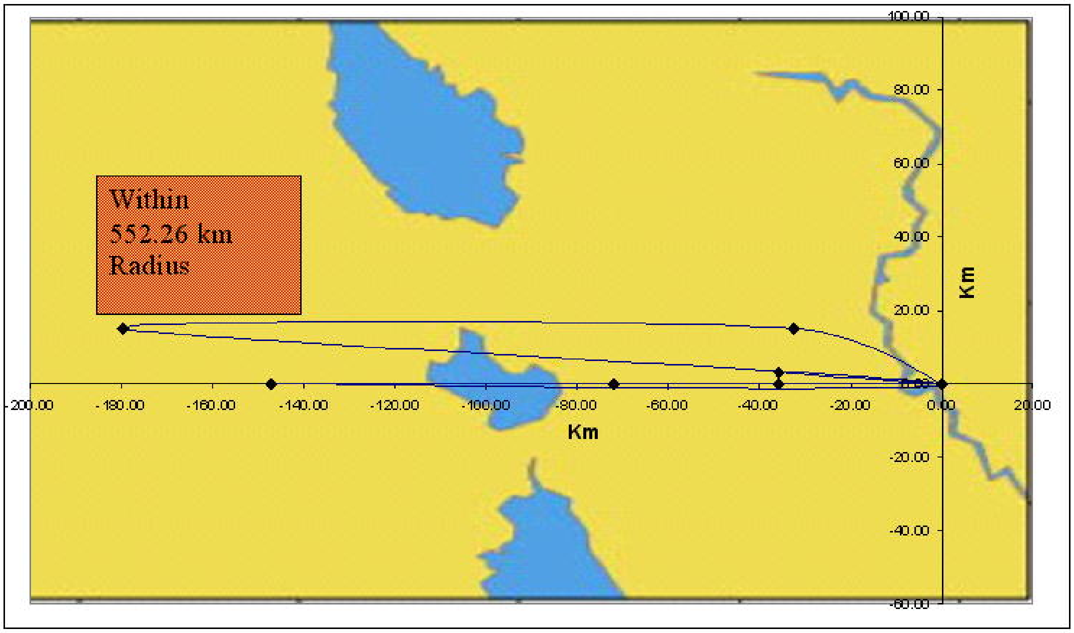

Figure 38: AS #1 Summer Displacement

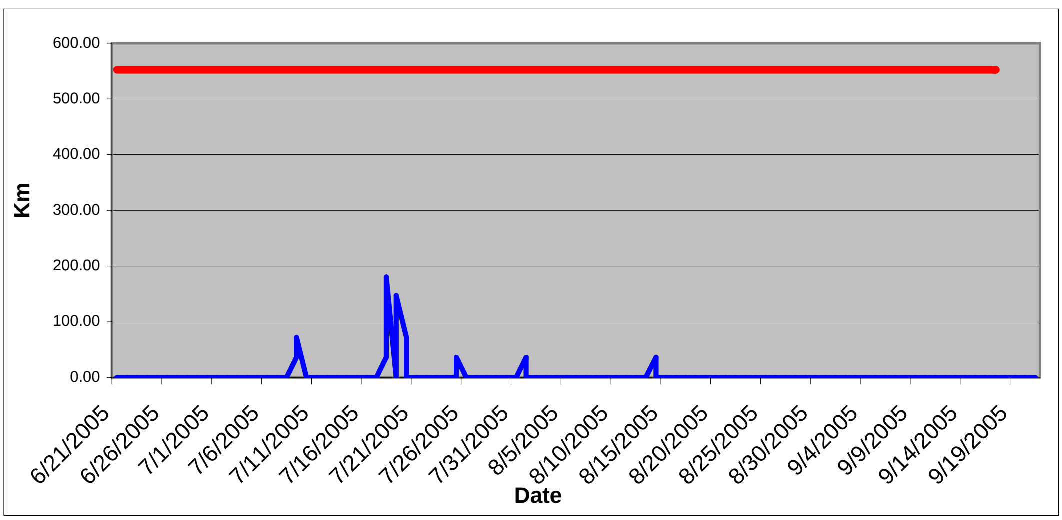

Figure 39: AS #1 Summer Total Distance from Target

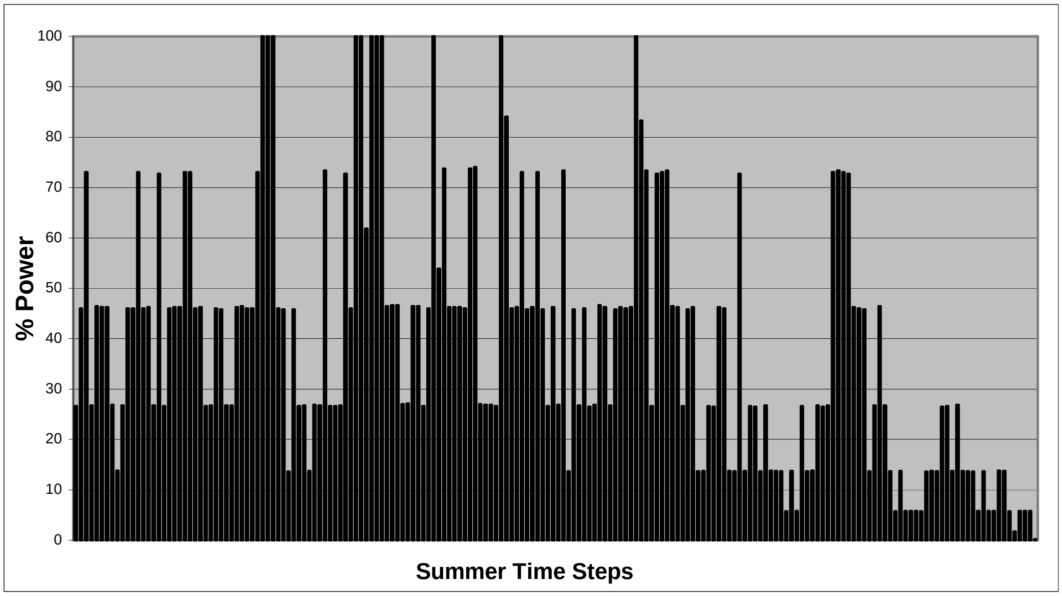

Figure 40: AS #1 Summer Total Percent Power Used

The increase in power used by the airship represents the higher wind velocities predicted during the summer season. Though the airships propulsion system was powerful enough to counter these upper atmospheric winds, a vehicle with a lower maximum speed may not fair as well during the summer.

4.2.4 Fall

The fall analysis shared similar characteristics with the spring mission results but the higher winds were observed in the latter part of the season and the lower winds were observed in the first part of the fall. The only displacement from the operational area occurred at the end of the season when winter westerly winds began to build in magnitude. These west winds displaced the airship to the east across northern India and into western China (Figure 41). AS #1 experienced only one departure from the operational area: 12/9/2005 to the end of the seasonal mission on 12/20/2005 for a total of 11 days outside coverage (Figure 42). This excursion resulted in the largest radial displacement from the target city (4,010 km). The total percent power used by the vehicle was relatively low during the first half of the season and maximized toward the end when the airship was displaced by the pre-winter westerly winds (Figure 43).

