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R E P O R T

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# High-Altitude Airships for the Future Force Army

Lewis Jamison, Geoffrey S. Sommer, Isaac R. Porche III

Prepared for the United States Army

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## Preface

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The U.S. Army's combat operations in Afghanistan and Iraq in 2001 and 2003, respectively, showed that the forces lacked adequate intra-unit communications, particularly at lower echelons, and that the use of satellite communications resources offered a future solution. The promise of satellites was borne out by the success of Blue Force Tracker, a communications system used to track the locations of units and vehicles connected to low-orbit communications satellites.

More overhead communications systems are needed, but satellites are costly and require either expensive geosynchronous satellites or many low- or mid-earth-orbit satellites. Potential alternative platforms are solar-powered high-altitude airships and airplanes flying at or above 65,000 feet. Aircraft payloads could support communications suites, such as the Adaptive Joint C4ISR Node (AJCN), and surveillance suites similar to Global Hawk equipment and space-based radar. Weapon systems are potential payloads not addressed in this report.

The purpose of this report is to inform the U.S. Army about the usefulness and limitations of airships in roles of supporting communications and surveillance functions in theater battlespace.

This research was sponsored by the U.S. Army CIO/G-6 and was conducted in RAND Arroyo Center's Force Development and Technology Program. RAND Arroyo Center, part of the RAND Corporation, is a federally funded research and development center sponsored by the United States Army. Questions and comments regarding this research are welcome and should be addressed to the project leader, Isaac R. Porche III, at [Isaac\\_Porche@rand.org](mailto:Isaac_Porche@rand.org).

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## Summary

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Across the services, there is an increasing demand for overhead communications capacity. For the U.S. Army, this is a result of its transition to a new force structure that will be knowledge-based and network-centric. Future forces may be more dispersed. Extending their range of communication will be key. Messages will have to be relayed through a multilayered network of terrestrial-, air-, and space-based retransmission nodes. Currently, satellite communications (SATCOM) is being relied on to connect distant units, hopefully in an assured manner.<sup>1</sup> However, the exclusive use of military or commercial SATCOM may not be available to meet all of the Army's connectivity needs, and high-altitude airships (HAAs) are being considered as an optional surrogate, which could be even more cost-effective if proved technically feasible.

New, lighter-than-air (LTA) vehicles that operate at very high altitudes have an obvious attraction for planners of surveillance and communication missions; the ability to see to a more distant horizon results in greatly expanded surveillance volumes (assuming that appropriately powerful sensors are carried onboard). Low probability of intercept (LPI) direct line-of-sight communications will also increase their reach.

In recent years, increased emphasis has been placed on systems that can provide extended surveillance and communications support at such high altitudes. These are generically known as High Altitude Long Endurance (HALE) systems or High Altitude Long Loiter (HALL) systems. The Global Hawk unmanned aerial vehicle (UAV) was perhaps the first of these systems to achieve operational success. Flight at high altitude (say, over 60,000 feet) for extended periods (for a matter of days or more) is an extreme technical challenge for fixed-wing aircraft.

In recognition of this fact, advocates of LTA systems have pointed out that systems relying upon aerostatic (buoyant) lift avoid many of the design difficulties associated with fixed-wing aircraft. High-altitude scientific balloons represent an existence proof of sorts, regularly operating far above the altitudes achievable by airplanes. On the other hand, LTA systems introduce their own set of unique technological and operational difficulties. Worse, many of these difficulties fall into the category of "unknown unknowns"—hence, the role of demonstrators (and in particular, operational trials of such demonstrators) is unusually critical. The purpose of this report is to examine both the potential benefits and the unique risks associated with the design and operation of HAAs, i.e., those intended to fly above 65,000

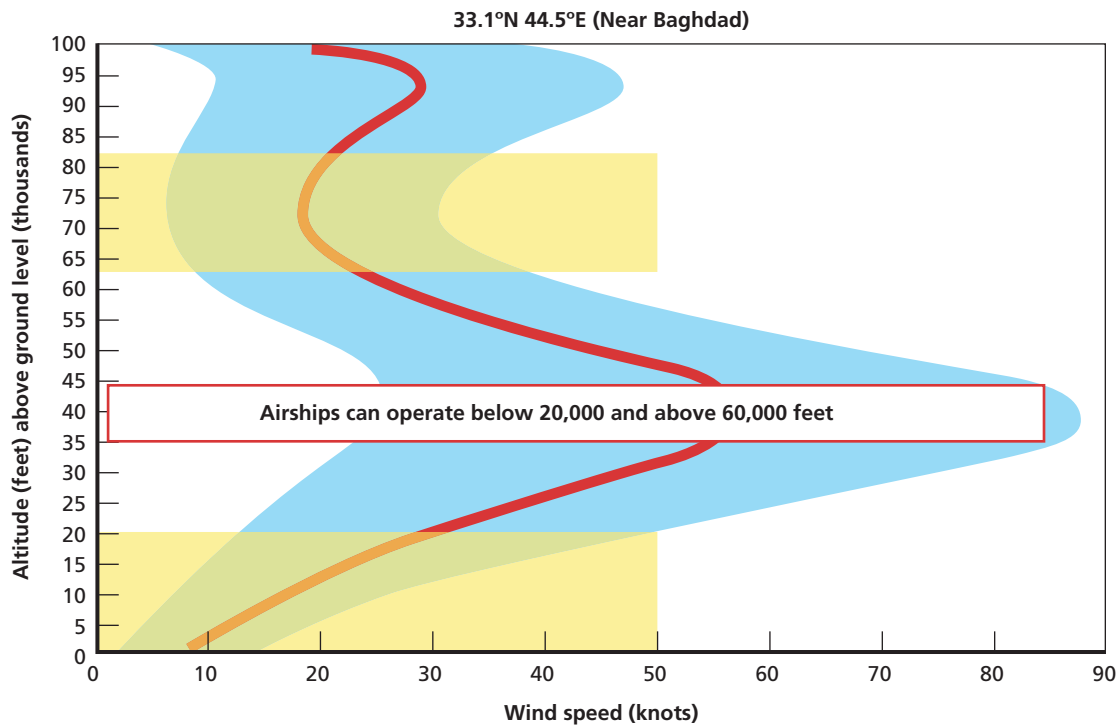
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<sup>1</sup> A SATCOM link that enables a simple connection (e.g., single hop) increases the probability of assured receipt and reduces the opportunities for signal intercept and interference.

feet.<sup>2</sup> This is an altitude that has been proposed to facilitate solar-powered station-keeping, which requires a fairly benign environment. There is a sweet spot where wind and turbulence are minimal. It is an area of the atmosphere<sup>3</sup> that is above the jet stream<sup>4</sup> and below the upper layers of the stratosphere (between 20 and 30 km). Figure S.1 shows a profile of peak wind speeds near Baghdad. This figure indicates that most weather occurs in the troposphere.<sup>5</sup>

Many organizations around the world, commercial and military, are interested in HAAs. Design efforts and prototype builds are in progress. Three U.S. combatant commanders are also interested in using HAAs in their overseas theaters for communications and surveillance.<sup>6</sup>

**Figure S.1**  
**Annual Winds Aloft Near Baghdad**



NOTE: Summary product created from raw weather data collections provided by AFCCC/DOPT (Asheville, North Carolina) dated from 1958 through 1990.

SOURCE: Stephen Huett, Director, Advanced Development Program Office for Airship Concepts, Naval Air Systems Command, "Current State-of-the-Art for LTA Systems," briefing, January 2005. Used with permission.

<sup>2</sup> But well below 350,000 feet.

<sup>3</sup> Wind speed is different at different heights.

<sup>4</sup> The jet stream can exist between 25,000 feet and 40,000 feet (7.6 to 12 km) with winds that can exceed 130 knots.

<sup>5</sup> The actual "boundary" of the troposphere varies with season and latitude. For example, in the tropics, thunderstorms have been known to rise to 50,000 feet.

<sup>6</sup> Central Command (CENTCOM), Pacific Command (PACOM), and United States Force Korea (USFK) seek HAAs for a variety of tasks.

Now, with efforts to expand commercial high-bandwidth data services (particularly the “last mile” to the consumer) and the high cost of using satellites for that purpose, manufacturers are proposing high-altitude platforms (HAPs, including fixed-wing aircraft and HAAs) to serve as surrogate satellites at a presumably reduced cost.

## Potential Benefits

Communication and surveillance capabilities could considerably improve force performance in a theater battlespace with the successful introduction of airships. Airships can function as surrogate satellites but offer the advantages over satellites of shorter transmission distances for relaying ground-based communications and shorter ranges for sensor surveillance of the battlefield and acquisition of ground targets.

Potentially, airships may provide communications satellite capabilities for the Warfighter Information Network–Tactical (WIN-T) network at less expense than satellites. An HAA communications platform could be a strong addition to the Multi-Sensor Command and Control Constellation (MC2C).<sup>7</sup>

Persistent surveillance from a fixed position is an important need that HAAs can meet. Over time, they can facilitate continuous collection and comparison analysis of terrain covered by different sensors, such as infrared (IR), electro-optical (EO), and hyper-spectral imagery (HSI). Comparisons can highlight changes, such as freshly turned dirt along a roadway where bombs have been emplaced, and the fusion of data from multiple sensors may furnish tracking data on targets under foliage.

Combatant commanders in a crisis situation may wish to use HAAs as soon as possible, but deployment times have to be considered. An HAA may take days to reach a distant theater after launching. For example, a deployment from the Las Vegas, Nevada area to a geostation near Baku, Azerbaijan at an airship airspeed of 30 knots (kt), with no favorable winds, would take eight and a half days by a great circle route in the summer, and ten days, via the 45° north latitude, during the winter.

## Limitations and Vulnerabilities

The HAA Advanced Concept Technology Demonstration (ACTD) program documentation summarizes the effort as having “some technical risk” but “enormous potential benefits.” It also includes the acknowledgment that “HAA is a fast-paced program.” Against these statements, it is critical to note the following sobering point: this program is attempting to design and fly an unmanned airship that is orders of magnitude larger (in terms of volume) than any other previously attempted. There is substantial uncertainty surrounding all aspects of vehicle performance and control at this scale.

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<sup>7</sup> Quoting from the GlobalSecurity.org web site (<http://www.globalsecurity.org/intell/systems/mc2c.htm>): “The Multi-Sensor Command and Control Constellation is a future ‘constellation’ of air and space command and control, intelligence, surveillance and reconnaissance capabilities—consisting of space-based systems, unmanned aerial vehicles, ground stations, and possibly a new multi-sensor command and control aircraft to replace the existing array of command and control (C2) intelligence, surveillance, reconnaissance (C2ISR) aircraft.”

Specific areas of technical risk are shown in Table S.1, based on a review of contractor design data, a review of LTA technical literature, and the experience of the authors with prior HALE UAV and LTA programs. There is a very tight interaction between technical risk and operational utility. Many risk areas can be lowered by restricting the use of the airship in adverse conditions, by accepting reduced performance, or by providing extra airships to relieve those that are on-station when environmental conditions warrant. These risks may not be manageable. In fact, there are recent assessments (Siomacco, 2005) suggesting that technical risks are too high for even proceeding with the HAA ACTD. Furthermore, there will likely be additional risks that are unpredictable and can result in catastrophic and unexpected system failure. These risks stem from the stochastic nature of the environment in which the vehicle operates: the effects of weather and particularly (in the case of an airship) wind.

Many of the risks depicted in Table S.1 can be lowered by operational restriction. However, envelope strength, weatherability, and launch and recovery all interact and are problematic in the sense that conditions will arise that are not forecast.<sup>8</sup> When this occurs, it will be of little solace that such conditions were beyond those exercised in the ACTD plan. The vehicle will be lost.<sup>9</sup>

A review of operational experience with existing commercial airships, coupled with prior airship operations in the U.S. Navy (and interviews by Naval Airship program office personnel with then-surviving airship pilots) resulted in the following principles that can be applied to HAA design with a corresponding increase in operational robustness.

**Table S.1**  
**HAA Issues and Risks**

Issues	Risk Management Approach
Envelope material (strength and weight)	Restrict ascent/descent conditions
Thermal control (superheat)	Incorporate reflective envelope
Helium leakage	Limit endurance; use hydrogen from fuel cells
Photovoltaic cells	Limit endurance
Fuel cells	Use Li-polymer batteries as fallback
Weatherability	Restrict ascent/descent conditions; improve weather prediction; provide emergency ballast dump; add sprint engine(s)
Survivability	Operate within own air defense envelope
Airspace access	Restrict ascent/descent locations and times
Launch/recovery	Mechanization; restrict ascent/descent locations/times

<sup>8</sup> Historically, this has been a major cause of loss of the surveillance aerostats on the U.S. southern border: thunderstorms bear down on the sites before the aerostats can be fully winched down.

<sup>9</sup> This was a fallacy realized early in the Naval Airship program. Contractors would design to “10 percent wind exceedance curves” (because, for example, a 1 percent exceedance curve would require truly prodigious amounts of propulsive power). Yet this implied that 10 percent of the time, the airship would either be held on the mooring mast, if lucky, or blown out to sea; an unacceptable result.



1. “Sprint power” is essential.
2. Immediately disposable ballast is essential to allow instant recovery from difficulties during ground handling.
3. Immediately disposable lift is essential to allow the airship to collapse to the ground in the event of difficulties.

Airships will be vulnerable to air defenses. Air superiority will be a prerequisite for airship operations near enemy-held areas. Complete destruction of long-range ground-to-air missile units will probably be necessary before the full communications and surveillance strengths of airship payloads can be realized. With that accomplished, however, the airships’ ability to rise to heights above the ranges of most air defense weapons and to operate in a benign high-altitude environment should allow these platforms to survive theater operations.

Detecting a stationary platform that may have a very small radar and thermal cross section will be a challenge for any air defense system. Firm conclusions about the vulnerability of HAAs to air defenses will have to await knowledge about the ultimate composition of HAA structures.

Weather will be a risk factor that could be significant if airships are not furnished with reliable sensors for on-site meteorological data by which airship controllers can predict turbulence, icing, and violent gusts that can jeopardize the craft. The experience with high-altitude tropospheric operations from around-the-world balloonist teams and weather teams must be collected and codified to aid computer predictions at higher altitudes. This aspect of airship operations will take strong preparation and close attention during operations.

An airship will be in the troposphere for over five hours while descending<sup>10</sup> to its home mooring base. The conditions in 65,000 feet of airspace at a home location will have to be within allowable weather parameters before a letdown can commence. This requirement could cause an airship to hold at 65,000 feet for up to two to five days before descending. Launch operations could cause similar time delays, although the ascent should be at a faster 1,000 feet per minute or 65 minutes long. Operational planning may have to allow days of nonproductive time in an airship rotation schedule for an ongoing operation.

Beyond proving the physical feasibility of using HAAs for communications relays, surveillance, and other tasks, a major feasibility challenge for military acquisition of HAAs is the issue of funding. A number of commercial uses for lower-altitude airships have been proposed. Scientists and entrepreneurs in the United Kingdom have been examining the usefulness of HAPs, either airships or airplanes, to serve as fixed, wireless communications and television relays over urban areas.<sup>11</sup> Potential military users will prefer to share development and production costs with civilian users and, in fact, may insist on a cost-sharing arrangement before contracting for HAAs, as has happened with low-altitude, heavy-lift airships.