Figure 41: AS #1 Fall Displacement

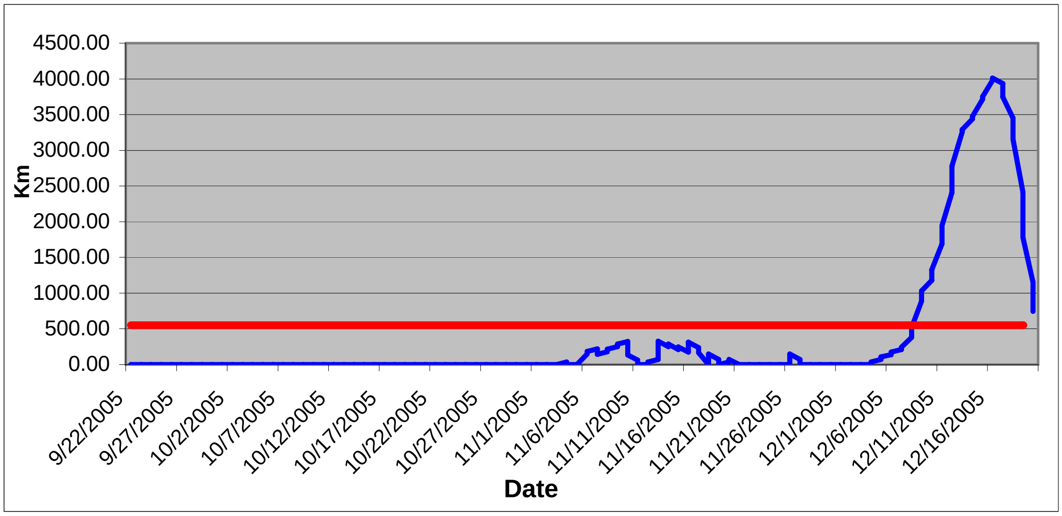

Figure 42: AS #1 Fall Total Distance from Target

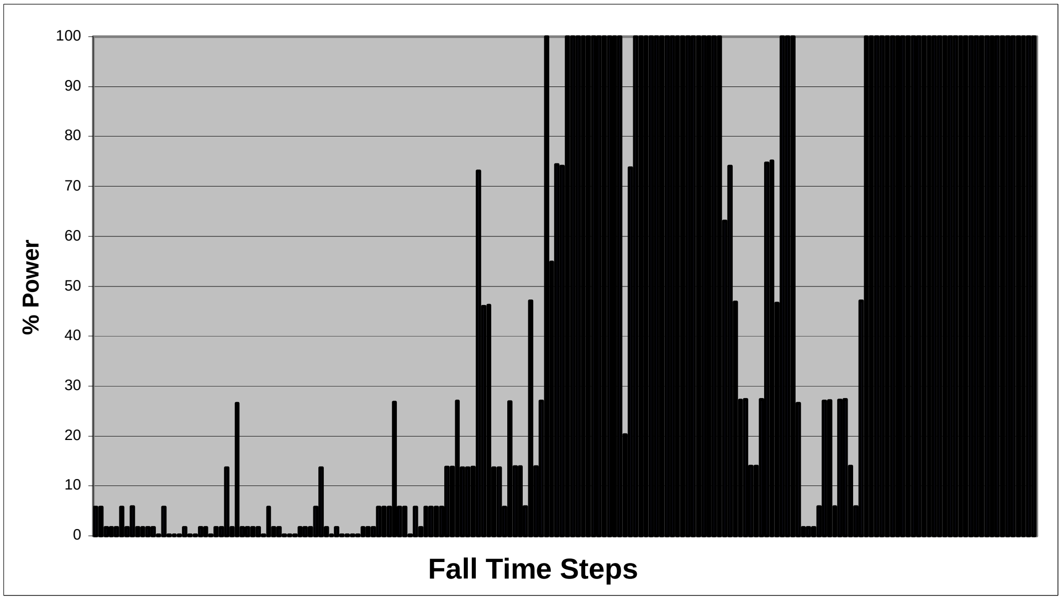

Figure 43: AS #1 Fall Total Percent Power Used

The airship experienced much lower winds in the first part of the fall compared to the summer mission duration. This reflects the minimal temperature gradients discussed in the spring results section. The wind magnitude dramatically increased in the latter part of the season due to the overlapping of the next winter wind conditions. AS #1 was able to propagate back toward the operational area after its initial displacement but the yearlong mission ended before the vehicle reentered the coverage space.

4.2.5 Airship #1 Mission Summary

The total number of days AS #1 spent outside the operational area was 45. Given the yearlong mission, the percentage of time spent on station during the 365 days of operation was 88%. As expected, the stronger winds were observed during the winter and the summer. These winds also overlapped the beginning of the spring and the end of the fall. The airships performance was exceptional in the summer, above average in the spring and fall, and below average in the winter. Without AS #1's high maximum velocity the vehicle would have not performed as well in the summer and might not have been able to station keep in the winter for any duration of the season.

4.3 Airship #2 Station-keeping Mission Results

Airship #2 was subjected to the same station-keeping analysis applied to AS #1. The mission criteria and target remained the same, along with the operational altitude and coverage radius. In this second analysis, the variance comes from the design of AS #2. Airship #2 is much smaller in size compared to AS #1 resulting in a decreased frontal area and less drag acting on the craft. Therefore, a smaller propulsion system is needed to propel the vehicle and the amount of lifting gas required to reach the operational altitude is decreased. However, this smaller size was derived from defining a lower vehicle maximum velocity, 11 m/s. This is approximately half the top speed of AS #1 and could significantly affect the airships station-keeping performance.

4.3.1 Winter

The strong winter westerly winds overwhelmed AS #2's propulsion system. With the airship unable to counter these winds, the vehicle was uncontrollably sent across China, Russia, the Bearing Straight, and into Canada (Figure 44). After only 35 days inside the coverage area, AS #2 was blown out of ranch from 1/7/2005 to 3/19/2005 for a total of 55 days off station (Figure 45). The analysis of this season was halted on 1/23/2005 when the airship reached a displacement of 13,643 km away from the target. Since the vehicle was approximately on the other side of the planet from Baghdad without any possibility of regaining its position over the target, the analysis was abandoned and written off as a mission failure for the rest of the season. Needless to say, the airships propulsion system was operating at 100% for the majority of the winter (Figure 46).

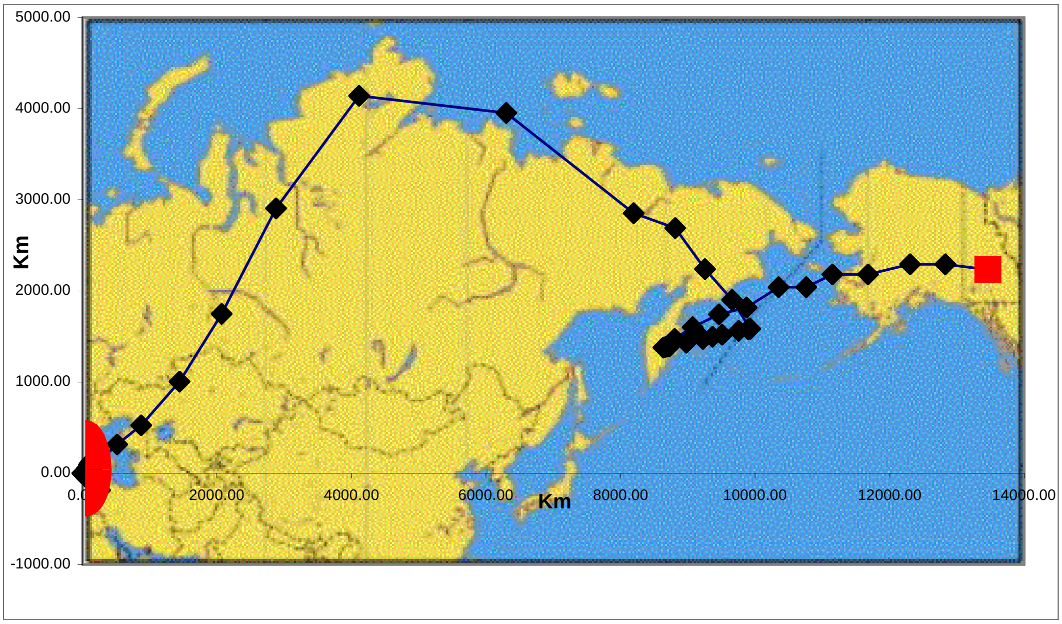

Figure 44: AS #2 Winter Displacement

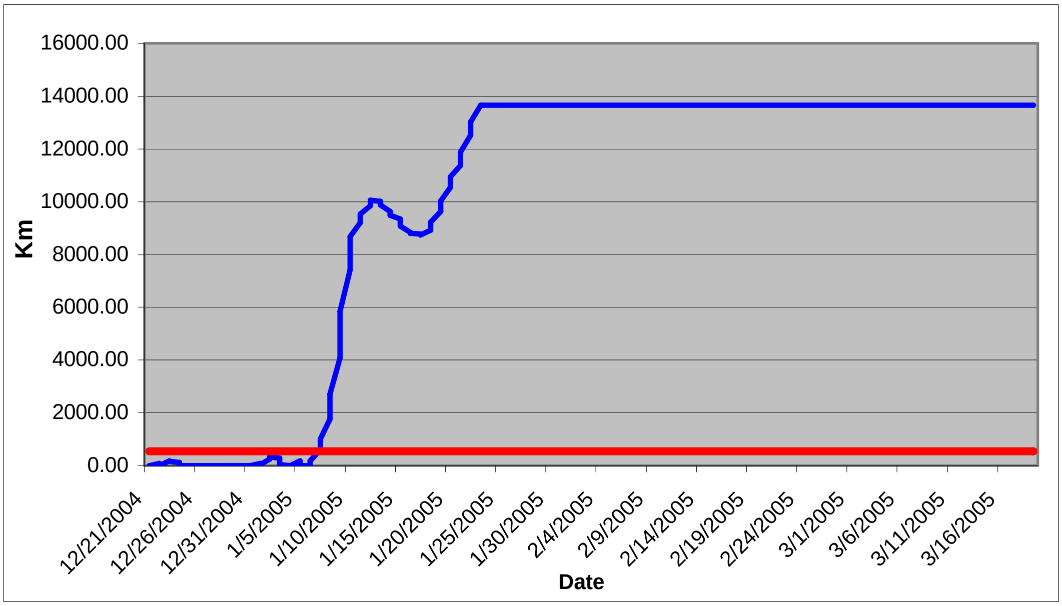

Figure 45: AS #2 Winter Total Distance from Target

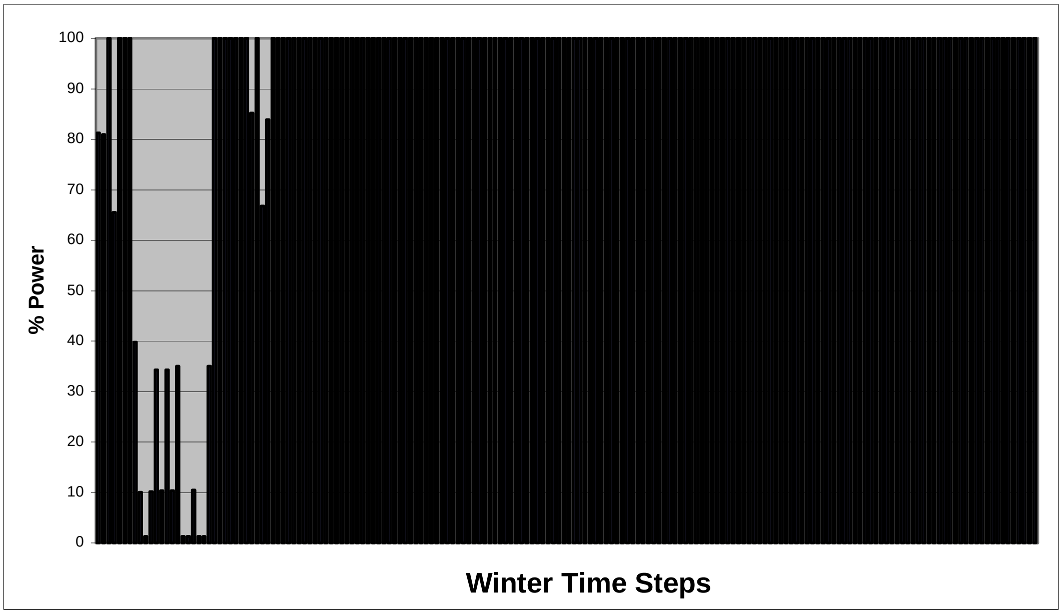

Figure 46: AS #2 Winter Total Percent Power Used

The lower vehicle maximum velocity devastated AS #2's winter station-keeping ability. Besides a brief period of operation in the beginning of the season, the airship was uncontrollably forced out of position by the strong winter winds with no hope of recovery. AS #2 was so greatly displaced that the vehicle analysis was terminated when the airship over flew United States territory (Alaska).

4.3.2 Spring

Airship #2 faired better during the spring portion of the yearlong mission. Much like the wind conditions in the spring for AS #1, there was an overlap of strong westerly winds in the beginning of the season. With a lower max speed AS #2 was unable to counter these winds and regain its station as rapidly as AS #1. Therefore, AS #2 was displaced across Russia before it could **Gain** distance back toward the target (Figure 47).

This was the only departure from the operational radius and it occurred from 3/21/2005 to 4/15/2005 for a total of 25 days of no coverage (Figure 48). The maximum displacement of the vehicle was 4,642 km from Baghdad, which is approximately 700 kilometers farther than AS #1's displacement in the spring. The total percent power used was 100% during the initial excursion, minimal in the middle of the season, and again maximized towards the end of spring (Figure 49).