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<sup>10</sup> The HAA ACTD airship will descend at about 200 feet per minute.

<sup>11</sup> Commercial HAAs would most likely be solar powered with fuel cell storage. Successful demonstrations of high-altitude operations, solar cells, and fuel cells are needed before serious commercial funding can be anticipated (Tozer and Grace, 2001).

## Suggested Actions

In view of the above airship capabilities and limitations in the near term, the U.S. Army should:

- Closely monitor the development and testing of HAA prototypes in combination with the Missile Defense Agency, U.S. Navy, U.S. Air Force, and U.S. Coast Guard while continuing to pursue detailed technical and operational analysis of high-altitude airships.
- Ensure that the major limiting factors for HAA development are among the Army's science and technology objectives for development by the Army research and development community.
- Recognize that an operationally useful HAA would most likely incorporate features that are not included in the HAA ACTD, which is being designed for the particular requirements of an ACTD demonstration. This would have the effect, all else equal, of reducing the operational ceiling, endurance, and/or payload of any production HAA.

In the longer run, if the HAA ACTD proves successful, the U.S. Army should:

- Join in efforts to interest potential commercial users of HAAs or HAPs and include them in development discussions.
- Conduct computer analyses of the potential value of HAA communications and surveillance payload capabilities to force-on-force operations in various scenarios but taking into consideration the likelihood of reduced ceiling, endurance, or payload relative to the HAA ACTD, as above.
- Consider basing HAAs in sparsely populated desert or island locations in latitudes of less than 38° to provide adequate sunlight and the best possible weather and security environment.
- Emphasize weather analysis in planning HAA routes and airborne control operations.
- Consider co-locating HAA control facilities with the control facilities of military satellites and Global Hawk to utilize existing command and control communications facilities and surveillance control and exploitation systems.
- Understand and exploit the Air Force's efforts to protect aircraft from attack by missiles, specifically, the efforts to improve and employ the ALQ-214 IDECM RFCM suite<sup>12</sup> on aircraft to detect and counter surface-to-air and air-to-air RF/IR/EO missiles.

Alternatively, if the HAA ACTD does not prove successful, and/or the financial constraints preclude adoption of fully maneuverable high-altitude airships, the U.S. Army should consider the options it has with respect to other types of balloons (free floaters and semi-steered balloons); these (possibly) cheaper and smaller balloons could serve as disposable

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<sup>12</sup> Quoting the web site of ITT Industries' Avionics Division (<http://www.ittavionics.com/214.asp>): "The ALQ-214 Integrated Defensive Electronic Countermeasures (IDECM) RFCM [radio frequency countermeasure] system is comprised of an on-board technique generator developed by ITT Industries integrated with an off-board fiber optic towed decoy that its developers claim will provide self-protection capabilities [for vulnerable aircraft]."

assets that could be employed in large numbers; they would not be stationary, however, and would not be able to carry the large mission packages envisioned for HAAs.



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## Glossary

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ACTD	Advanced Concept Technology Demonstration
AD	Air Defense
AJCN	Adaptive Joint C4ISR Node
AMSAA	Army Materiel Systems Analysis Activity
AoA	Analysis of Alternatives
ARC	Airborne Relay Communications
ATIRCM	Advanced Threat Infrared Countermeasures
BAMS	Broad Area Maritime Surveillance
BDA	Bomb Damage Assessment
BMDO	Ballistic Missile Defense Office
B-FWA	Broadband Fixed Wireless Access
C2	Command and Control
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance
CAA	Center for Army Analysis
CDR	Critical Design Review
CL	Cargo Lifter
CMD	Cruise Missile Defense
COMINT	Communications Intelligence
CONUS	Continental United States
DARPA	Defense Advanced Research Projects Agency
DCGS	Distributed Common Ground Stations
DEM	Digitized Elevation Model
DERA	Defense Evaluation and Research Agency

DIRT	Distributed Imaging Radar Technology
DSTL	United Kingdom (U.K.) Defence Science and Technology Laboratory
DVSI	Deformation—Vertical Shear Index
EO	Electro-Optical
ESA	European Space Agency
EW	Electronic Warfare
FAA	Federal Aviation Administration
FCS	Future Combat Systems
HAAAs	High-Altitude Airships
HALE	High Altitude Long Endurance
HALL	High Altitude Long Loiter
HAPs	High Altitude Platforms
HRTI	High-Resolution Topographic Information
HSI	Hyper-Spectral Imagery
HTA	Heavier Than Air
HULA	Hybrid Ultra Large Aircraft
ICAO	International Civil Aviation Organization
IDECM	Integrated Defense Electronic Countermeasures
IR	Infrared
ISR	Intelligence, Surveillance, and Reconnaissance
JASA	Joint Airborne Signal Intelligence (SIGINT) Architecture
JAXA	Japanese Aerospace Exploration Agency
JSTARS	Joint Surveillance and Target Attack Radar System
JTRS	Joint Tactical Radio System
kg	Kilograms
km	Kilometers
kt	Knots
kW	Kilowatt
LEO	Low Earth Orbit
LPI	Low Probability of Intercept



LTA	Lighter-than-Air
MC2C	Multi-Sensor Command and Control Constellation
MDA	U.S. Missile Defense Agency
MIT	Massachusetts Institute of Technology
MMA	Multi-mission Maritime Aircraft
MMP	Multi-mission Maritime Platform
nm	Nautical Mile
NORAD	North American Air Defense
ODM	Operational Development Model
PACE	Patrol Airship Concept Evaluation
RCS	Radar Cross Section
RF	Radio Frequency
RFCM	Radio Frequency Countermeasure
RSTA	Reconnaissance, Surveillance, and Target Acquisition
SAR	Synthetic-Aperture Radar
SATCOM	Satellite Communication
SBR	Space-Based Radar
SIGINT	Signals Intelligence
SMTI	Surface Moving Target Indicator
SSW	Stratospheric Warming
SWaP	Size, Weight, and Power
TMD	Tactical Missile Defense
UAV	Unmanned Aerial Vehicle
USASMDC	U.S. Army Space and Missile Defense Command
UV	Ultraviolet
W	Watts
WAI	Westinghouse Airship Industries
WIN-T	Warfighter Information Network–Tactical



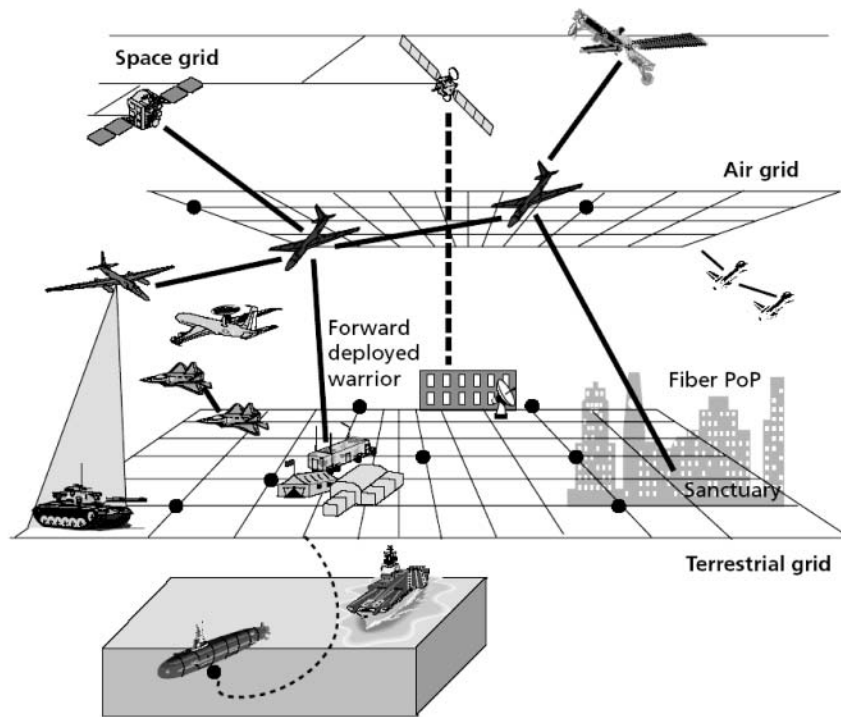
## Introduction

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The U.S. Army's combat operations in Afghanistan and Iraq in 2001 and 2003, respectively, showed that the forces lacked adequate intra-unit communications, particularly at lower echelons, and the use of satellite communications resources offered a future solution. The promise of satellites was borne out by the success of Blue Force Tracker, a communications system used to track the locations of units and vehicles, connected to low-orbit communications satellites.

Future forces will be even more dispersed. Extending their range of communication will be key. Messages will have to be relayed through a multilayered network of terrestrial-, air-, and space-based retransmission nodes, as suggested in Figure 1.

**Figure 1**  
**Layers of the Infosphere**



SOURCE: DARPA

More vertical nodes (air and space) will be needed. According to an analysis of alternatives (AoA) done by AMSAA (2005), mobile subscribers can reliably communicate throughout the area of operations (assuming a Caspian Sea theater), only with vertical nodes. Military and commercial satellites are costly (Bonds, 2000) and require either expensive geosynchronous satellites or many low- or mid-earth-orbit satellites. Potential alternatives to satellites are solar-powered, high-altitude airships and airplanes flying at 65,000 feet or above. The AoA report determined that airborne line-of-sight resources reduce SATCOM use by more than a third, as compared to without it. Thus, there is strong motivation for using airborne line-of-sight relays like high-altitude airships. Airship proponents envision payloads that could support communications, surveillance suites, and/or weapon systems. The objective of this report is to inform the Army about the usefulness and limitations of airships in roles of supporting communications and surveillance functions in a theater “infosphere.”

## **Background**

While this report will center on lighter-than-air (LTA) maneuvering airships, other varieties of LTA craft that can carry payloads with different characteristics exist and may also be considered by the Army for some tasks. The following categories of LTA craft describe three different levels of maneuvering capabilities.

### **Free-Floating Balloons**

“Free floaters are basically the simple weather balloons many people imagine when they think of lighter-than-air [craft]. They are very straightforward to construct and launch and very inexpensive but lack station-keeping capabilities. . . . Once launched, they are at the mercy of the existing winds. Limited steering is possible by variable ballasting, causing the balloon to float at different altitudes to take advantage of different wind directions and speeds. These balloons can take tens to thousands of pounds to over 100,000 feet, but more typical weather balloon payloads are on the order of tens of pounds. Free-floater systems have already demonstrated commercial viability as communications platforms” (Tomme, 2005, p. 18).

### **Steered Free-Floaters**

“Steered free-floaters also drift on the wind, but they are able to exploit the wind much like sailing ships to maneuver almost at will. Sailing requires the vehicle to be immersed in two media moving at different speeds. . . . A large balloon at high altitude moves at a different speed through the air than a wing suspended below the balloon at a different altitude. The air around the wing is moving at a different speed than the air pushing the balloon. The entire platform is then steered when the differential wind between the two parts of the platform enables the wing to become aerodynamically effective. With the limited steering, these balloons can stay on station for short periods.” A constellation of steered free-floater platforms would generally be necessary to maintain persistence (Tomme, 2005, p. 19).

### **Maneuvering Airships**

The airship (synonymous with the term “dirigible”) has a means of propulsion and a means of control. Propulsion can rely on fossil fuel, nuclear, or solar energy. Control can be at-

tained through both aerodynamic and aerostatic means. These are maneuvering vehicles that do not require the continual replenishment of free-floaters or the large constellations of steered free-floaters to provide persistence. “It is primarily maneuvering vehicles that are the revolutionary technology behind the paradigm shift to effects-based space” (Tomme, 2005, p. 20).

Maneuvering airships have a long history of operations at lower altitudes. Germany developed long-range zeppelins and had made over 160 trans-Atlantic passenger-carrying flights until the Hindenburg, filled with flammable hydrogen, burned while mooring in 1937. The cause of the fire has been attributed not to the hydrogen but to electrostatic ignition of the flammable aluminum in the skin’s silver paint. The U.S. Navy successfully operated patrol airships filled with helium for years before, during, and after World War II. Since World War II, commercial organizations such as Goodyear have successfully flown blimps for sightseeing, sports coverage, advertising, and other uses. The improvements in airship structures and operational procedures have progressed through the last century.

In the last few years, low-altitude transport airships have been examined by companies and organizations such as CargoLifter AG in Germany and Skycat Technologies in the United Kingdom. These airship concepts have been intended to lift heavy loads, up to 1,000 tons, and operate at altitudes below 10,000 feet mean sea level. None of these concepts have come close to fruition. The Center for Army Analysis (CAA) made an extensive study of transporting Army forces to overseas theaters using a CargoLifter CL 160 airship concept (CAA, 2001).

### **Aerostats**

Another use of an airship-like concept is the aerostat, a tethered balloon-borne radar system that has been operational since 1980, used in an air defense and drug enforcement network with eight sites operated by the U.S. Air Force. The network uses two sizes of aerostats, 275,000 and 420,000 cubic feet, which carry two sizes of radars and operate at 15,000 feet. The radar products are fed to the U.S. Customs Service for anti-drug surveillance and to the North American Air Defense command (NORAD) for air defense (U.S. Air Force, 2003).

The use of aerostats for air defense has generated interest in the capabilities of high-altitude airships (HAAs) flying untethered but holding stationary positions to form a comprehensive surveillance net along U.S. coastlines. Furthermore, the Army Science Board in 1998–99 recommended that the Army “develop a surrogate satellite capability to augment/replenish space capabilities” (NORAD, USASMDC, 2003). Relatively speaking, aerostats are a mature concept. However, as noted by Bolkom (2004), “the primary operational concern with employing aerostats appear to be vulnerability to weather and enemy ground fire.” He notes that the latter is debatable: “Proponents argue that despite their large size, aerostats are survivable because of a low radar cross section and their ability to endure numerous punctures before gradually losing altitude. Low flying aircraft and UAVs are also vulnerable to enemy ground fire.”

An Advanced Concept Technology Demonstration (ACTD) was initiated in 2003. Sponsored by the U.S. Missile Defense Agency (MDA), the goal of the effort is to design, build, and test an HAA prototype that is able to operate unmanned, maintain a geostationary position at 65,000 feet (21.33 kilometers (km)) for up to six months, generate its own power, and carry a variety of payloads. A study by the Massachusetts Institute of Technology (MIT) concluded that a line of ten HAAs could provide the needed air defense surveillance

coverage. The Technical Center of the U.S. Army Space and Missile Defense Command (USASMDC) is the user unit, and the U.S. Army is the lead service for the ACTD (NORAD, USASMDC, 2003).

As the Army's demands for communications traffic continue to increase and the launches of additional military satellites remain limited, combatant commanders<sup>1</sup> and the military services have been seeking other means to maintain assured communications among dispersed units. The HAA is viewed as a possible substitute for satellites supporting communications and other missions. The limited availability of programmed communications satellites makes the potential communications capabilities of HAAs very attractive.

## Comparative Advantage

### Military

With successful production of airships, the communications and surveillance capabilities of a deployed force should improve. Airships can function as surrogate satellites but offer the advantage of shorter transmission distances for relaying ground-based communications and ranges shorter than those of satellite sensors for surveillance of the battlefield and acquisition of ground targets.

Potentially, airships may provide communications satellite capabilities for the Warfighter Information Network–Tactical (WIN-T), and do so at much less expense than satellites. The communications platform should be a strong addition to the Multi-Sensor Command and Control Constellation (MC2C).

The persistent surveillance from a fixed position by airships, in contrast to periodic snapshots from the moving platforms that satellites provide, furnishes two long-needed changes to military surveillance. These changes will allow continuous collection and comparison analysis over time of terrain covered by different sensors, such as infrared (IR), electro-optical (EO), and hyper-spectral imagery (HSI). Comparisons can highlight changes like freshly turned dirt along a roadway where bombs have been emplaced.

### Commercial

The comparative advantage of HAAs or high-altitude platforms (HAPs), either airships or aircraft, to other means of broadband services, especially cell phones, has been assessed by Tim C. Tozer and David Grace (2001) of the University of York, where the study of commercial communications services for major United Kingdom cities is ongoing. They advocate for high-altitude platforms for commercial use, and their cited comparative advantages over satellites and ground antennas is summarized in Table 1. The table shows the HAP as needing larger cells than a terrestrial station but smaller than those of satellites.<sup>2</sup> Larger numbers of small cells facilitate better flexibility, frequency control, and more overall capacity as a result of frequency reuse (Tozer and Grace, 2001). The high cost of a terrestrial infrastructure

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<sup>1</sup> Central Command (CENTCOM), Pacific Command (PACOM), and United States Force Korea (USFK) seek HAAs for a variety of tasks.

<sup>2</sup> Tozer and Grace (2001) explained that the larger minimum cell size associated with the use of GEO satellites is a result of the physical constraints of onboard antenna dimensions resulting in a larger spot beam (i.e., cell) diameter on the ground and thus more constrained ability for frequency reuse.

build-out for the advancing movement to 3G cell phones worldwide should make the less expensive HAP attractive to the telecom industry (Mock, 2001).

## Organization of This Report

This report is organized as follows. Chapter Two provides a summary of some of the research and development efforts associated with airships for both commercial and military applications. Chapter Three reviews the types of missions and associated payloads for airships. Chapter Four represents a key contribution of this report and discusses the limitations and risks associated with HAAs. Chapter Five provides a brief discussion that considers the relative merits of unmanned aerial vehicles (UAVs) and HAAs as competing options for high-altitude long-loiter<sup>3</sup> vehicles. Finally, the conclusions are in Chapter Six, which provides a concise summary and review of the potential benefits of this concept, the technical and operational risks, and suggested actions for the Army with respect to the pursuit of this concept. An appendix is provided that quantifies the tradeoff between airship size and operating altitude.

**Table 1**  
**Comparison of Terrestrial, HAP, Low-Earth-Orbit, and Geosynchronous Satellite**

	Terrestrial (e.g., B-FWA)	HAP	LEO Satellite (e.g., Teledesic)	Geosynchronous Satellite
Station coverage (typical diameter)	< 1 km (spot service)	Up to 200 km (regional service)	> 500 km (global service)	Up to global (quasi-global service)
Cell <sup>a</sup> size (diameter)	0.1–1 km	1–10 km	~ 50 km	400 km min.
System deployment <sup>b</sup>	Several base stations before use	Flexible	Many satellites before use	Flexible, but long lead time
Estimated cost of infrastructure	Varies	\$50 million upward?	~ \$9 billion	> \$200 million

<sup>a</sup> The term “cell” refers to the geographical area covered by the transmitter.

<sup>b</sup> This relative comparison of system deployment assumes that the satellites are not already deployed and orbiting.

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<sup>3</sup> Also known as high-altitude long endurance (HALE).





## Research and Development

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### Commercial Efforts

As noted by Bolkcom (2004), there is growing commercial interest in airships worldwide. Quoting: “At least 32 companies are involved in the design or manufacture of commercially available airships and aerostats in Cameroon, Canada, China, Czech Republic, France, Germany, India, South Korea, Netherlands, Russia, United Kingdom, and the United States.”

Commercial manufacturers are proposing high-altitude platforms (HAPs), including fixed-wing aircraft and HAAs, to serve as surrogate satellites at a presumably reduced cost. These efforts are driven by a desire to expand commercial high-bandwidth data services (particularly the “last mile” to the consumer). The high cost of using satellites for that purpose has motivated the development of high-altitude airships and airplanes for these commercial communications purposes. Some of the progress made by a number of countries is detailed as follows (Tozer et al., 2000; Mock, 2001).

- **Japan.** SkyNet, funded by the Japanese government to realize a commercial broadband platform by 2005.
- **South Korea.** In 2002, the Korean Ministry of Commerce, Industry, and Energy established a ten-year R&D program to develop a stratospheric airship that will operate at an altitude of approximately 20 km (greater than 65,000 feet) (Koenig and Penny-packer, 2002).
- **Brazil.** ARC (Airborne Relay Communications), using a tethered aerostat at 15,000 feet to provide a range of cellular services.
- **Europe.** Heliplat, a solar-powered aircraft with a wingspan of 70 meters to operate at 20 km, being designed under the European Framework V program to provide broadband communications. Additionally, the United Kingdom’s Defense Science and Technology Agency and the European Space Agency are researching HAPs.
- **United States.** SkyTower/Aeroenvironment’s Helios solar-powered aircraft, designed as part of a NASA program to provide communications and surveillance, and Angel Technologies HALO-Proteus aircraft, designed to provide a range of communications services over cities.

### Aerospace Spherical Airship

Techsphere Systems plans to produce spherical airships with 60-foot and 200-foot diameters and perform flight tests at 15,000 feet and 65,000 feet, respectively. The Aerosphere’s outer skin is made from Spectra fiber, an ingredient used in the body armor issued to U.S. troops in Iraq. An inner envelope of mylar polyester film contains helium to provide lift. The air-

ships will be manned and will be propelled by gas engine–driven propellers mounted around the sides. The engines will rotate up and down for flight and landing maneuverability (Minor, 2004).

## Military Efforts

In the early 1980s, the U.S. Navy conducted a Patrol Airship Concept Evaluation (PACE), which led to an acquisition program known as the Naval Airship. In the course of a decade (1985–1994), this program invested on the order of \$200 million on a design for a very large (423-foot), nonrigid airship intended to provide organic air surveillance for Navy noncarrier battle groups.<sup>1</sup> The design progressed through critical design review (CDR) before it was shelved as a result of funding cuts associated with the end of the Cold War, combined with significant program cost growth.<sup>2</sup> Nevertheless, the Navy interest and funding support gave new life to a generation of airship designers and gave LTA, in general, a respectability in the minds of investors that it had not enjoyed in decades.

On the heels of the Naval Airship program, a new interest in low-altitude, heavy-lift airships arose, particularly in Europe. CargoLifter AG in Germany achieved the most success. In the end, though, development difficulties and cost growth led to a withdrawal of funding support. Today, the Defense Advanced Research Projects Agency (DARPA) is attempting to rekindle that interest with a heavy-lift airship concept called WALRUS<sup>3</sup> (see Figure 2), but that project is still at an early stage. The Navy now has a similar effort called HULA (Hybrid Ultra Large Aircraft). As noted by Bolkcom (2004): “Advocates hope that airships may potentially be capable of carrying a complete Army brigade directly from the fort to the fight.”

A more developed effort is the U.S. Missile Defense Agency’s ACTD airship. It is described below. This is followed by descriptions of several commercial airships.

### Missile Defense Agency ACTD

The primary ongoing U.S. effort to develop an HAA is the MDA ACTD, which began in September 2003. This effort investigates the feasibility of a high-altitude airship (HAA) for homeland defense. Bolkcom (2004) summarizes the effort as follows: “The ACTD seeks to demonstrate a prototype by 2006 that could fly for 30 days at a time. Cost goals are for \$50

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<sup>1</sup> The Naval Airship program intended to build an Operational Development Model (ODM) airship, designated the YEZ-2A by the Navy, and Sentinel 5000 by the contractor, Westinghouse Airship Industries (WAI). The ODM concept was unique to that program and, although forgotten today, was a forerunner of today’s ACTDs.

<sup>2</sup> In 1988, the Naval Airship program transitioned to DARPA management, in the hope that multi-service applications could be found for the design. Regarding cost growth, optimistic cost estimates have been a hallmark of airship advocacy. It should be remembered that all the systems of a conventional fixed-wing aircraft are present in an airship: flight control and mission avionics, propulsion, electrical systems, environmental control, etc., and new systems are added: gas management systems and ground handling systems. Furthermore, designers are challenged by several unique airship operational requirements. For example, load distribution in nonrigid structures is problematic: mooring loads, thrust loads, acceleration loads, gust loads—all must be evenly distributed and reacted through a flexible airship hull. In general, there is no particular reason to believe that an airship should be significantly less costly than a fixed-wing aircraft of equivalent *mass* (as opposed to size or weight). It may well be more costly.

<sup>3</sup> The WALRUS concept considers a cargo capacity between 500 and 100 tons with a goal of being able to fly 60,000 miles in 4 days and be capable of delivering brigade-sized units of action anywhere in the world.

**Figure 2**  
**Early Suggested Design for the WALRUS HTA Airship**



SOURCE: Image courtesy Military.com.

million airships capable of flying for one year at a time. A total \$101.2 million has been provided thus far for HAA. MDA is requesting \$29 million for FY2005.” The characteristics of the ACTD HAA, taken from USASMDC (2004) and Lavan (2004b), are:

- Size: Experimental—430 feet long, 140 feet in diameter, and 3,700,000 cubic feet in volume; Objective—480 feet long, 150 feet in diameter, and 5,700,000 cubic feet in volume.
- Altitude: 65,000 feet.
- Airspeed: 30 knots.
- Endurance: ACTD—one month; Desired—one year.
- Coverage: 314 nautical miles (nm) line-of-sight.
- Guidance: Autonomous and exterior C2.
- Payload: 4,000 pounds and 10 kW in an internal pressured and temperature-controlled bay.
- Power: ACTD will have batteries and possibly fuel cells.
- Propulsion: Four electrically powered engines with 25-foot diameter propellers that vector in pitch.
- Launch: from CONUS; no foreign theater logistics.

The artist’s concept in Figure 3 shows the ACTD airship with a conventional dirigible shape and photovoltaic cells across the upper surfaces. Four engines, two on each side, will drive the airship at a cruise speed of 30 knots. A significant requirement is reconfigurable payloads. Prototype payloads will be approved by or furnished by the U.S. government.

**Figure 3**  
**Artist's Concept of MDA ACTD Prototype by Lockheed Martin**



SOURCE: U.S. Missile Defense Agency. Image courtesy Lockheed Martin Maritime Systems & Sensors.

Lockheed Martin Naval Electronics and Surveillance Systems—Akron was selected by the U.S. Missile Defense Agency in September 2003 to perform the HAA ACTD Phase 2 contract award.<sup>4</sup> The \$40,000,000 contract through June 2004 calls for the design of a prototype and risk-reduction efforts (Maritime Systems & Sensors, 2004). Lockheed Martin has an option for a Phase 3 to develop, build, and demonstrate an HAA prototype for \$50,000,000 by June 2006. A prototype may be built in Akron, Ohio, at the Akron Airdock, a hangar 1,175 feet long, 325 feet wide, and 22 stories high (GlobalSecurity.org, 2003).

HAA ACTD program documentation summarizes the effort as having “some technical risk” but “enormous potential benefits.” It also includes the acknowledgment that “HAA is a fast-paced program.” Against these statements, it is critical to note the following points:

- This program is attempting to design and fly by far the largest air vehicle built in almost seven decades (the largest since the German zeppelins Hindenburg and Graf Zeppelin II (both approximately 804 feet)).

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<sup>4</sup> Phase 1 was a concept definition study undertaken by three groups, including teams led by Lockheed Martin, Boeing, and Worldwide Aeros Corporation.

- This program is attempting to design and fly a nonrigid airship that is over twice the volume of the largest ever constructed. (The U.S. Navy's Goodyear ZPG-3W airship, flown until the early 1960s.)
- This program is attempting to design and fly a super-pressure light gas dirigible, never before attempted.
- This program is attempting to design and fly the first airship built for high-altitude operation since the zeppelin raiders of the First World War, vehicles that enjoyed the use of hydrogen rather than helium as a lifting gas. Long endurance at high altitude is easier for airships than airplanes, but achieving that high altitude is, if anything, much harder because increasing velocity to provide lift is not a viable option. For all reasons, other than weather avoidance, airships prefer low altitudes.
- There is substantial uncertainty surrounding all aspects of vehicle performance and control at this scale. Wind tunnel fidelity is dubious, the aerodynamic regime is unfamiliar, and the structural and control responses associated with such a large, flexible structure are unknown and difficult to predict.
- The desired operational altitude is at the limits imposed by flight physics, when considering available structural materials and their associated weights. This drives vehicle architecture toward designs with structural elements that have multiplicity of function (to save weight), e.g., nonrigid design, and photovoltaics integrated into the hull. This reduces system redundancy and consequently increases risk.
- The industrial base for this technology is practically nonexistent. Airship designers and operators associated with past efforts are largely retired or dead. The government has no institutional memory of efforts as recent as the Naval Airship program, which was carried through CDR solely to leave a complete airship design package available for future LTA efforts such as HAA—a trove of detailed design information that evidently lies untapped, if it still exists.

The ACTD demonstration, as planned, shares the faults of those conducted for many other air vehicles that are less than operationally robust. Specifically, the variability of the atmosphere, when combined with the immature state of the system, will ensure that HAA operations will be attempted only under the most benign of conditions. The demonstration thus runs the risk of proving only what is already known; a high-altitude payload has operational benefits.

The foregoing has discussed the HAA ACTD at some length, since it is the most relevant to future U.S. Army needs. Lockheed does have some competitors in the field with far less industrial gravitas. Three of these are discussed below in order to provide context.

### **Lindstrand Airship**

The European Space Agency (ESA) is developing a solar-powered airship being built by Lindstrand Balloons. The airship will have a single 8-meter diameter propeller. Fuel cells will store the sun's energy during the day and produce 90 kW at night to drive the propeller and provide 15 kW to power a communications base station payload. The fuel cells have a mass of 1.1 tons as compared to 16 tons for batteries of equivalent energy storage. At the present level of fuel cell efficiency, 8 percent, the Lindstrand airship will have enough daylight sunshine in the winter to provide yearlong coverage only between 45° latitude north and south. This limitation precludes its use in the London area during winter until fuel cells improve



but will be useful in areas like Rome and countries surrounding the Mediterranean Sea (Harris, 2004).

### **Ascender**

Ascender, a current project of the U.S. Air Force, is a concept for an unmanned vehicle to loiter at altitudes of between 100,000 and 120,000 feet for five days, carrying a payload of 100 pounds, and enjoying a surveillance radius of 370 km. A V-shaped prototype Ascender, 175 feet, was built by JP Aerospace working with the Air Force's Space Battlelab and Space Warfare Center at Schriever Air Force Base, Colorado. This prototype, shown in Figure 4, was scheduled to be flight tested at Fort Stockton, Texas in June 2004. The test called for the airship to climb to 100,000 feet (30.5 km), navigate by remote control, maintain position for a short time, and return to earth. A 93-foot variant has had successful tests in a hangar. The design feature that makes the altitude possible is the use of helium for lift and aerodynamic control. Some aerodynamic shape to the cylinder "wings" and the shifting of helium between wings is intended to aid the maneuvering of the Ascender (Boyle, 2004).