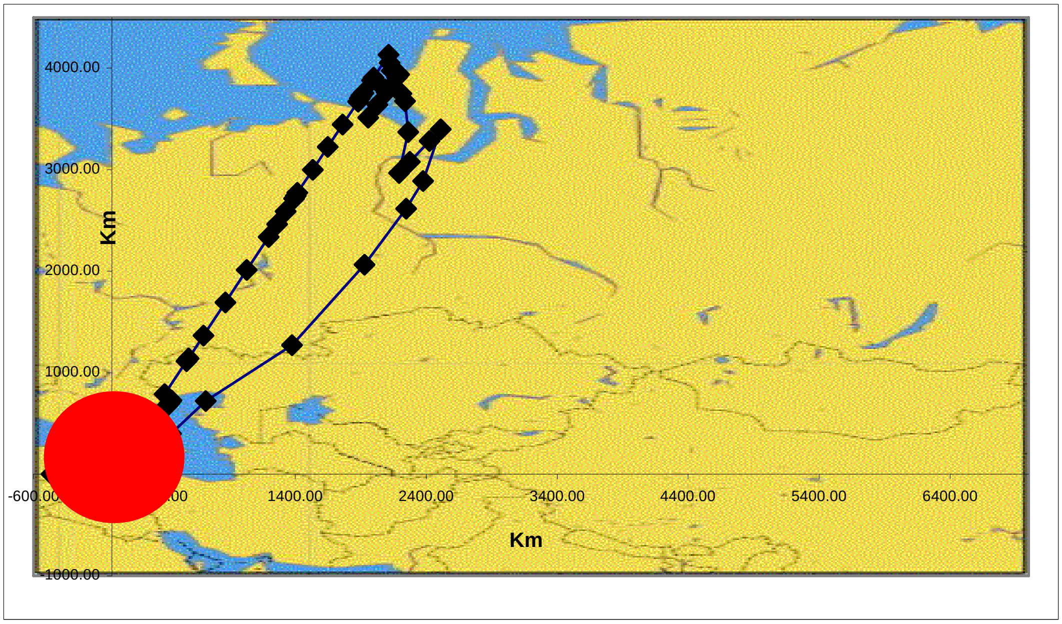

Figure 47: AS #2 Spring Displacement

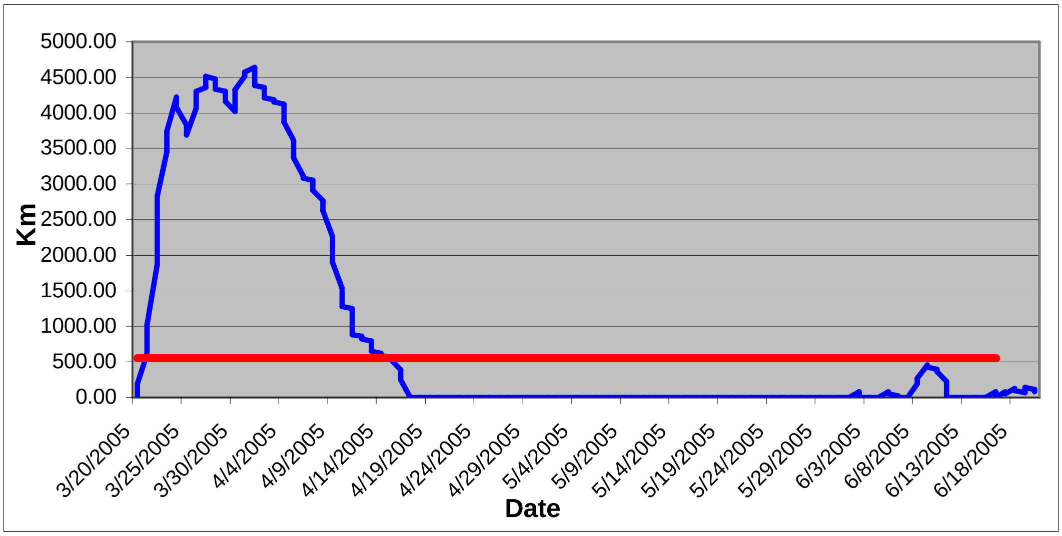

Figure 48: AS #2 Spring Total Distance from Target

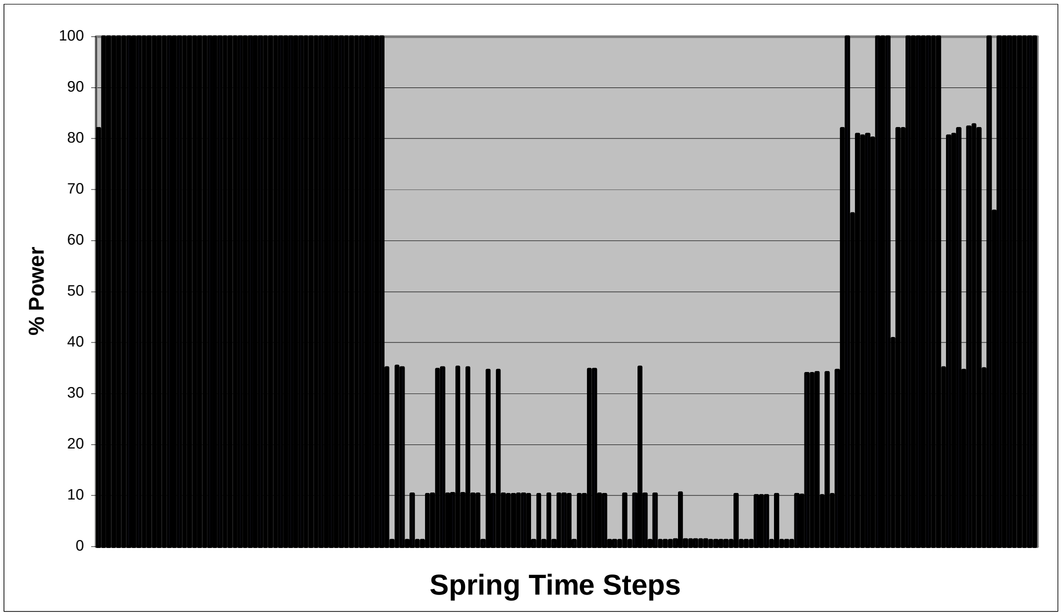

Figure 49: AS #2 Spring Total Percent Power Used

The winter wind overlapping was again observed in this spring analysis by the total percent power used plot, but another overlap of initial summer winds can also be seen. This effect is much more pronounced for AS #2 because the vehicles available power and maximum speed is significantly smaller than AS #1; hence more percent power is required to resist the same wind magnitudes. Though the airships propulsion plant was running at maximum power toward the end of the season, the wind was still unable to displace AS #2 from the operational area.

4.3.3 Summer

Airship #2 was no match for the stronger summer winds. These easterly upper atmospheric gusts displaced the airship immediately and sent AS #2 clear across the Atlantic Ocean (Figure 50). The vehicle was only on station for the first three days of the mission and outside the coverage area from 6/24/2005 to 9/21/2005 for a total of 89 days (Figure 51). This season resulted in the poorest on station performance of the entire analysis. Similar to the AS #2 winter mission, the summer analysis was abandoned on 8/22/2005 when the vehicle was 14,180 km away from the target. At this distance the airship was flying over the United States with no chance of recovery and the mission was considered a complete seasonal failure. Strong easterly winds were incident on the vehicle from the first time step up to the termination of the analysis. Therefore, the crafts propulsion system was running at 100% for this entire season (Figure 52).