### **Dark Sky Station**

JP Aerospace is also designing shapes that can rise to 100,000 to 140,000 feet (30 to 42 km). The Dark Sky Station, shown in Figure 5, would drift at an altitude above 100,000 feet buoyed by helium-filled cells stretching out as far as two miles.

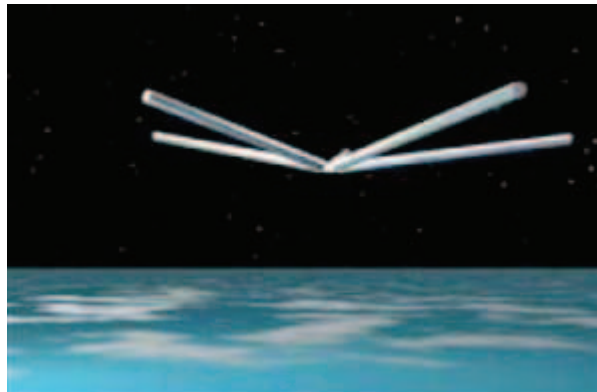
On the other hand, conventional scientific balloons regularly operate above 100,000 feet, and it is unclear whether the aerostatically inefficient shape and the associated challenges with load distribution of these segmented craft is worth the gain in maneuverability that may result.

**Figure 4**  
The V-shaped Ascender with 175-foot-long Sections



SOURCE: Image courtesy John Powell, JP Aerospace.

**Figure 5**  
The Dark Sky Station



SOURCE: Image courtesy John Powell, JP Aerospace.





## Missions and Payloads

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The ACTD lists these potential missions for HAA:

- communications relay,
- broadcast communications,
- missile warning,
- airspace surveillance and control,
- maritime surveillance and control,
- aerial and ground reconnaissance, surveillance, and target acquisition (RSTA),
- fires coordination,
- position/navigation,
- weather monitoring,
- battlespace environmental monitoring,
- electronic countermeasures,
- air defense (AD)/cruise missile defense (CMD)/tactical missile defense (TMD) weapons platform, and
- air-to-ground weapons platform (NORAD, USASMDC, 2003).

Airship missions envisioned for overseas theaters would start in the continental United States, where airships would be based and maintained. Basing airships in desert areas in lower-latitude locations with a high average of sunny days should minimize snow and icing problems if they are moored in the open. Isolated desert basing and island basing (for forward basing, discussed later) should also have a higher probability of good security because the uninhabited land or water areas surrounding the base would improve security surveillance and active response. Base location decisions might consider soil and elevation parameters that would allow the creation of sunken shelters of excavated earth and surrounding berms to form blast-resistant shelters on which football stadium-like sliding roofs could be installed to cover hangared airships. These hangars should be easy to construct, blast resistant, inexpensive, wind-resistant (a serious consideration in the desert), and operationally convenient for tie-down.

Intentions for the ACTD airship prototype are for the airship to climb at a rate of 2,000 feet/minute and, on return, to descend at 200 feet/minute. Descent is planned to about 2,000 feet over a landing site, where mooring lines will be dropped and attached to mechanical “mules” (ground handling vehicles). The “mules” will drive away from the landing point while winching in the mooring lines. The airship engines will turn up to drive the airship down onto a padded rail car. When the airship is successfully tied down, the engines

will remain up to press the airship down on the rail car for stability as it is driven into a hangar.

Ascent and descent will require air traffic control clearances, a situation that may limit flexibility in launch times. Launch and recovery windows will also be limited by the need to avoid severe weather. Weather monitoring and flight planning will be critical during flight operations. Some limiting conditions, such as turbulence, are discussed below.

Flying from CONUS to a theater, an airship faces two major factors: wind and solar efficiency. Enroute flight could be done in the atmosphere below 65,000 feet, utilizing winds of up to 200 knots in jet streams, as long as severe turbulence can be avoided. At these levels, airships must circumnavigate thunderstorms and other severe conditions.<sup>1</sup> Alternately, if winds or weather are adverse at lower levels, airships can climb above 65,000 feet, where winds should generally be below 10 knots and the weather calm. This situation would protect airships from adverse weather, but at a cruising airspeed of about 30 knots with no winds, enroute flight times will be long.

Solar cell efficiency, as well as wind, can affect the optimum routing of an airship. The need to generate its own power using a solar system will limit an airship's operating latitudes to areas with adequate daily sunshine. If an airship is not tasked to use its payload, e.g., to perform surveillance enroute and use power that would otherwise charge fuel cells for nighttime power, it should be able to fly at latitudes greater than that of an operational location where it will be consuming power for both the engines and payload.

The daylight differences affecting solar flux between summer and winter days are shown in Figure 6. The figure compares the power levels for the 36°, 40°, and 45° latitudes throughout a year at 17 km altitude (below the 20 km of the ACTD airship). The data indicate that the peak solar flux is 1.8–2.3 times as much on the longest summer day than on the shortest winter day.

When the two factors of wind and solar power are combined, the time enroute can be greatly affected. For example, an airship departing the Las Vegas, Nevada area and flying to Baku, Azerbaijan<sup>2</sup> in the summer, when the sun will predominate over the great circle route overlying Greenland, flying time at an average airspeed of 30 knots will be 8.6 days. If an airship can take advantage of lower-level favorable winds and achieve an average airspeed of 70 knots, the enroute time is reduced to 3.7 days. In the winter months, however, when an airship with currently anticipated fuel cells or batteries must remain south of about 45° latitude, flight times will be 10.1 days at 30 knots average airspeed and 4.4 days at 70 knots. The difference between the worst combination of wind and solar cell efficiency and the best in this example is 6.4 days.<sup>3</sup>

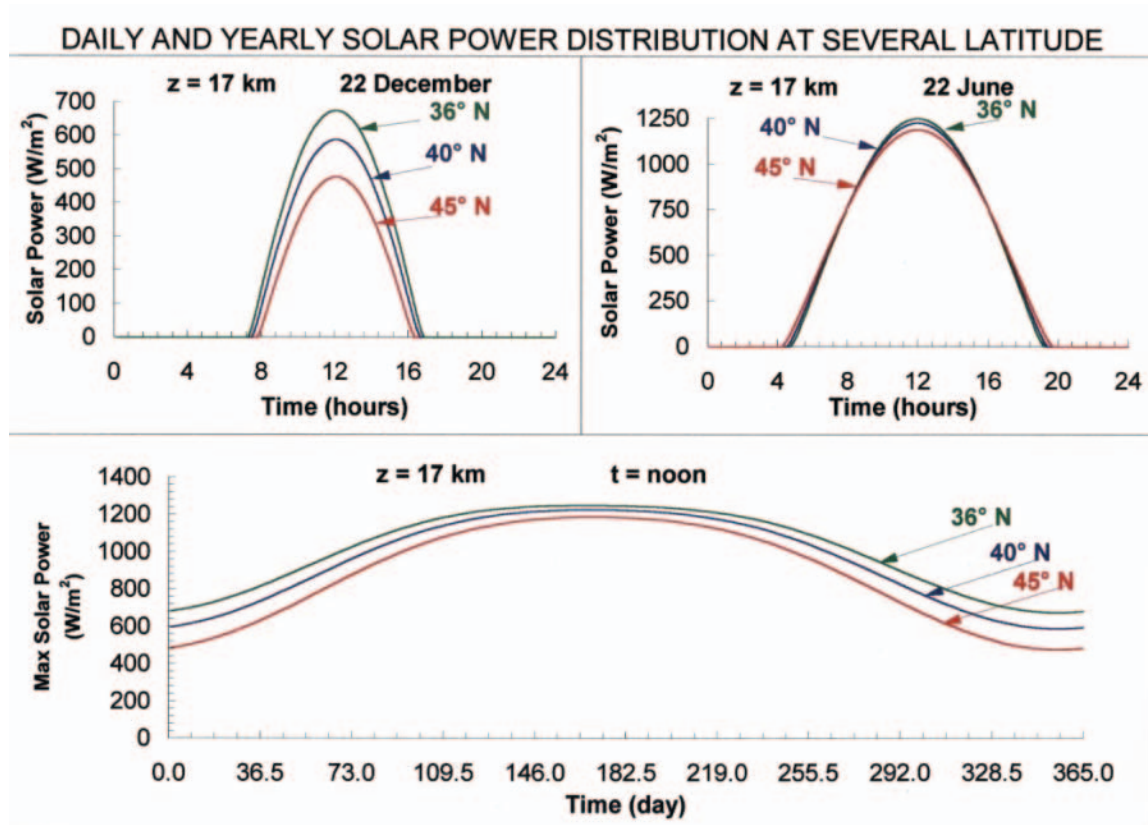
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<sup>1</sup> Note, however, from the previous discussion of HAA performance that at lower altitudes, the airship may not have the speed to avoid being blown into a thunderstorm. The designers of the YEZ-2A airship, even with its 90-knot top speed, were so worried about this that the normal weather radar field of view in azimuth was deemed insufficient.

<sup>2</sup> Distances used for Las Vegas to Baku were (1) a great circle route of 6,200 nautical miles (nm) and (2) a route following the great circle route to the 45° latitude, continuing on that latitude to intercept the great circle route to Baku for 7,300 nm.

<sup>3</sup> Note that the favorable winds at the lower altitudes must be greater than an average 40 knots on the tail (i.e., 70 knots minus 30 knots) since, as discussed above, airship airspeeds are reduced at lower altitudes. On the other hand, more fuel can be carried for fuel cells or sprint engines, if so equipped, since the lower altitudes allow a greater sea-level helium fill and consequently greater useful load. Airship cruise airspeeds can thus be increased above 30 knots, and which effect predominates depends on the details.

Figure 6  
Solar Flux



SOURCE: Illustration courtesy Giulio Romeo, Turin Polytechnic University.

Planners for an operating HAA will have to select an operating location that can assure that the airship will have the power to continuously operate its engines and provide the 10 kW of power for the payload aboard. Having to perform the assigned functions with the initial power limitation of 10 kW will limit the types of loads that can operate aboard the airships. Some useful communications and sensor packages should be feasible. With very low drag at high altitudes, an external configuration with antennas of all sorts should also be feasible, even though transits through lower altitudes are problematic.

## Communication Payloads

One possible communication system for HAA is the adaptive joint command, control, communications, computers, intelligence, surveillance, and reconnaissance (C4ISR) node (AJCN) for which DARPA, other government agencies, and BAE Systems are conducting an ACTD. The goal is to design a Joint Tactical Radio System (JTRS) and Joint Airborne SIGINT Architecture (JASA) compliant, programmable radio frequency (RF) system that supports multiple missions (i.e., communications simultaneously with communications intelligence (COMINT), electronic warfare (EW), and electronic operations. It will be software reprogrammable and have scalable architecture, automatic routing of voice and data, and an open system design. Because of its scalability and multiple missions, the AJCN is an-

anticipated to be the airborne communications node for the Multi-mission Maritime Platform (MMP) submarine, Future Combat Systems (FCS), Warfighter Information Network–Tactical (WIN-T), and potentially for the Multi-Sensor Command and Control Constellation (MC2C), Broad Area Maritime Surveillance (BAMS) UAV, and Multi-mission Maritime Aircraft (MMA). Air platforms would include sizes from the A-160 helicopter, Predator, and Global Hawk to smart tanker aircraft (NKC-135) (DARPA, 2004).

The BAE Systems specifications for the AJCN planned for the NKC-135 serve as an example of what an HAA might support for a multifunctional mission (DARPA, 2004). These are shown in Table 2.

An interesting comparison of the HAA with other platforms for the support of commercial television broadcasting was made by T. R. Tozer and is shown in Table 3.

Potentially, airships may provide communications satellite capabilities for the WIN-T network at less expense than satellites and increase communications capabilities by providing bandwidth alternatives not available on current satellites. An HAA communications platform should be a strong addition to the MC2C.

## Surveillance

The HAA is envisioned as a persistent eye-in-the-sky that can provide electronic and optical observation of a large country. From 70,000 feet, it would have line-of-sight coverage of 325 miles and could cover the area in Afghanistan shown in Figure 7, except for areas behind

**Table 2**  
**AJCN Specifications for the NKC-135 Aircraft**

SWaP	1500 pounds, 7.5 kW (within HAA ranges)
Simultaneous channels	15 transmit channels
Communications waveforms	Most of the conventional Army and Air Force waveforms plus others
Communication ranges	60–140 nm @ 30,000 feet (Air-Ground), 55–300 nm @ 30,000 feet (Air–Air)
Other	Jamming and Psychological Operations

**Table 3**  
**Comparison of Broadband Terrestrial, HAP, and SATCOM**

	Terrestrial (e.g., B-FWA)	HAP	LEO Satellite (e.g., Teledesic)	Geosynchronous Satellite
Station coverage (typical diameter)	< 1 km	Up to 200 km	> 500 km	Up to global
Cell size (diameter)	0.1–1 km	1–10 km	c. 50 km	400 km minimum
System deployment	Several base stations before use	Flexible	Many satellites before use	Flexible, but long lead time
Estimated cost of infrastructure	Varies	\$50 million upwards?	c. \$9 billion	> \$200 million

NOTE: It should be noted that transmission rate is determined by radio selection (and corresponding frequency and bandwidth allocation) and not wholly by the type of vehicle that hosts the radio.

SOURCE: Tozer and Grace (2001), p. 134.

**Figure 7**  
**HAA Line-of-Sight Radius**



high ground and mountains.<sup>4</sup> This loss of coverage worsens as the range from an HAA's sensor increases or its altitude decreases. The HAA's payload size and power should allow the support of surveillance capabilities such as that on the Global Hawk and those planned for the space-based radar (SBR) and the F-22. The intended SBR mission, control, and payload serve as good examples for surveillance HAAs. The planned SBR payload includes a synthetic-aperture radar (SAR) for imagery, surface moving target indicator (SMTI) with high resolution for enhancing discrimination and tracking, and digitized elevation model (DEM) data provided through high-resolution topographic information (HRTI) collection for production or precision targeting and digitized terrain data products (Siemens, 2003, Para 2.a). The SBR program of nine satellites has been cut severely in the final conference report from Congress for the 2005 defense budget (HR 4613—H Rept 108-622) (Anselmo, 2004).

<sup>4</sup> The HAA ACTD originally had a goal of a 70,000-foot mission altitude and a 4,000-pound, 15 kW payload. These have been reduced to 65,000 feet and a 10 kW payload (Cathy W. Spencer, "Missile Defense Agency Advanced Systems," briefing, March 2003). Line-of-sight radius to the horizon is thus reduced from 325 nm to 314 nm. It is conceivable that further reductions in mission altitude will occur as the program progresses. This was the pattern with the Global Hawk UAV ACTD.



The U.S. Army is developing a radar sensor for high-altitude battlefield surveillance that advocates say could augment existing satellite and airborne systems for battlefield surveillance and reconnaissance (Singer, 2004). It is called the Distributed Imaging Radar Technology (DIRT) system and reportedly would be able to collect high-resolution imagery and track moving targets—the two main capabilities envisioned for the U.S. Air Force’s proposed Space Based Radar. Quoting (Singer, 2004): “DIRT sensors would be mounted on platforms capable of loitering high above the battlefields for extended periods of time.” HAAs are envisioned as possible hosts.

Accuracy specifications for the SBR are classified, but if similar equipment were used aboard the HAA, the resolution of the HAA sensor products at surveillance distances of 22 km to over 500 km should be significantly better than the resolution of the space-based radar at 1,000 km from earth. Further, while the radar range from 22 km altitude will be much less, the radar null area at the center of coverage—the “nadir hole”—will be considerably smaller. Atmospheric attenuation of signals to and from an HAA, however, will be greater across the mean distance of coverage because of the relative increase in grazing angle and greater exposure to lower-altitude atmosphere.

The HAA could fill the role of or supplement the SBR in the surveillance network planned for the SBR. More study may be needed.<sup>5</sup> The HAA would feed its data to the MC2C, a theater constellation, and simultaneously to the Joint Surveillance and Target Attack Radar Systems (JSTARS), the E-8Cs, the Multi-Sensor Command and Control Aircraft (MC2A) and the Distributed Common Ground Stations (DCGS) of the Army and the Air Force. At these nodes, the HAA’s data can be fused with data from numerous other sources and can be disseminated to lower echelons for situation awareness, targeting, and bomb damage assessment (BDA) purposes. The persistence and resolution of its data should be invaluable to the theater constellation. The HAA surveillance would be allocated and tasked by the MC2C and also tasked by a Theater ISR (Intelligence, Surveillance, and Reconnaissance) Manager. HAA participation in the constellation would require modifications of the planned system (Siemens, 2003, Para 2.c.(2)(b)).

Persistent surveillance from a fixed position is an important need that HAAs can meet. Over time, they can facilitate continuous collection and comparison analysis of terrain covered by different sensors, such as IR, EO, and HSI. Comparisons can highlight changes like freshly turned dirt along a roadway where bombs have been emplaced, and fusion of data from multiple sensors may furnish tracking data on targets under foliage.

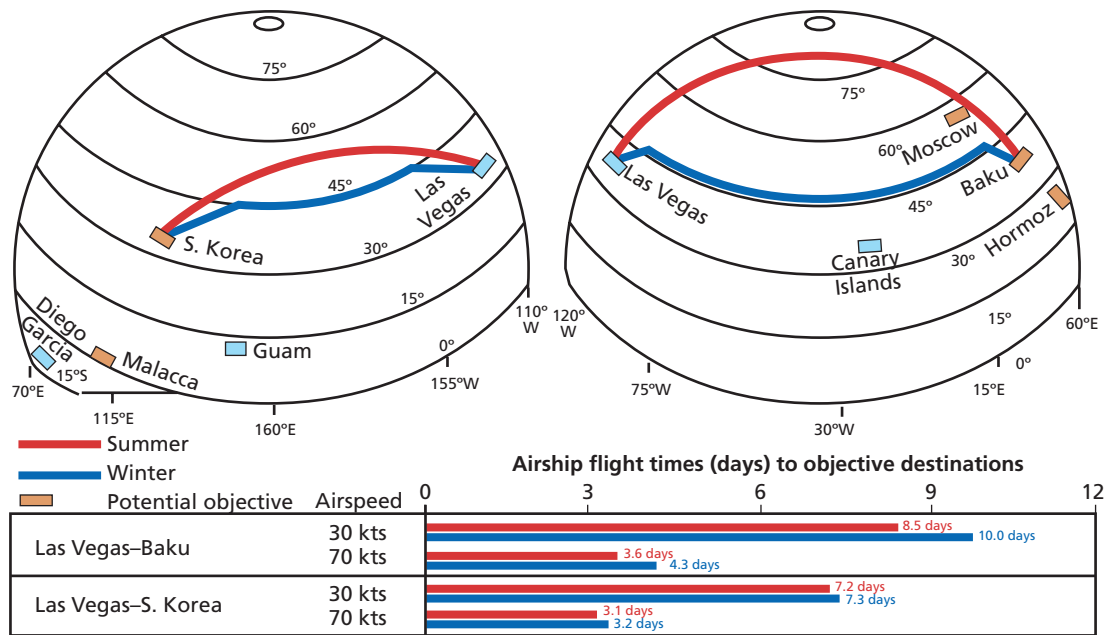
## Deployment Operations in Theater Missions

Combat commanders may wish to use HAAs as soon as possible in a crisis, but HAAs will take days to reach distant theaters after launching from the United States. Deployment times to orbits near Baku, Azerbaijan, and Taejon, South Korea, during the winter and the summer with airspeeds of 30 knots and 70 knots enroute are shown in Figure 8. Note that it could take ten or more days to reach Baku in winter months with no favorable winds.

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<sup>5</sup> Wiley (2004) notes that platform stability and velocity requirements to implement SAR capability on an HAA are a concern, as are the radar’s “deep cycle” power requirements.

**Figure 8**  
**Deployment Flight Routes to Forward Destinations**



Las Vegas-Baku distance is 6,085 nm in summer and 7,200 nm in winter. Las Vegas-South Korea distance is 5,215 in summer and 5,400 in winter.

The figure shows two potential routes: (a) routes that are great circle routes, the shortest distance between two points on a sphere, and (b) routes that begin and end as great circle routes; but at the intersection of a limiting latitude—45° north latitude in our example—the route continues along that latitude until arriving at the termination of the great circle route to the destination. The longer latitude route is necessary during the winter months because the hours of sunlight and energy generation by the solar cells are insufficient on routes further north to charge the batteries or fuel cells with enough energy to drive the electric motors and support systems through the night. The 45° north latitude used in our example should be considered the worst case for the shortest winter day and for solar cell efficiencies that should hopefully improve in the future. Note that the Las Vegas–Baku great circle route passes over Russia and to the east of Moscow.

The routes pass over many countries, most of which are friendly to the United States. Each requires prior arrangements and often a diplomatic clearance to fly in the airspace of the overflowed country. If a clearance is denied, the country must be avoided and time-consuming course changes are made necessary. The U.S. Transportation Command controls aircraft flying over countries all over the world and routinely arranges clearances for overflights and landings daily. The fact that HAAs are unmanned may cause some red tape and delays with air traffic control, but a precedent was set with the flights of an unmanned Global Hawk aircraft from the United States to Australia and later return flights. These flights pointed the way for acquiring air traffic control clearances from the Federal Aviation Administration (FAA) for U.S. operations and the International Civil Aviation Organization (ICAO) for international operations.

Once in theater, an HAA can be assigned a geostationary location to provide persistent battlespace coverage according to the needs of the theater commander. This coverage will have the advantages over satellites of shorter ranges to surface objects and persistence that orbiting satellites cannot provide.<sup>6</sup> Also, an HAA could conceivably be more responsive to a commander's needs in changing coverage more quickly than satellite coverage can be adjusted.

Included on the hemispheres in Figure 8 are the locations of the Straits of Hormuz and the Straits of Malacca as well as Baku and South Korea to illustrate the relative positions of these potential trouble areas to the United States. The great distances to these locations from the United States make the option of forward-basing HAAs during periods of rising international tension a consideration. Further, maintenance limitations on-station may require more frequent rotation of HAAs than planned. The ratio of enroute time to operating time may become unacceptably high without forward deployment. Placing mooring locations and below-surface shelters at locations such as Diego Garcia, Guam, and the Canary Islands would provide protective environments to HAAs if forward combatant commanders decide that a faster reaction time is needed.

Control facilities and communications for the control of HAA flight maneuver and payload operations can be similar to the systems used to control satellites and Global Hawk. Each of these functions could be performed by different sets of people using different communications for each and usually in different physical locations. However, consolidation of the HAA control system with SATCOM or Global Hawk controls could save infrastructure development and installation funds. Army CONUS command and control authorities can have direct communications with the HAA control system regardless of its location. So long as communications are assured, such operations could be optimum. At the same time, the ability to task the payload from the battlefield would be a valuable capability that should be considered.

The next chapter will discuss various limitations and vulnerabilities of HAAs.

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<sup>6</sup> Wiley (2004) counter-argues that shorter ranges to surface objects are not always advantageous because a reduction in distance to the relay platform also reduces the requirements to effectively jam the system.



## Airship Limitations and Vulnerabilities

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### Structural Issues

Hull fabric strength determines the largest feasible size for a nonrigid airship (such as an HAA). Hoop stresses rise with diameter, and in a nonrigid airship, this diameter must be relatively large because of the need to resist hull-bending moments (the same moments that cause “hog” and “sag” in a surface ship). Although great advances have been made in airship fabric technology over the last thirty years, an HAA has unique requirements that demand further improvements.

An HAA must stay aloft for a period of months. This is demanded both for reasons of persistence of mission services and to minimize time spent ascending and descending through the potentially hazardous, turbulent lower atmosphere. Consequently, leakage of helium through the skin must be minimized, an enormously difficult task. It is likely that helium permeation will represent the binding constraint to HAA endurance.

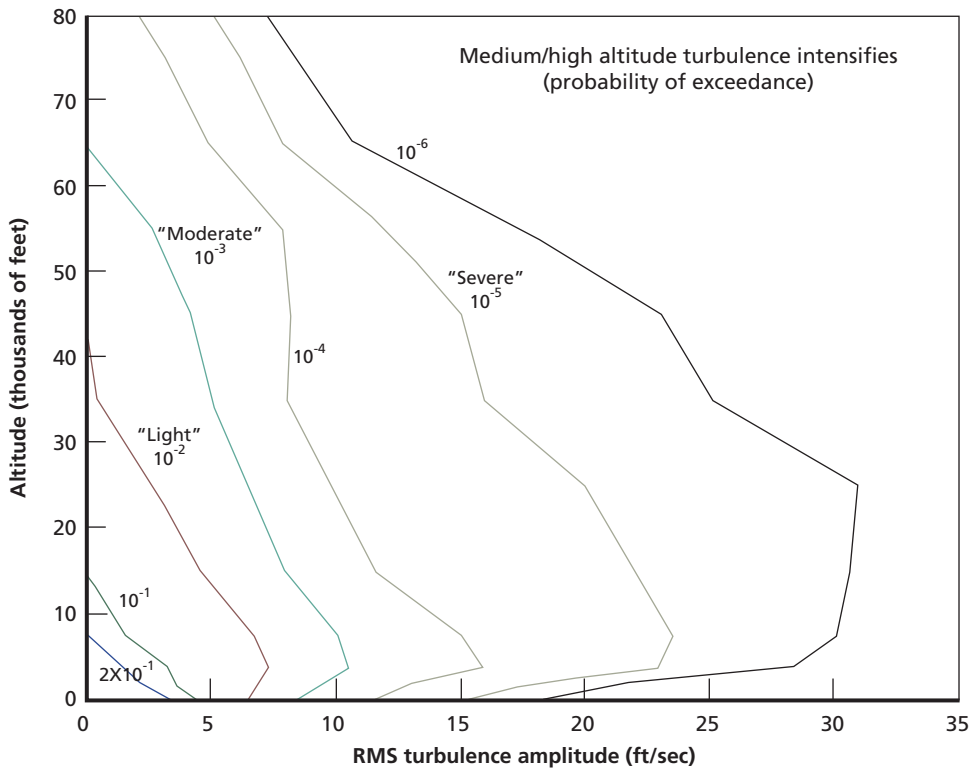
Ultraviolet (UV) radiation at high altitudes will degrade the HAA hull fabric. UV degradation is already a concern for today’s airships and aerostats that operate at low altitudes, and the Tedlar UV barriers used in many of those vehicles are inadequate at higher altitudes.

The HAA is a super-pressure airship. This means that diurnal temperature variations have the effect of raising and lowering airship internal helium pressures (rather than raising or lowering airship lift). This design avoids the flight path and gas management problems usually associated with superheat, but at the expense of higher stresses in the hull fabric. Incorporation of a metallized, reflective coating into the hull fabric has been suggested. But this specific suggestion would require further study, since there may exist some valid concern that the use of a reflective envelope could increase the radar cross section and create other problems for both radar and communication systems (Wiley, 2004).

The design and testing of airship fabric relies to a great degree on empirical techniques. Problems of wide variation in test results have generally been handled by ensuring that large factors of safety are incorporated in hull strength specifications. An HAA, because of its required altitude performance, has a much lower payload weight-fraction than a low-altitude airship; hence, any growth in design empty weight has a greater likelihood of resulting in “negative payload.” In a very real sense, the HAA designer is operating in a “coffin

corner” that is analogous to that associated with high-altitude fixed-wing aircraft. There will be two almost irresistible demands on the airship designer from his or her management: one is to reduce hull factors of safety, and the other is to relax design gust criteria.<sup>1</sup> One might think that a solution might be to reduce HAA operating altitude below 65,000 feet. The problem is that even a 5,000-foot decrease in altitude results in a much stronger gust for a given probability of exceedance (see Figure 9), thus increasing the strength requirements for the hull and consequently its weight.

**Figure 9**  
**Turbulence**



SOURCE: The MathWorks, Natick, Massachusetts. See <http://www.mathworks.com/access/helpdesk/help/toolbox/aeroblks/drydenwindturbulencemodelcontinuous.html>.

<sup>1</sup> Gust criteria have an enormous influence on airship hull strength requirements and thus airship weight and, in the case of an HAA, sheer feasibility. The main difficulty here is that gust criteria have been developed over the years for fixed-wing aircraft whose size relative to the gust scale length (1,750 feet, according to both MIL-F-8785C and MIL-HDBK-1797) is small, whose speed relative to the gust velocity is high, and whose structures deflect in response to a gust in a manner entirely different from those of airships. Thus, the fact that an HAA is designed to extant gust criteria gives false comfort. The aerostructural interactions of an ultralarge airship with the real atmosphere are difficult to predict. This was an unpleasant realization for the managers of the Naval Airship program, and the situation is unlikely to have changed in the years since.

## Control Issues

To put matters into perspective, the HAA is somewhat larger than the YEZ-2A design<sup>2</sup> yet has about one-twentieth of the installed propulsive power. The YEZ-2A was designed to cruise at 40 knots for 2.5 days, with a “sprint” speed of 80 knots. In 2002, the program objective for the HAA was a cruise speed of 35 knots for 23 days, and 90 knots for another seven days.<sup>3</sup> The MDA HAA, however, is being designed for a 30-knot cruise speed.

The reason for this difference is simple. The HAA propulsion system is matched to the vehicle’s operating altitude. The low air density at the design point altitude of 65,000 feet allows similar speeds to be reached with much less power. The solar-electric propulsion of the HAA would not allow higher installed power in any event. This means that an HAA with a maximum airspeed of 90 knots at 65,000 feet will have a top speed of only 38 knots (reduced by the cube root of the air density ratio) at sea level. Consequently, HAA operations in the lower atmosphere will always be difficult. Ascents and descents will need to accommodate long segments where the vehicle is being blown downwind, which complicates airspace issues. More seriously, airship control near the surface is impaired. It is often forgotten that a lifting gas reduces an airship’s weight but not its inertia. Furthermore, a revelation from the Naval Airship program was that not only the airship’s mass but also the mass of entrained air behind or above the vehicle must be considered when calculating airship dynamic behavior.

It may seem trite to say, but an airship runs into trouble when it blows away and then runs into hard objects.<sup>4</sup> Forces on an airship are extremely large because of its “sail area,” and the vehicle’s inertia is considerable. To resist these forces, and to thus increase operational robustness, an airship pilot has lift control and power control at his disposal, but only if designed into his vehicle.