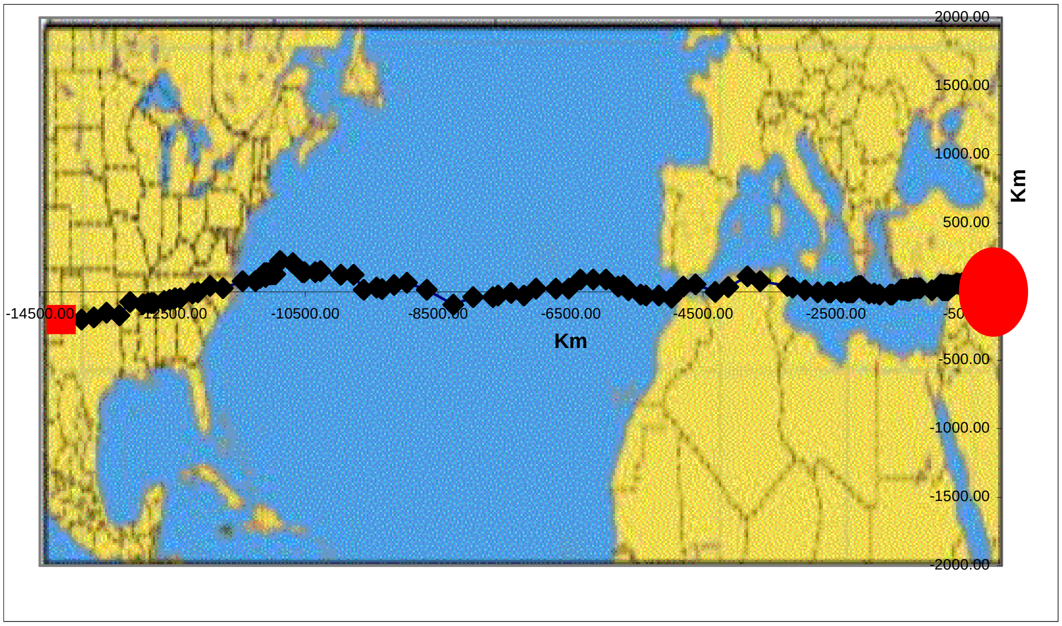

Figure 50: AS #2 Summer Displacement

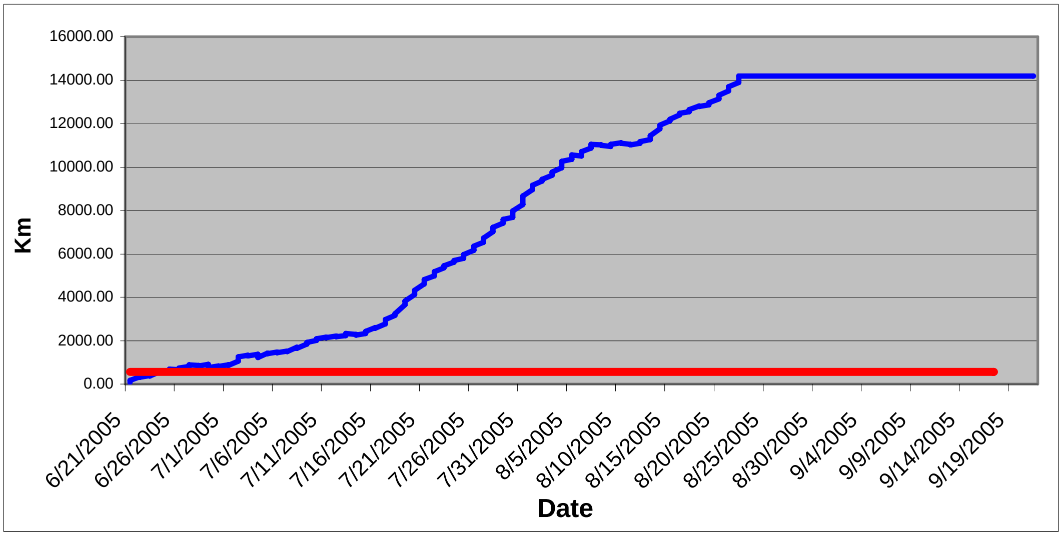

Figure 51: AS #2 Summer Total Distance from Target

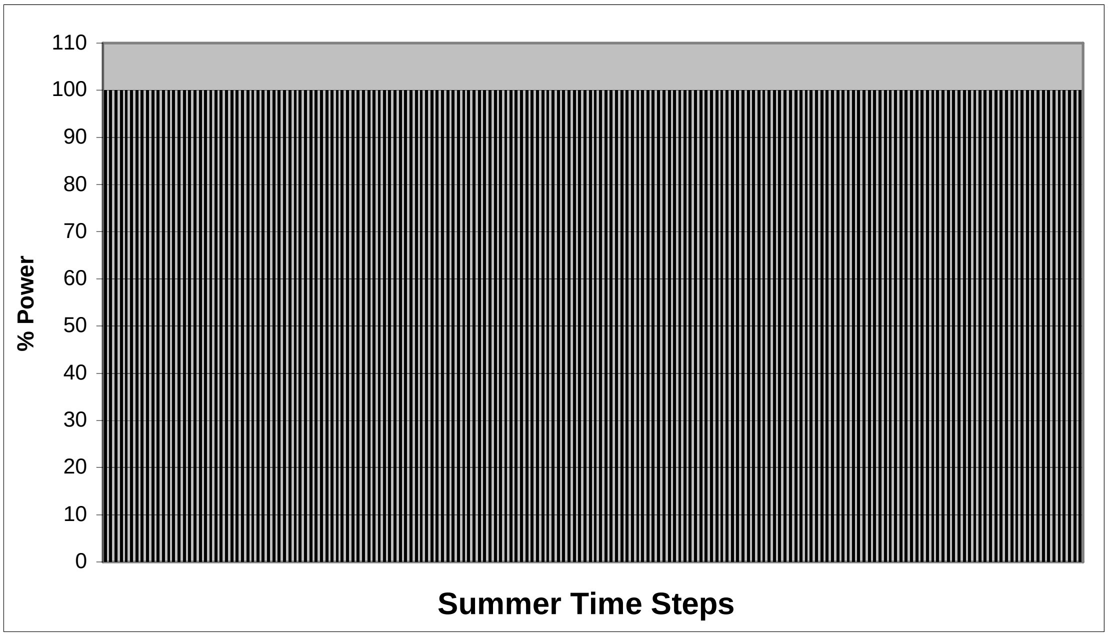

Figure 52: AS #2 Summer Total Percent Power Used

The summer analysis for AS #2 resulted in a complete failure of the station-keeping mission. Strong winds at the 30 mb pressure height quickly displaced the vehicle at the beginning of the analysis. The constant operational altitude of 24 km could have caused this. Airship #2 was not in the lowest wind region of the upper atmosphere at the specified 30 mb level for this particular season. A side investigation of the surrounding pressure heights showed that on the initial dates of this seasonal analysis, weaker winds were found at the 100 mb level.

4.3.4 Fall

The AS #2 fall analysis yielded similar results to the fall AS #1 study. Light winds were observed in the beginning of the season as the weather conditions shifted from the peak summer temperatures to the minimum winter temperatures. Just like the AS #1 analysis, a winter wind overlap was apparent toward the end of the fall. These increased westerly winds displaced the airship as far east as the Pacific Ocean (Figure 53). The vehicle also departed the coverage zone much sooner in the season compared to AS #1 because of its lower maximum velocity. After 37 days of operation, AS #2 remained outside the 552 km mission radius from 10/29/2005 to 12/20/2005 for a total of 52 days (Figure 54). The total percent power used by the propulsion system was maximized in the latter half of the season (Figure 55). 100% power was required in order to resist the building winter westerly winds; however, the airship was still underpowered and displaced a maximum distance of 11,406 km.

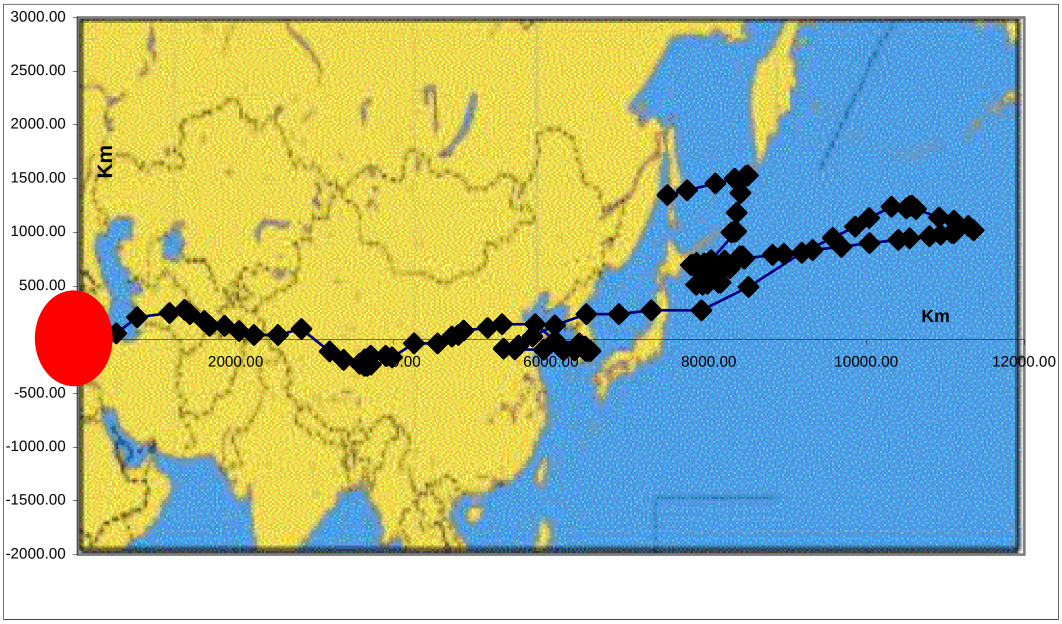

Figure 53: AS #2 Fall Displacement

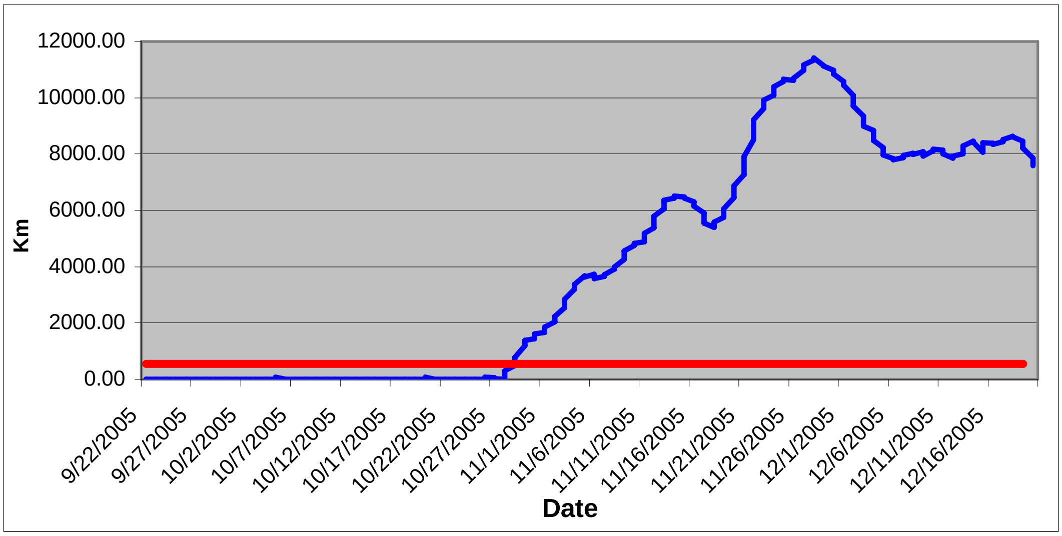

Figure 54: AS #2 Fall Total Distance from Target

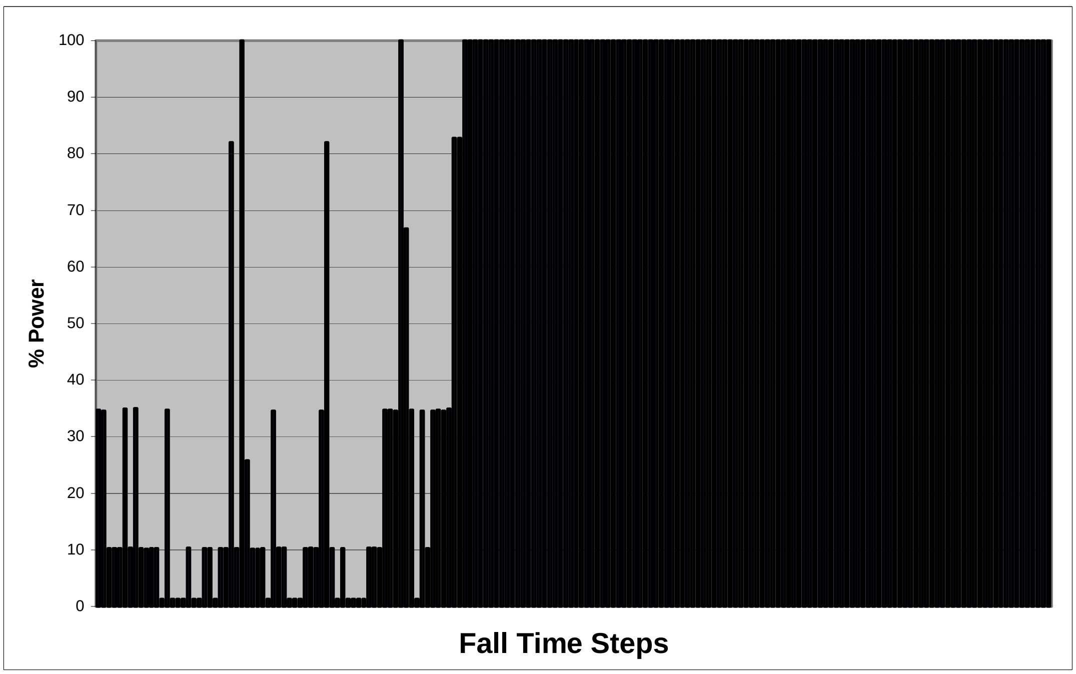

Figure 55: AS #2 Fall Total Percent Power Used

The fall season was not as much as a failure as the previous summer season, but the overlapping winter winds displaced AS #2 from the operational area for the majority of the analysis. It was again apparent that a lower maximum airship velocity significantly affects the vehicles station-keeping performance.