Lift control can be provided by two means: (1) instantly jettisonable ballast (e.g., drop tanks, fuel or water ballast discharge through pipes) provides prompt aerostatic net lift; and (2) helium venting, in a noncompartmented nonrigid airship by means of a “rip panel” at the top of the airship hull. Power control can be provided by a “sprint engine,” a small and allowably inefficient engine selected for low empty weight, probably turbomachinery.<sup>5</sup>

The point of all this is not that such features are necessary for the HAA ACTD. They will, however, probably be necessary for an operationally useful HAA. Unfortunately, features such as these, intended to increase system robustness, will also tend to reduce HAA ceiling and endurance, which may bring the airship down into weather and controlled airspace and increase its exposure to low-altitude events that the features themselves are designed to counter.

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<sup>2</sup> YEZ-2A was the official designation for the DARPA/Navy Airship of the 1980s/1990s, where Y refers to “prototype,” E refers to “electronic mission,” and Z refers to “airship.”

<sup>3</sup> “High Altitude Airship Industry Day Briefing, Program Objective,” October 23, 2002.

<sup>4</sup> A summary of design features intended to increase the *environmental* (as opposed to military) survivability of large airships is found in G. Sommer and R. Adams, “Airship Survival—Damage Avoidance and Control for Large Ocean-Going Airships,” *8th LTA Technology Conference of the American Institute of Aeronautics and Astronautics (AIAA)*, Jacksonville, Florida, October 1989 (AIAA-89-3166).

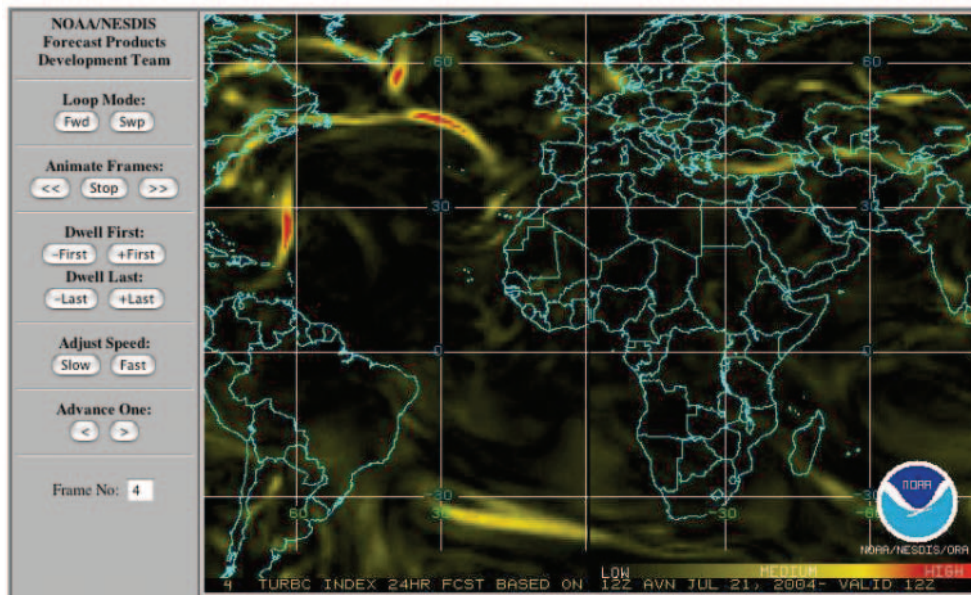
<sup>5</sup> The YEZ-2A design was modified to include turbine “bow-thrusters” for ground yaw control as a result of operational evaluation of a smaller demonstrator airship, the WAI Sentinel 1000. This was in addition to its General Electric T700 sprint engine used for continuous high speeds.

## Weather and Choice of Operating Altitude

HAA will be concerned with the weather in the troposphere, i.e., from ground level to about 37,000 feet (in standard day conditions), and the stratosphere up to the planned operational minimum altitude of 65,000 feet.

As HAAs fly to and from their assigned stations passing through the troposphere, they will pass through various weather conditions. Turbulence in thunderstorms and on the edge of jet streams can damage or destroy an HAA, so severe turbulence must be avoided. Thunderstorms are plotted on weather maps and tracked on radar. Clear air turbulence can be visualized in a National Oceanic and Atmospheric Administration/National Environmental Satellite, Data, and Information Service forecast of the Deformation—Vertical Shear Index (DVSI)<sup>6</sup> as shown in Figure 10.<sup>7</sup> The map shows high nonconvective turbulence near jet streams across the Atlantic Ocean as they existed on July 21, 2004. These areas must be avoided. Turbulence data in another format and data on thunderstorms and lightning are also available from the Aviation Weather Center.<sup>8</sup> To counter the threat of wind shear, HAAs might be equipped with the sort of microburst sensors currently installed on some aircraft and used for shear avoidance during approaches and landings.

**Figure 10**  
Example of Clear Air Turbulence at 30,000–34,000 Feet over the Atlantic Ocean, July 2004



SOURCE: Courtesy Gary Ellrod, NOAA/NESDIS.

<sup>6</sup> DVSI combines east-west and north-south horizontal wind variations and vertical wind shear between two pressure areas and indicates a strengthening of an upper-level front.

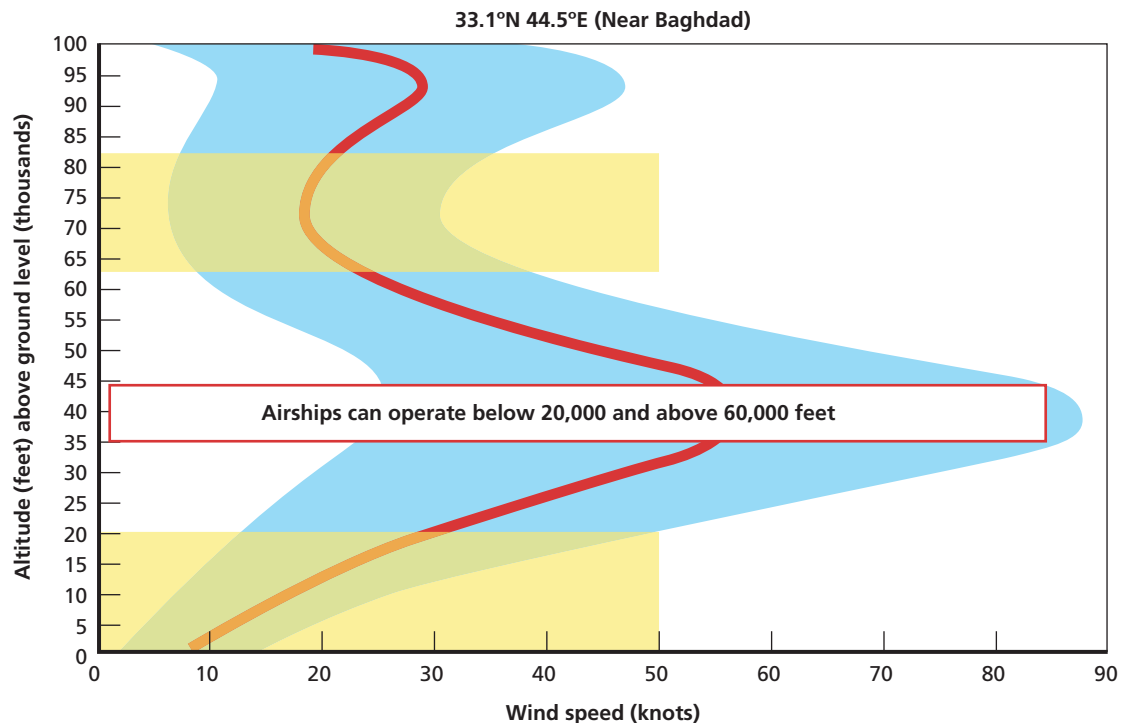
<sup>7</sup> This forecast was retrieved from the National Satellite, Data, and Information Service, which has a web site available at <http://www.orbit.nesdis.noaa.gov/smcd/opdb/aviation/turb/tifcsts.html>.

<sup>8</sup> The Aviation Weather Center is at <http://aviationweather.gov/>.

The Navy used airships, as long ago as the 1920s and 1930s, when their biggest threat was stormy weather. Without good weather forecasting, airships on missions faced severe conditions. In one of the worst naval airship disasters, 73 crewmembers were killed in 1933 when the USS *Akron* crashed in a storm off the New Jersey coast. Eight years earlier, 14 crewmembers were killed when the USS *Shenandoah* was lost in a storm over Ohio.

In the stratosphere, winds at 70,000 feet average about  $\pm 8$  knots in most parts of the world (Hitchman et al., 1997). Generally, turbulence on the edges of tropospheric jet streams, even on the hottest days, will rarely occur above 60,000 feet, so conditions at the DARPA HAA operating altitude of 65,000 feet should normally be benign. See the profile of peak wind speeds in Figure 11. Winds and temperature at high altitudes may vary during polar anomalies, such as sudden stratospheric warming (SSW) and convection waves between the troposphere and stratosphere. During a SSW, polar stratospheric temperatures rise by tens of degrees Celsius, the normal easterly polar flow can reverse in a few days, and the polar vortex can move south to about 80° north, usually over Greenland (Limpasuvan, Thompson, and Hartmann, 2004). In the troposphere, these events produce cold, stormy weather over the Atlantic Ocean and Europe. SSWs occur only in the winter and normally have a 30- to

**Figure 11**  
**Annual Winds Aloft Near Baghdad**



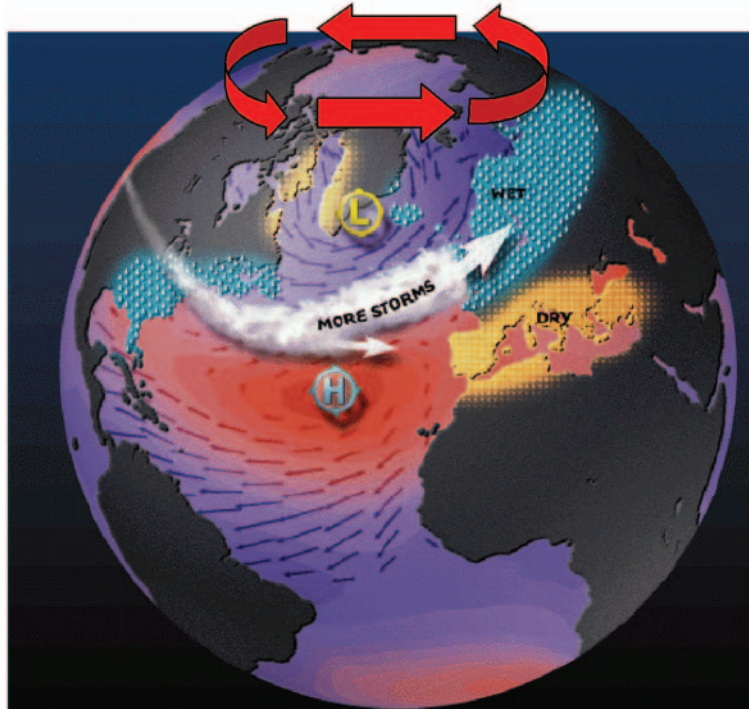
NOTE: Summary product created from raw weather data collections provided by AFCCC/DOPT (Asheville, North Carolina) dated from 1958 through 1990.

SOURCE: Stephen Huett, Director, Advanced Development Program Office for Airship Concepts, Naval Air Systems Command, "Current State-of-the-Art for LTA Systems," briefing, January 2005. Used with permission.

60-day cycle. During a mature stage of a polar vortex cycle, stratospheric horizontal and vertical wind speeds can reach 30 knots. Wind and temperature anomalies descend from the upper stratosphere to the middle troposphere. Turbulence increases in these areas. The movement by the polar vortex to an Atlantic location results in the area over Alaska having less wind and turbulence.

In summary: The rationale behind airships operating above 65,000 feet<sup>9</sup> is provided in Figures 9 through 12. Figure 11 shows wind speeds<sup>10</sup> at various altitudes and indicates (along with Figure 9) that most weather occurs in the troposphere.<sup>11</sup> The altitudes that are considered for HAAs are chosen because they facilitate solar-powered station-keeping, which requires a fairly benign environment. Clearly, there is at least one sweet spot where wind and turbulence are minimal. It is an area of the atmosphere<sup>12</sup> that is above the jet stream<sup>13</sup> and below the high winds of the upper layers of the stratosphere (between 20 and 30 km).

**Figure 12**  
**An Intense North Polar Vortex During Winter Months**



SOURCE: Image courtesy Dr. Martin Visbeck.

<sup>9</sup> But well below 350,000 feet.

<sup>10</sup> 10 m/s (meters/second) equals 19.4 knots (nautical miles per hour).

<sup>11</sup> The actual “boundary” of the troposphere varies with season and latitude. For example, in the tropics, thunderstorms have been known to rise to 50,000 feet.

<sup>12</sup> Wind speed is different at different heights.

<sup>13</sup> The jet stream can exist between 25,000 and 40,000 feet (7.6 to 12 km) with winds that can exceed 130 knots.



Airships historically handle snow and ice well when in flight. No blimps were lost to icing in World War II. In the Naval Airship program, it was believed that the greatest cold weather threat to an airship was wet snow while it was moored to a mast. Lightning is more problematic: likely points of attachment and pathways for the current are predictable for fixed-wing aircraft, and test facilities exist. However, a slow-flying nonrigid airship will have different electromagnetic characteristics: this issue was a significant concern in the Naval Airship program before its ultimate cancellation. Nevertheless, an HAA has a tremendous advantage over the YEZ-2A. An HAA can climb above all weather and loiter above weather until the way is clear for its descent when needed.

## Power Issues

HAA power in the DARPA HAA and other future airship designs will consist of solar cells on top of the airship to collect the sun's energy, and batteries (and possibly fuel cells later) to store daylight energy and furnish nighttime power. Power demands will arise from the electrically driven propellers, airship support machinery such as gas pumps and compressors, and the payload. Solar cells have to furnish the necessary power at an acceptable weight. Some sample achievements and objectives in the community are the following. Photovoltaics that have a specific power of over 1,400 watts per kilogram have been successfully produced by DayStar Technologies.<sup>14</sup> A power demand of 90 kW, published for the Lindstrand airship, would result in a weight of 64.3 kg for the solar array. DayStar estimates a cost of \$20 million for a plant to produce solar cells for 100 megawatts per year (Missile Defense Agency, 2003).

## Gas and Heat Management Issues

The Lockheed Martin HAA will have four sections or cells in which helium is allowed to expand as the airship rises. It will rise until the helium is fully expanded (which defines the airship's pressure height). For the Lockheed Martin HAA, design pressure height will be 65,000 feet. Variations in atmospheric pressure will result in the airship's actual altitude above mean sea level varying by about plus or minus 500 feet. It is critical for load distribution and consequent stresses in the airship hull that the helium cells expand and contract at the same rate. Note that the Naval Airship program considered and rejected such compartmentalization in its nonrigid airship design. This followed the dictum of Burgess (1934), who advised against such measures.

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<sup>14</sup> Daystar Technologies was contracted in 1999 by the Ballistic Missile Defense Office (BMDO), precursor to the Missile Defense Agency. A continuous in-line manufacturing process must be developed to produce cells at an affordable price. United Solar Ovonic, funded by the U.S. Air Force, is developing UNI-SOLAR modules suitable for space conditions with demonstrated specific power of greater than 1,250 W/kg and a goal of 2,500 W/kg (United Solar Ovonic, 2001).

## Operational Issue: Air Defenses

An HAA may be subject to airborne and ground dynamic and electronic attacks. The HAA structure may have the advantage of a low radar cross section (RCS), and there is likely to be little infrared emission from the motors. However, the airship will have distinctive IR emissions during daylight from the high temperature of the skin and internal gases accumulated from the continuous sunshine of the day. Depending on its payload, an airship will have the RF signature of any platform emitting RF communications broadcasts or the emissions of a surveillance radar.

A dynamic attack could be made by an airborne platform—fighter, bomber, or UAV—detecting an airship and firing a missile with enough energy to climb from the attacking platform's altitude to the airship. If our air defense system allows some platform to penetrate to the firing range of an advanced air-to-air missile—about 100 nm—detection and target acquisition by an attacker platform and guidance for a missile might occur using some combination of

- RF radar detecting the HAA's payload,
- Passive radiometer detecting an object against space,
- IR sensor detection of an airship's warmth (estimated to be 0 degrees Centigrade or 273 degrees Kelvin at night) against a background of the surrounding cold, black space (about 4 degrees Kelvin),
- RF seeker against any RF communication broadcasts from the airship payload, and
- Radar signal detection of any active surveillance radar signals.

Detecting a stationary platform that may have a very small radar and thermal cross section will be a challenge for any air defense system. Conclusions about the vulnerability of HAAs to air defenses will have to await the ultimate composition of HAA structures.

Countermeasures for airships are possible. The AN/ALQ-214 Integrated Defense Electronic Countermeasures (IDECM)<sup>15</sup> used on aircraft could be modified for and installed on airships. However, the lack of movement by the airship would severely limit the effectiveness of the decoy countermeasures. Decoys towed behind fast-moving aircraft effectively offer alternative targets to missiles. A similar alternative for a slow-moving airship will be difficult to furnish unless decoys with IR and electronic emissions can be floated away from an airship to lure missiles. Lack of movement ability will also deny the escape tactics used by high-value targets, e.g., AWACS, in West Germany during the Cold War of flying away from airborne threats approaching from East Germany.

Dynamic attack by a ground-based missile with the energy to reach 65,000 feet is also possible. Missiles that could reach 65,000 feet and have a range of over 100 nm are the Russian SA-5, SA-10, SA-12, SA-20, and the export model S-400. The basic specifications for the SA-20 follow Lenox (2004), but calculating missile performance for a high-altitude engagement needs additional classified data.

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<sup>15</sup> An IDECM suite consists of a radio frequency (RF) subsystem to divert RF SAMs and the Advanced Threat Infrared Countermeasures (ATIRCM) system to counter IR-seeking missiles. Both systems employ an AL/ALE-47 dispenser of smart chaff and flares. A towed decoy on aircraft used by the RF subsystem to emit a distracting signal is an essential part of countermeasures (Military Periscope.com, 2004).



- Weight: 1,840 kg
- Warhead: 180 kg
- Guidance: inertial with updates and semi-active radar with track-via-missile
- Range: 200 km
- Surveillance radar range: 300 km
- Engagement radar range: 120 km

The SA-10/20 missile has been exported to Eastern Europe, the Middle East, former Soviet states, India, Greece, and other nations. China has produced the MIM-104 2000 using SA-10 technology (Lenox, 2004).

The blast force of a SA-20 180 kg high-explosive warhead, assuming it is fused to achieve an explosion within an airship envelope, should destroy an HAA. An expanding rod warhead should also destroy the airship. No test data or estimates of damage have been found for a hit from a Russian SA-20 surface-to-air missile. The effects of a proximity explosion at different distances are unknown.

For the effects of small munitions, the Defense Evaluation and Research Agency (DERA) subjected a small nonrigid airship to combat damage and found that it could withstand numerous holes but could not maintain its altitude of 15,000 feet. In these tests, the damaged airships descended to the ground in complete control for varying periods of time.<sup>16</sup> A danger to an airship is a long tear in the hull that allows lift gas to escape rapidly, and so tear strength to resist “unzipping” is as critical as static strength when selecting an airship hull fabric.

## Risk Areas

The specific areas of technical risk shown in Table 4 are based on a review of contractor design data, a review of LTA technical literature, and the experience of the authors with prior HALE UAV and LTA programs.

There is a very tight interaction between technical risk and operational utility. It is not clear if these risk areas can be successfully managed. However, risk could be reduced by restricting the use of the airship in adverse conditions, by accepting reduced performance, even if combat operations are constrained, or by providing extra airships to relieve those on station when environmental conditions warrant. In fact, there are recent assessments (Siomacco, 2005) suggesting that the technical risks are too high for even proceeding with the HAA ACTD. Furthermore, there will always be those risks that are unpredictable and that can result in catastrophic and unexpected system failure. These risks stem from the stochastic nature of the environment in which the vehicle operates: the effects of weather and, particularly (in the case of an airship), wind.

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<sup>16</sup> 200 small holes from machine gun fire through the envelope resulted in pressure loss sufficient to make the airship unflyable (about one-seventh of the gas volume). The time needed to make a controlled descent to the ground was 25 minutes if ballonets (air envelopes inside the exterior helium envelope) were pressurized and 138 minutes if ballonets were not pressurized. In further tests, an aerostat at 15,000 feet was subjected to 25 rounds (50 holes) of 50-caliber machine gun fire, and the vehicle descended to the ground gradually for over three hours. With one Stinger missile, the airship at 15,000 feet took 1.4 hours, and with 50 rounds (100 holes) of 20mm cannon fire it took 0.7 hours before it was on the ground (CAA, App G, 2001).

**Table 4**  
**HAA Issues and Risks**

Issues	Risk Management Approach
Envelope material (strength and weight)	Restrict ascent/descent conditions
Thermal control (superheat)	Incorporate reflective envelope
Helium leakage	Limit endurance; use hydrogen from fuel cells
Photovoltaic cells	Limit endurance
Fuel cells	Use Li-polymer batteries as fallback
Weatherability	Restrict ascent/descent conditions; improve weather prediction; provide emergency ballast dump; add sprint engine(s)
Survivability	Operate within own air defense envelope
Airspace access	Restrict ascent/descent locations and times
Launch/recovery	Mechanization; restrict ascent/descent locations/times

Many of the risks depicted in Table 4 can be managed by operational restriction. However, envelope strength, weatherability, and launch and recovery all interact and are problematic in the sense that conditions will arise that are not forecast.<sup>17</sup> When this occurs, it will be of little solace that such conditions were beyond those exercised in the ACTD demonstration plan. The vehicle will be lost.<sup>18</sup>

A review of operational experience with existing commercial airships, coupled with prior airship operations in the U.S. Navy (and interviews by Naval Airship program office personnel with then-surviving airship pilots) resulted in the following principles that can be applied to HAA design with a corresponding increase in operational robustness.

“Sprint power” is essential. When combined with vectoring propulsors, excess power can both increase robustness to transient conditions of high headwind and improve vehicle response to pitch and yaw disturbances. The weight of the more capable power system (and its fuel) may be offset to a degree by a reduced empennage weight, which normally represents a large fraction of total vehicle empty weight.

Immediately disposable ballast is essential to allow instant recovery from difficulties during ground handling. Altitude is an airship’s equivalent of “sea room” in nautical parlance. Immediately disposable lift is essential to allow the airship to collapse to the ground in the event of difficulties. In a nonrigid airship, this takes the form of a “rip panel” at the top of the envelope (although the sheer size of the YEZ-2A and any future HAA causes difficulties of implementation).

Operational flexibility can be greatly enhanced by trading payload for ceiling. Sea-level helium fill can be increased when the mission (and enroute weather) does not require high altitudes.

<sup>17</sup> Historically, this has been a major cause of loss of the surveillance aerostats on the U.S. southern border: thunderstorms bear down on the sites before the aerostats can be fully winched down.

<sup>18</sup> This was a fallacy realized early in the Naval Airship program. Contractors would design to “10 percent wind exceedance curves” (because, for example, a 1 percent exceedance curve would require truly prodigious amounts of propulsive power). Yet this implied that 10 percent of the time, the airship would either be held on the mooring mast, if lucky, or blown out to sea; an unacceptable result.

Finally, notwithstanding the design gust specifications, eventually a gust will arise that will destroy an HAA. Given that the cost of an HAA is predominantly concentrated in its payload, consideration should be given to equipping an external payload module with wings or a parachute to allow it to separate cleanly from the collapsing envelope above for recovery by friendly ground personnel and subsequent refurbishment. In recent history, airships have crashed with regularity, but “hull losses,” in the insurance sense, are rare since LTA flight is inherently nonenergetic.

Airships may be vulnerable to air defenses. Air dominance may be a prerequisite for airship operations near enemy-held areas. Complete destruction of long-range surface-to-air missile units will probably be necessary before the full communications and surveillance strengths of airship payloads can be realized on the battlefield. With that accomplished, however, the airships’ ability to rise to heights above the range of most air defense weapons and to operate in a benign high-altitude environment should allow these platforms to survive. Detecting a stationary platform that may have a very small radar and thermal cross section will be a challenge for any air defense system. Conclusions about the degree of vulnerability of HAAs to air defenses will have to await knowledge about the ultimate composition of HAA structures and payload equipment.

Weather will be a risk factor that could be significant if airships are not furnished with reliable sensors for on-site meteorological data with which their controllers can predict turbulence, icing, and violent gusts that can jeopardize the craft. The experience with high-altitude tropospheric operations from around-the-world balloonist teams and weather teams must be collected and codified to aid computer predictions at higher altitudes. This aspect of airship operations will take strong preparation and close attention during operations.

An airship will be in the troposphere for over five hours while descending<sup>19</sup> to its home mooring base. The conditions in 65,000 feet of airspace at a home location will have to be within allowable weather parameters before a letdown can commence. This requirement could cause an airship to hold at 65,000 feet for up to two to five days before descending. Launch operations could cause similar time delays, although the ascent should be at a faster 1,000 feet per minute or 65 minutes long. Operational planning may have to allow days of nonproductive time in an airship rotation schedule for an ongoing operation.

Beyond proving the physical feasibility of using HAAs for communications relays, surveillance, and other tasks, a major feasibility challenge for military acquisition of HAAs is the issue of funding. A number of commercial uses for lower-altitude airships have been proposed. Scientists and entrepreneurs in the United Kingdom have been examining the usefulness of HAPs, either airships or airplanes, to serve as fixed, wireless communications and television relays over urban areas.<sup>20</sup> Potential military users will prefer to share development and production costs with civilian users and, in fact, may insist on a cost-sharing arrangement before contracting for HAAs, as has happened with low-altitude, heavy-lift airships.

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<sup>19</sup> The HAA ACTD airship will descend at about 200 feet per minute.

<sup>20</sup> Commercial HAAs would most likely be solar-powered with fuel-cell storage. Successful demonstrations of high-altitude operations, solar cells, and fuel cells are needed before serious commercial funding is anticipated (Tozer and Grace, 2001).



## Alternatives

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From a cost standpoint, it is difficult to compare future long-loiter UAVs (heavier-than-air [HTA] vehicles) with yet-to-be-built HAAs (lighter-than-air [LTA] vehicles). Some comparisons can be made between existing endurance UAVs (e.g., Global Hawk) and past efforts to design airships. This is shown in Table 5, which contains approximate estimates of cost.

**Table 5**  
**Approximate Cost Comparisons**

Global Hawk	\$70 million
Past airship costs	\$7.5 to \$75 million
Weight-based airship cost estimate	\$25 million
Military satellites	Hundreds of millions

Global Hawk production is minimal, so it is hard to assess its true, “high-volume” unit costs. Some assessments from past development work<sup>1</sup> can be used. On a per-unit cost basis, cost goals (in the past) for the Global Hawk have been as low as \$10 million, but the most recent assessment by the General Accounting Office (GAO, 2004) puts the per-unit cost to be over ten times that goal. Specifically, the GAO assessed the procurement cost to be nearly \$70 million dollars per unit. When development costs are included, that estimate is reported to be \$123.2 million for 51 air vehicles and 10 ground stations. Some proponents of HAAs foresee per-unit costs as much less.

For HAAs, a 70-meter aerostat system was about \$15 million in 1992. A Skyship 600 airship was about \$5 million. The Westinghouse YEZ-2A was estimated to cost about \$50 million in mid-1980s dollars.

According to RAND cost analyst Rob Leonard, the rule of thumb for estimating airframe structural and systems costs in military aircraft is \$1,000/lb, with costs roughly half that for commercial passenger aircraft. Assuming the lower commercial aircraft figure, the cost estimate<sup>2</sup> for a 5.7 million cubic foot HAA is approximately \$24 million.

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<sup>1</sup> Quoting from the Globalsecurity.org web site ([http://www.globalsecurity.org/intell/systems/global\\_hawk.htm](http://www.globalsecurity.org/intell/systems/global_hawk.htm)): “On 16 February 2000 Northrop Grumman Corp. of San Diego CA was awarded a \$71,999,635 modification to a cost-plus-award-fee contract, MDA972-95-3-0013, to provide for two prototype Global Hawk unmanned aerial vehicles, associated system modification, and engineering support.”

<sup>2</sup> If we (1) assume that a volume of 5.7 million cubic feet for an HAA, (2) assume that 1,000 cubic feet of helium lifts 62.5 pounds, and (3) ignore lightness at takeoff, then HAA gross weight (absent helium) is about 5,700 times 62.5 times 0.068,

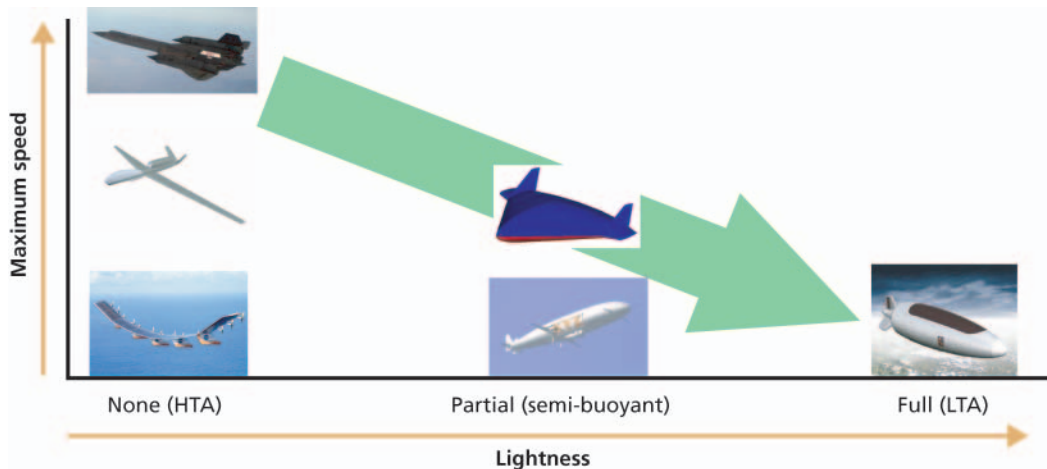
Many of the systems of a conventional fixed-wing aircraft are present in an airship: flight control and mission avionics, propulsion, electrical systems, environmental control, etc. Furthermore, new systems are added: gas management systems and ground handling systems. Thus, it could be argued that the cost contribution of an airframe, whether an aluminum monocoque or a balloon, is relatively small. Hence, there is no reason to believe that an airship's unit cost should be significantly less costly than that of a fixed-wing aircraft.