4.3.5 Airship #2 Mission Summary

The total number of days AS #2 spent outside the operational area was a staggering 221. This resulted in only 39% of on station operation over the course of the entire yearlong mission. The airship performed average in the spring, below average in the winter and the fall, and completely failed the mission during the summer. Overall, AS #2's station-keeping capacity was dramatically less proficient compared to AS #1. The 39% operation time is unacceptable from a military perspective and the uncontrollability of the vehicle during the displacements could result in the craft entering hostile airspace. AS #2 had a much more favorable design with respect to its smaller size but the sacrifice in its maximum velocity devastated the vehicles station-keeping abilities.

4.4 NOGAPS and AFCCC Wind Data Comparison

Before answering the research questions, some validation of the wind data is required in order to accept these results. One question that should be answered is: How does the wind data generated for the 2005 mission compare to the mean and standard deviation wind speeds generated by the Air Force Combat Climatology Center? Both AS #1 and AS #2 were designed using the AFCCC wind data over Baghdad that only ranged from 1973 to 1990 and a comparison in wind velocities must be conducted to determine if 2005 experienced higher, lower, or similar relative winds speeds. This was done by first extracting wind magnitudes from the station-keeping analysis from each time step when the baseline airship was located within the operational radius. Then the 2005 wind mean and standard deviation were calculated. These values are summarized in Table 11.

Table 11: Baghdad 2005 Wind Data at 30 mb

Wind Speed Mean	20	knots
Standard deviation	11.01	knots

These values match well with the AFCCC data (Figure 24): mean wind speed equal to 21 knots and a standard deviation of 13 knots. Therefore, we can accept the data obtained from NOGAPS and acknowledge this station-keeping analysis as an experiment using standard wind speeds over the defined target. This validates the wind data for the 2005 yearlong mission and now the research questions can be answered using the generated results.

4.5 HAA and Baseline Design Performance Comparison

Using the results from the station-keeping analysis of AS #1 and AS #2 a performance comparison can be made to the HAA. The HAA is projected to reach altitudes of up to 60,000 ft (18.29 km) and withstand winds of 35 knots (18 m/s). The equivalent pressure height to the HAA's maximum altitude of 60,000 ft is approximately 70 mb. This altitude is about 17,000 ft lower than the operational altitude of the two baseline airship designs; hence the HAA has a much smaller lifting gas envelope compared to AS #1 and AS #2. A smaller gas envelope is beneficial from an engineering perspective but the lower service ceiling will deny the HAA the ability to reach the low wind regions in the upper atmosphere. The stratonull varies greatly with respect to location and season but it is essential for an airship to reach an operational altitude of at least 24 kilometers in order to take full advantage of this low wind region. Using the AFCCC wind data over Baghdad, it can be seen that the annual mean wind velocity in the upper atmosphere decreases as pressure height decreases starting at the 200 mb level up to the 50 mb level (Figure 56). This clearly shows that the annual mean location of the stratonull over Baghdad is at or above the 50 mb pressure level.

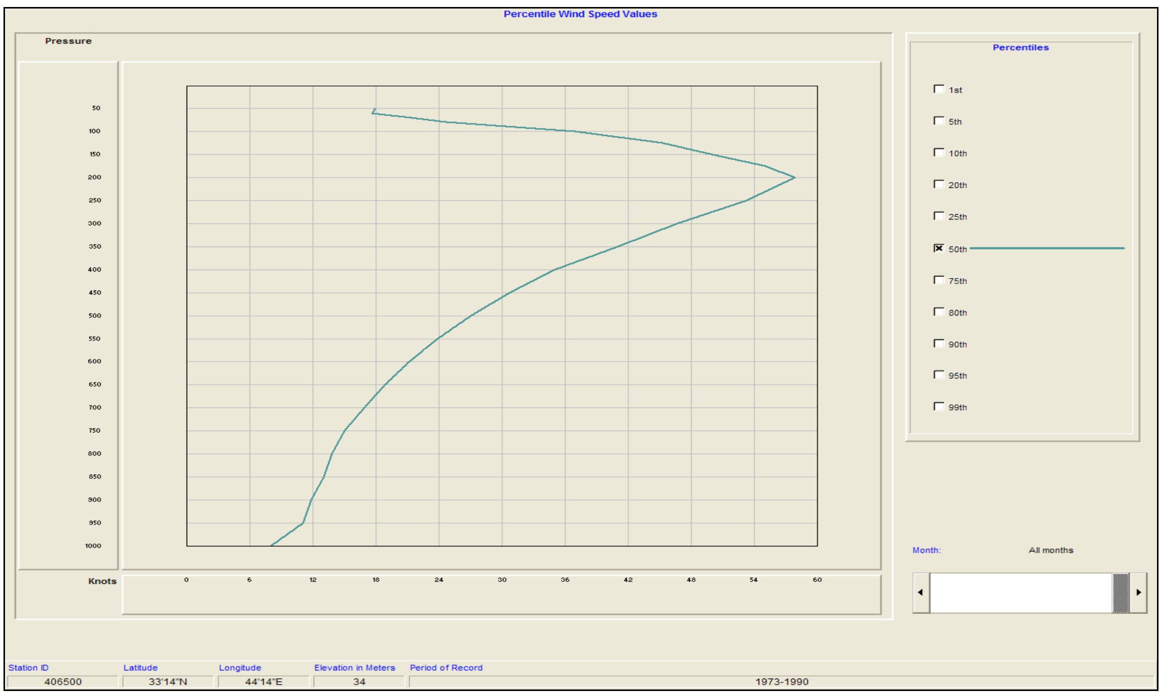

Figure 56: Annual Mean Wind Velocity over Baghdad with Increasing Altitude [18]

The mean and standard deviation at the 70 mb pressure height can also be generated by the AFCCC to compare the HAA's maximum velocity to the annual and monthly wind values over Baghdad (Figure 57). The figure shows that the annual mean and standard deviation at 70 mb is 26 knots and 15 knots, respectively. As expected, the annual mean wind velocity is higher than the mean at the 50 mb level (21 knots). The HAA's maximum velocity of 35 knots is superimposed on Figure 57 and it is apparent that this speed does not reach one standard deviation above the annual mean wind velocity. The results from the baseline airship station-keeping analysis showed that an airship designed at one standard deviation above the annual mean wind velocity (AS #1) was operational 88 % of the yearlong mission and an airship designed at the annual mean wind velocity was operational only 39% of the year. The HAA's maximum velocity of 35 knots is only half of one standard deviation above the annual mean wind velocity at 70 mb, therefore its station-keeping performance should be between the 88% operation time of AS #1 and the 39% operation time of AS #2. Assuming a linear relationship, an average of the two baseline airship performances would approximate the HAA on station time to be 64% of the same yearlong mission.

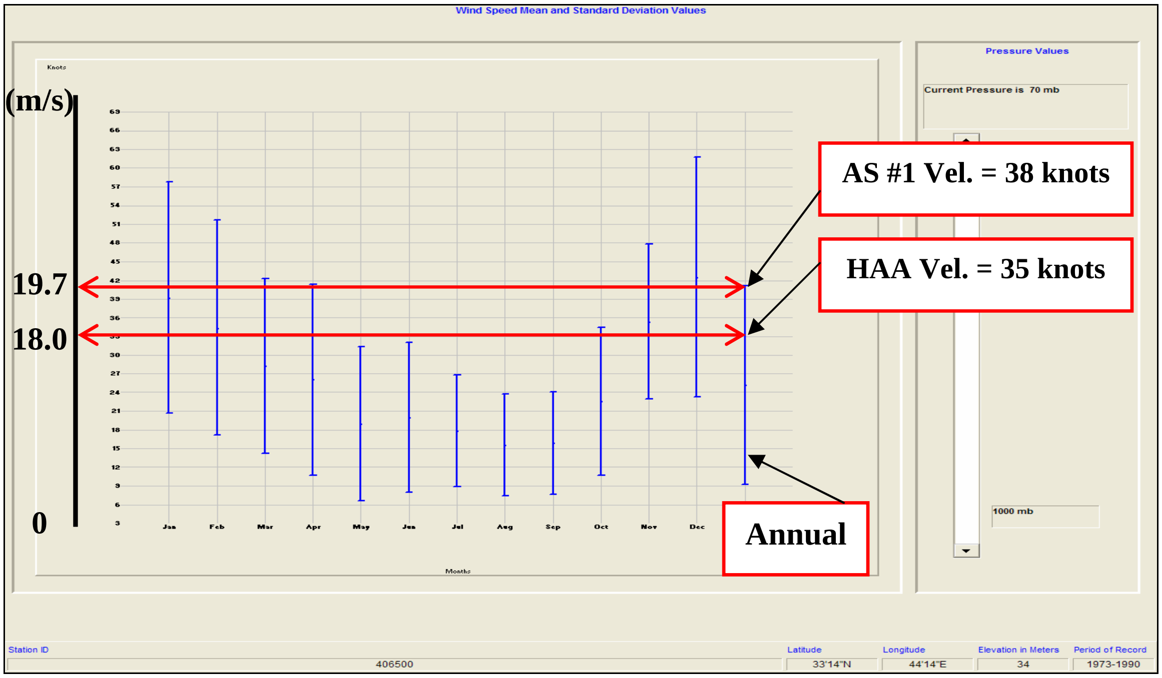

Figure 57: Wind Speed Mean and Standard Deviation over Baghdad at 70 mb [18]

4.6 Chapter Summary

This chapter reviewed the results of the station-keeping analysis for both Airship #1 and Airship #2. Plots were made of the vehicles movements across the surface of the earth, its total radial distance from the target, and the total percent power used during each time step over the duration of the yearlong mission. These graphs and the amount of time the craft spent outside the operational area were used to determine the station-keeping abilities of the two airships. AS #1 was far superior in maintaining its position over the target compared to AS #2 (88% of the time operational during the yearlong mission vs. 39%). The decreased maximum velocity of AS #2 significantly affected its station-keeping performance and ultimately showed that the design was uncontrollable during the summer and for the majority of the winter and fall. To accomplish a successful yearlong station-keeping mission, the high altitude airship must at least be capable of generating a maximum velocity higher than one standard deviation above the annual mean wind velocity at the specified operational altitude and target. It was also shown that the HAA design does not meet these criteria and would be expected to maintain its station only 64% of the time over the same yearlong mission designated for AS #1 and AS #2.

The following chapter will draw conclusions from the analytical results presented in the previous sections. The research questions proposed in the introduction chapter of this thesis will then be answered using these conclusions.

5 Conclusions and Recommendations

5.1 Chapter Overview

The objective for this station-keeping analysis was to determine the feasibility of loitering a high altitude airship over a specified target for a yearlong mission. Two baseline airship designs were chosen after defining the vehicle's operational altitude and maximum speed (AS #1 and AS #2). These designs were compared to the largest non-rigid airship operated by the United States, ZPG-3W, and Lockheed Martin's proposed High Altitude Airship. The baseline airship's movements were modeled using predicted wind data generated by the Navy's NOGAPS climatological program for each time step of the yearlong mission. By evaluating the displacement of both airships with respect to the calculated 552 km operational radius, the station-keeping capacity of AS #1 and AS #2 for a yearlong mission over Baghdad was determined. Conclusions to the research questions will now be made.

5.2 Conclusion of Research

Before the station-keeping research could be conducted, preliminary questions needed to be answered. These questions included the sizing of two baseline airship designs and a comparison of the baseline designs to past and projected airships. Once the baseline designs were attained, the station-keeping analysis was carry out and the results were used to answer the research questions proposed in the Introduction chapter. Answers to the preliminary and research questions are summarized in Table 12.

Table 12: Answers to Research Questions

Preliminary Question	**What size airship is required to lift a sensor payload and propulsion system to near space altitudes?**
Answer	The size of the airship is highly dependent on the vehicle's operational altitude and the desired maximum velocity. For this analysis two baseline airship designs were generated using a operational altitude of 24 km and two maximum velocities of 19.7 m/s and 11 m/s (AS #1 and AS #2). The gas volumes and lengths for these designs were: 1,041,000 m^3, 349 m for AS #1 and 503,000 m^3, 274 m for AS #2 (Table 8).
Preliminary Question	**How do the baseline airship designs used in the analysis compare to past and present airships?**
Answer	Both AS #1 and AS #2 have larger designs than any past or proposed non-rigid airship. Compared to the ZPG-3W and Lockheed Martin's HAA: AS #1 is 2.28 times longer and its gas volume is 7.07 times the HAA volume, AS #2 is 1.7 times longer and its gas volume is 3.4 times the HAA volume. Both baseline designs surpass the ZPG-3W and HAA in size but the AS #2 design is more likely to be attainable from an engineering perspective compared to the extremely large AS #1 design. The baseline airships were much larger than the HAA because they were designed to operate 17,000 ft above the HAA's service ceiling. This dramatically increased the lifting gas volume for the baseline designs compared to the HAA.
1	**What is the station-keeping capacity of a high altitude airship over the course of a yearlong mission?**
Answer	The larger AS #1 performed the best out of the two baseline designs. AS #1 remained on station for 88% of the time during the yearlong mission. AS #2 performed relatively poorly due to its lower maximum speed. AS #2 remained on station for only 39% of the time during the yearlong mission. The projected HAA design is also expected to have limited station-keeping abilities if operated in the middle east. The HAA's service ceiling of 60,000 ft proved too low to take full advantage of the stratonull and its projected maximum speed of 35 knots was not one standard deviation above the mean wind velocity at Baghdad. Compared to the AS #1 and AS #2 station-keeping analysis, it was approximated that the HAA could maintain coverage over Baghdad only 64 % of the time during a yearlong mission.
2	**What maximum velocity must a high altitude airship generate in order to counter upper atmospheric winds at a specified target?**
Answer	The optimal maximum velocity chosen for a station-keeping airship must be above one standard deviation of the mean wind speed at the target location and operational altitude for continuous target coverage. The airship that preformed the best was AS #1 and it was designed for a maximum speed one standard deviation above the annual mean at the operational altitude over the target. The station keeping results for AS #1 also showed that if the designated maximum velocity was above one

	standard deviation of the mean for any single month out of the year, AS #1 was capable of nearly 100% on station operation.
3	**Is it advantageous to design a high altitude airship for one particular operational altitude?**
Answer	No, it is not advantageous to design an airship for one particular altitude. The summer analysis for AS #2 resulted in the vehicle being displacement immediately by strong winds at the 24 km operational altitude. Further investigation showed that calmer winds were located near the 100 mb pressure level. If the airship could vary its operational altitude, AS #2 would have increased its time on station. However, it should be noted that if this multi-altitude capability is designed into the airship the mass of the vehicle could possibly increase due to the more robust control system. The additional weight would increase the airship's gas volume and could degrade the vehicles performance.
4	**Is the high altitude airship loitering mission a viable concept in terms of airship size and station-keeping ability?**
Answer	With the current state-of-the-art technology and materials it does not seem feasible for a high altitude airship to maintain continuous target coverage for an extended period of time. AS #1 did perform well in the station-keeping analysis but the overwhelming size of the design could be impossible to engineer. AS #2's design was much more reasonable but its station-keeping performance for the yearlong mission was well below average.

The high altitude airship concept should not be discarded completely. Innovations in gas envelope fabric, power supply systems, or propulsion systems could result in lighter and smaller airships that have the ability to reach speeds and altitudes beyond the baseline airship designs. It has been shown that the greatest challenge to on-station operation for a high altitude airship is the strong and somewhat unpredictable upper atmospheric winds. In order for this concept to be successful, the vehicles propulsion system must be strong enough to counter these drag forces over any target of interest on the planet.

Other problems could also arise from the airships inability to station-keep over the designated target. The Airship #2 analysis showed that a vehicle with an inadequate propulsion system would be uncontrollably displaced from the theater of operation within a span of only twenty-four hours. AS #2 lacked the power to control its movements and made numerous over flights of nations unfriendly to the United States (i.e. China, Iran, North Korea). This breach of enemy airspace might result in escalated tensions with the United States that could lead to further conflicts. The airship must be capable of controlling its movements to ensure it is only displaced over international areas or allied nations.

5.3 Significance of Research

A high altitude airship acting as a communications and surveillance platform would be a fantastic asset to the United States Military. Continuous on-station coverage of the battle space would increase the decision-making capacity of our military leaders by supplying the allied forces with real time communications and surveillance. This research showed that 24-hour coverage by a high altitude airship is not currently feasible but future advancements in technology could make this a viable concept.

This research also provided a methodology for determining the station-keeping abilities of a high altitude airship design using actual wind data at a specified target. Similar investigations can be conducted in the future to help high altitude airship designers determine the required propulsion system and optimal operational altitude for constant station-keeping over a specific target. The available tools for modeling actual wind data were also identified and discussed in detail. The Air Force Combat Climatology Center and The Navy Fleet Numerical METOC Detachment provided the best weather modeling database for near space altitudes. Limitations of these sources were explained and should be taken into account if the SSUAC or NOGAPS programs are utilized in the future.

5.4 Recommendations for Future Research

Follow-on sensitivity studies could complement the research and conclusions of this analysis. One question that should be answered is: "How much would the airship's station-keeping performance improve if the vehicle was allowed to alternate its operational altitude?" This investigation showed that AS #2 would have benefited from varying its altitude and future research should try and identify which specific altitude experiences the lowest winds during each day of a station-keeping mission. A second sensitivity study should also determine how much the technology would need to improve to decrease the size of the airship design to make the engineering more feasible. What are the trends in technology development and determine how far into the future engineers should wait until the airship design becomes more feasible? These follow-on studies would help developers optimize the high altitude airship mission and construction.

The methodology of this analysis could also be rearranged and expanded to provide more global results. Instead of designing a baseline airship for one target and investigating its station-keeping capacity in that region of the world alone, a study could identify the upper atmospheric wind velocities at multiple locations on the planet and then determine the required baseline airship design capable of countering such wind velocities. The study could also identify the varying seasonal winds over the array of locations and a parametric analysis could be conducted for different design velocities.

Further mission studies must be conducted to investigate the areas of airship operation that were not covered in this analysis. For example, one of the most daunting problems that face airship operations is the danger involved in launching and landing lighter-than-air vehicles. Light surface winds acting on the airship's large gas volume can result in uncontrollable forces on the vehicle and cause injuries to the ground crew or catastrophic damage to the airship. Ground handling operations should be studied and reviewed intensively before a high altitude airship can be put into operation.

Research should also be conducted on other station-keeping strategies. This analysis required that the vehicle take the most direct path back toward the target during a **Gain** situation. The station-keeping performance of the vehicle could have improved if alternate routes were taken back to the target area. Another strategy that should be evaluated is the idea of utilizing more than one airship. Multiple airships or balloons could be placed upwind of the target and allowed to drift one-by-one through the operational area in order to maintain continuous coverage.

Bibliography

1. Moomey, Eric R. *Technical Feasibility of Loitering Lighter-than-air Near-Space Maneuvering Vehicles*. Dayton: Air Force Institute of Technology Masters Thesis, 2005.

2. Hale, Francis J. *Introduction to Space Flight*. Upper Saddle River: Prentice Hall Publishing Company, 1994.

3. Petrone, F. J., and Wessel, P. R. "HASPA Design and Flight Test Objectives," AIAA Paper No. 75-924, presented at the AIAA Lighter-than-air Technology Conference, Snowmass, Colorado, July 1975.

4. Airship, Lighter-than-air Craft Homepage Website. n. pag. Accessed Dec 2005. http://spot.colorado.edu/~dziadeck/airship.html.

5. Maritime Systems & Sensors. "High Altitude Airship," n. pag. Accessed from Lockheed Martin Website Dec 2005. http://www.lockheedmartin.com/wms/findPage.do?dsp=fec&ci=14477.

6. Pike, John. "High Altitude Airship (HAA)," n. pag. Accessed from Global Security Organization Website Jan 2006. http://www.globalsecurity.org/intell/systems/haa.htm.

7. Aeragon Website. n. pag. Accessed Jan 2006. "Airships, Transitional Craft," http://www.aeragon.com/index.html.

8. Goodyear Blimp Website. n. pag. Accessed Dec 2005. http://www.goodyearblimp.com/basics/anatomy.html.

9. AIAA Lighter-Than-Air Systems Technical Committee Website. n. pag. Accessed Jan 2006. http://www.aiaa.org/portal/index.cfm?getcomm=73&adview=0.

10. Bond, Larry. "Airships History and Tactics." n. pag. Accessed from Website Dec 2005. http://www.magweb.com/sample/snav/sn10airs.htm.

11. Webb, W. L. *Structure of The Stratosphere and Mesosphere*. New York: Academic Press, 1966.

12. Panofsky, H. A. "Temperature and Wind in the Lower Stratosphere," *Advances in Geophysics*, H. E. Landsberg and J. Van Meighem, Editors. Vol. 7. New York: Academic Press, 1961.

13. Lecture Notes, LSC MET 101, The Earth and Its Atmosphere, "Vertical Profile of the Atmosphere by Composition," Accessed from Website Feb 2006. http://apollo.lsc.vsc.edu/classes/met130/notes/chapter1/vert_comp.html.

14. Hobbs, Peter V. and Wallace, John M., *Atmospheric Science, an Introductory Survey Second Edition*, Canada: Elsevier Publishing Company.

15. Ahrens, Donald C. *Essentials of Meteorology Third Edition.* Pacific Grove: Brooks/Cole Thomson Learning, 2001.

16. United States Navy Fleet Numerical Meteorological Detachment Website. n. pag. Accessed from Oct 2005 to May 2006. https://navy.ncdc.noaa.gov/.

17. "Map-it: Form-based Simple Map Generator," United States Geological Survey Website Accessed Mar 2006. http://stellwagen.er.usgs.gov/mapit/.

18. Air Force Combat Climatology Center Website. n. pag. Accessed from Oct 2005 to Dec 2006. https://notus2.afccc.af.mil/SCISPublic/.

19. "How to Read a Wind Barb," Southeast U. S. Atlantic Coastal Ocean Observing System Website Accessed Feb 2006. http://seacoos.org/Data%20Access%20and%20Mapping/wind_product_desc/.

20. Geospatial Training and Analysis Cooperative Website. n. pag. Accessed Nov 2005. http://geology.isu.edu/geostac/Field_Exercise/topomaps/grid_assign.htm.

21. Hill, Philip and Peterson, Carl. *Mechanics and Thermodynamics of Propulsion Second Edition*. Addison-Wesley Publishing Company, Incorporated, 1992.

22. Lewis, Jeff. "Theoretical Max Propeller Efficiency," Website n. pag. Accessed Dec 2005. http://www.jefflewis.net/aviation_theory-theo_prop_eff.html.

23. Hepperle, Martin. "How a Propeller works," Website n. pag Accessed Dec 2005. http://www.mh-aerotools.de/airfoils/propuls4.htm.

Vita

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14. ABSTRACT

Lighter-than-air vehicles were once widely utilized by most major militaries. The airship's extended range and flight endurance made them the optimal vehicle for surveillance and reconnaissance. These flight characteristics have created new interest in using lighter-than-air vehicles as high altitude surveillance and communications platforms. Future Department of Defense plans include high altitude airships that will operate at near space altitudes and take advantage of the low wind region in the upper atmosphere located at approximately 24 km. A high altitude airship could provide 24-hour coverage of a target area if operated in this low wind region. This study investigated the station-keeping abilities of two such high altitude airships: a large/fast design (AS #1) and a smaller/slower design (AS #2). The two baseline airship designs were subjected to the same simulated yearlong station-keeping mission using realistic upper atmospheric wind data over the designated target of Baghdad. Actual wind data was generated by the Navy's Fleet Numerical METOC Detachment and used to model the movements of both baseline airships. Their station-keeping capacity was determined by the duration of time each vehicle spent inside the targets coverage radius (552 km). The AS #1 design remained inside the operational radius for 87.67% of the year and the AS #2 design was only operational for 39.45% of the year. Neither airship maintained its station for the entire yearlong mission. This study concluded that advancements are required in propulsion or power production to decrease the size of the airship designs and increase the vehicles maximum velocity in order to counter the upper atmospheric winds.

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