With regard to design, speed and lightness are two fundamental tradeoffs between HTA vehicles (e.g., UAVs) and LTA vehicles (e.g., HAAs). These are depicted in Figure 13, which includes some hybrids (semi-buoyant vehicles) of HTAs and LTAs.

There are a number of other dimensions to the tradespace. They include (1) altitude, (2) speed, (3) endurance, and (4) robustness. We note the following.

- Altitude. High-altitude flight can be achieved via high speed or low wing loading (i.e., large wing area per unit weight) or aerostatic lift.
- Speed. Airplanes can reasonably achieve high speed, with operational benefits attendant to more robust structures and increased weatherability, but at the cost of reduced endurance. Airships are restricted to lower speeds.
- Endurance. In the absence of nuclear propulsion or beamed energy (e.g., using a microwave antenna), extreme endurance on station (weeks or greater) can only be achieved with solar-electric propulsion. Weatherability can be enhanced with sprint propulsion systems.
- Robustness. This is critical for operational suitability, but the controlled environment of developmental test and evaluation (DT&E) and operational trials may lead to discounting of inherent flaws.

**Figure 13**  
**Design Tradeoffs**



which equals 24,225 pounds. This assumes no crew, that propulsion weight is minimal, and no fuel. This method gets around the issue of costs of fabric versus aluminum.

There are other factors to consider when doing cost comparisons. Specifically:

1. How many UAVs equal one HAA in terms of coverage and endurance?
2. What is the relative cost of the ground package for sustainment?
3. How much of the total cost of a UAV or HAA is airframe/structure versus the mission package?
4. How many UAVs will be lost to the frequent take-offs and landings (that HAAs can avoid)?

Thus, it is possible that a detailed analysis would suggest that HAAs are significantly less expensive to acquire and operate than winged UAVs.





## Conclusions

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Many organizations are interested in HAAs, and in some cases the interest has extended to support of design efforts and construction of prototypes. These organizations include:

- U.S. Missile Defense Agency (MDA).
- U.S. Defense Advanced Research Projects Agency (DARPA).
- U.S. Air Force.
- United Kingdom (U.K.) Defence Science and Technology Laboratory (DSTL).
- European Space Agency (ESA).
- Japanese Aerospace Exploration Agency (JAXA).

There are also a number of commercial ventures for communications services (Harris, 2004; Lavan, 2004a). The MDA effort, an Advanced Concept Technology Demonstration (ACTD), is directed toward surveillance and communications support of U.S. air defenses.<sup>1</sup> Three U.S. combatant commanders are also interested in using HAAs in their overseas theaters for communications and surveillance.<sup>2</sup>

### Potential Benefits

The Army has a critical need for an airborne layer for future force networks. The successful production of airships could satisfy this requirement: their communications and surveillance capabilities should considerably improve force performance in the theater battlespace. Airships can function as surrogate satellites. In comparison to space-based assets, they offer the advantages of shorter transmission distances for relaying ground-based communications and shorter ranges for sensor surveillance of the battlefield and acquisition of ground targets. In fact, a host of innovative uses for such a platform have been proposed, including but not limited to (a) the use of HAAs as optical relay platforms from a ground station, (b) the use of

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<sup>1</sup> MDA's ACTD lists these potential military missions for HAAs: communications relay; broadcast communications; missile warning; airspace surveillance and control; maritime surveillance and control; aerial and ground reconnaissance, surveillance, and target acquisition (RSTA); fires coordination; position/navigation; weather monitoring; battlespace environmental monitoring; electronic countermeasures; air defense/cruise missile defense/tactical missile defense (AD/CMD/TMD) weapons platform; and air-to-ground weapons platform (NORAD, USASMDC, 2003).

<sup>2</sup> Central Command (CENTCOM), Pacific Command (PACOM), and United States Force Korea (USFK) seek HAAs for a variety of tasks.

HAA as hub nodes that relay communications to and from satellites, or (c) perhaps the use of HAAs as mobile computing platforms (Wiley, 2004).

Airships may provide communications satellite capabilities for the WIN-T network at much less expense than satellites and increase mission flexibility by being able to change communications payloads periodically during mission rotations, supportability issues aside. The communications platform should be a strong addition to the MC2C.

The ability to provide persistent surveillance from a fixed position has long been needed. Over time, it can facilitate the continuous collection and comparison analysis of terrain covered by different sensors, such as IR, EO, and HSI. Comparisons can highlight changes like freshly turned dirt along a roadway where bombs have been emplaced.

Operating airships from CONUS would furnish capability to commanders without a corresponding logistics burden. However, under these conditions deployment times will be an issue. HAAs can take days to reach distant theaters after launching from CONUS. For example, a deployment from the Las Vegas, Nevada area to a geostation near Baku, Azerbaijan at an airship airspeed of 30 knots with no favorable winds would take 8.5 days by a great circle route in the summer and 10 days via the 45° north latitude during the winter.

## Limitations and Vulnerabilities

A number of specific areas of technical and operational risk were outlined in this report (e.g., envelope material, thermal control, etc). It is important to note that there is a very tight interaction between technical risk and operational utility. It is not yet clear that these risk areas can be successfully managed. However, risk can be reduced by restricting the use of the airship in adverse conditions, by accepting reduced performance, even if combat operations are constrained, and by providing extra airships to relieve those on station when environmental conditions warrant. In effect, these risks can be lowered because operational utility can be degraded gracefully. However, there will always be those risks that are unpredictable and that can result in catastrophic and unexpected system failure. These risks stem from the stochastic nature of the environment in which the vehicle operates—the effects of weather and, particularly (in the case of an airship), wind.

Many of the risks can be managed by operational restriction. However, envelope strength, weatherability, and launch and recovery all interact and are problematic in the sense that conditions will arise that cannot be forecast.<sup>3</sup> Some of these conditions may be beyond those exercised in the ACTD demonstration plan.<sup>4</sup>

A review of operational experience with existing commercial airships, coupled with prior airship operations in the U.S. Navy (and interviews by Naval Airship program office personnel with then-surviving airship pilots) resulted in the following principles that can be applied to HAA design, with a corresponding increase in operational robustness:

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<sup>3</sup> Historically, this has been a major cause of loss of the surveillance aerostats on the U.S. southern border: thunderstorms bear down on the sites before the aerostats can be fully winched down.

<sup>4</sup> This was a fallacy realized early in the Naval Airship program: contractors would design to “10 percent wind exceedance curves” (because, for example, a 1 percent exceedance curve would require truly prodigious amounts of propulsive power). Yet this implied that 10 percent of the time, the airship would either be held on the mooring mast (if lucky) or blown out to sea (if not)—an unacceptable result.

- “Sprint power” is essential to increase the robustness to transient conditions of high headwind and to improve vehicle response to pitch and yaw disturbances.
- Immediately disposable ballast is essential to allow instant recovery from difficulties during ground handling.
- Immediately disposable lift is essential to allow the airship to collapse to the ground in the event of difficulties.
- Operational flexibility can be greatly enhanced by trading payload for ceiling.

Airships will be vulnerable to air defenses. Air superiority will be a prerequisite for airship operations near enemy-held areas. Complete destruction of long-range surface-to-air missile units will probably be necessary before the full communications and surveillance strengths of airship payloads can be realized on the battlefield. With that accomplished, however, the airships’ ability to rise to heights above the range of most air defense weapons and to operate in a benign high-altitude environment should allow these platforms to furnish invaluable services of continuous, high-bandwidth communications and persistent, high-resolution surveillance to the combatant commander.

Weather will be a risk factor that could be significant if airships are not furnished with reliable sensors for on-site meteorological data with which airship controllers can predict turbulence, icing, and violent gusts that can jeopardize the craft. The experience with high-altitude tropospheric operations from around-the-world balloonist teams and weather teams must be collected and codified to aid computer predictions at higher altitudes. This aspect of airship operations will take strong preparation and close attention during operations.

An airship will be in the troposphere for over five hours while descending<sup>5</sup> to its home mooring base. The conditions in 65,000 feet of airspace at a home location will have to be within allowable weather parameters before a letdown can commence. This requirement could cause an airship to hold at 65,000 feet for up to two to five days before descending. Launch operations could cause similar delays, although the ascent should be at a faster 1,000 feet per minute or 65 minutes long. Operational planning may have to allow days of nonproductive time in an airship rotation schedule for an ongoing operation.

Beyond proving the physical feasibility of using HAAs for communications relays, surveillance, and other tasks, a major feasibility challenge for military acquisition of HAAs is the issue of funding. A number of commercial uses for lower-altitude airships have been proposed. Scientists and entrepreneurs in the United Kingdom have been examining the usefulness of HAPs, either airships or airplanes, to serve as fixed, wireless communications and television relays over urban areas.<sup>6</sup> Potential military users will prefer to share development and production costs with civilian users and, in fact, may insist on a cost-sharing arrangement before contracting for HAAs, as has happened with low-altitude, heavy-lift airships.

Finally, notwithstanding the design gust specifications, eventually a gust will arise that will destroy an HAA. Given that the cost of an HAA is predominantly concentrated in its payload, consideration should be given to equipping an external payload module with wings or a parachute to allow it to separate cleanly from the collapsing envelope above, for

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<sup>5</sup> The HAA ACTD airship will descend at about 200 feet per minute.

<sup>6</sup> Commercial HAAs would most likely be solar-powered with fuel-cell storage. Successful demonstrations of high-altitude operations, solar cells, and fuel cells are needed before serious commercial funding is anticipated (Tozer and Grace, 2001).

recovery by friendly ground personnel and subsequent refurbishment. In recent history, airships have crashed with regularity, but “hull losses” in the insurance sense are rare, since LTA flight is inherently nonenergetic.

Technical risks persist. HAA ACTD program documentation summarizes the effort as having “some technical risk” but “enormous potential benefits.” It also includes the acknowledgment that “HAA is a fast-paced program.” Against these statements, it is critical to note that the program is attempting to design and fly an unmanned airship that is orders of magnitude larger (in terms of volume) than any other previously attempted. There is substantial uncertainty surrounding all aspects of vehicle performance and control at this scale.

## Future Study

Power generation and storage, as well as power conservation methods, need further study to assure the ability to self-sustain missions through a year of operation. However, a study may be considered of the potential for replenishing power by absorbed energy from an exterior source of directed energy while enroute to station and while on station. The latter would require in-theater support and counters the goal of relieving the theater commander of any support of an airship.

The size of the HAA might permit very large conformal antennae and a synthetic aperture radar as part of the skin. Multiple platforms with slow movement might provide good bi-static or multi-static radar arrays.

## Suggested Actions

In view of the above airship capabilities and limitations, in the near term, the U.S. Army should:

- Closely monitor the development and testing of HAA prototypes in combination with the Missile Defense Agency, U.S. Navy, U.S. Air Force, and U.S. Coast Guard while continuing to pursue detailed technical and operational analysis of high-altitude airships.
- Ensure that the major limiting factors for HAA development are among the Army’s science and technology objectives for development by the Army research and development community.
- Recognize that an operationally useful HAA would probably incorporate features that are not included in the HAA ACTD, which is being designed for the particular requirements of an ACTD demonstration. This would have the effect, all else equal, of reducing the operational ceiling, endurance, and/or payload of any production HAA.

In the longer run, if the HAA ACTD proves successful, the U.S. Army should:

- Join in efforts to interest potential commercial users of HAAs or HAPs and include them in development discussions.
- Conduct computer analyses of the potential value of HAA communications and surveillance payload capabilities to force-on-force operations in various scenarios (but

taking into consideration the likelihood of reduced ceiling, endurance, or payload relative to the HAA ACTD, as above).

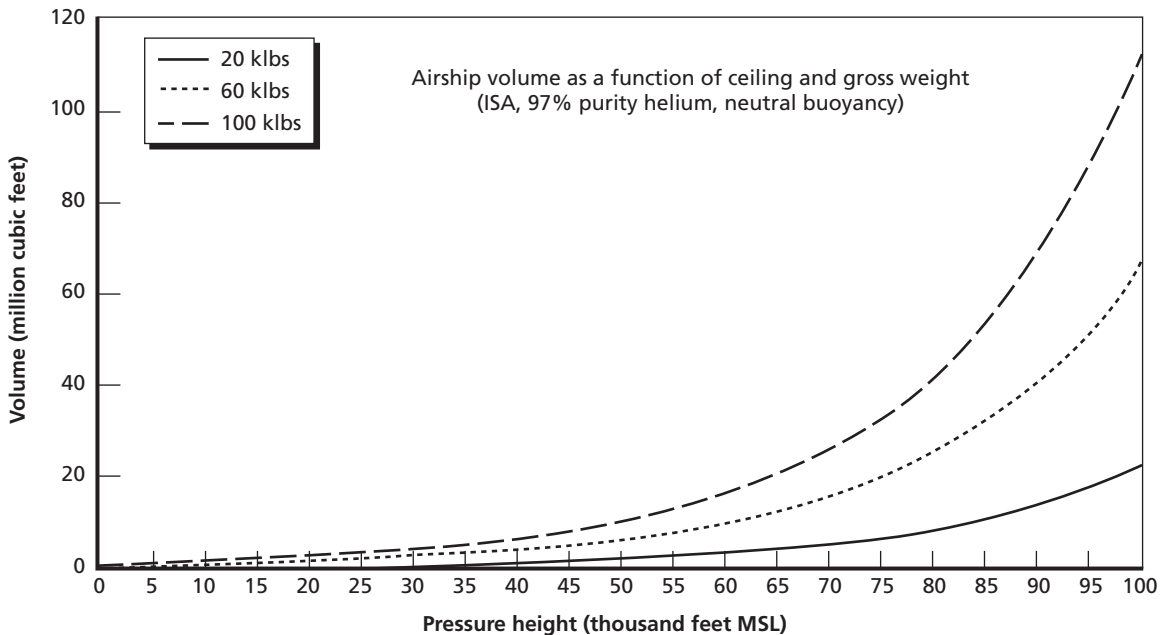
- Consider basing HAAs in sparsely populated desert or island locations in latitudes of less than 38° to provide adequate sunlight and the best possible weather and security environment.
- Emphasize weather analysis in planning HAA routes and airborne control operations.
- Consider co-locating HAA control facilities with the control facilities of military satellites and Global Hawk to utilize existing command and control communications facilities and surveillance control and exploitation systems.
- Understand and exploit the Air Force's efforts to protect aircraft from attack by missiles; specifically, efforts to improve and employ the ALQ-214 IDECM RFCM suite on aircraft to detect and counter surface-to-air and air-to-air RF/IR/EO missiles.

Alternatively, if the HAA ACTD does not prove successful, and/or the financial constraints preclude adoption of fully maneuverable high-altitude airships, the U.S. Army should consider the options it has with respect to other types of balloons (free floaters and semi-steered balloons); these (possibly) cheaper and smaller balloons could serve as disposable assets that could be employed in large numbers; they would not be stationary, however, and would not be able to carry the large mission packages envisioned for HAAs.



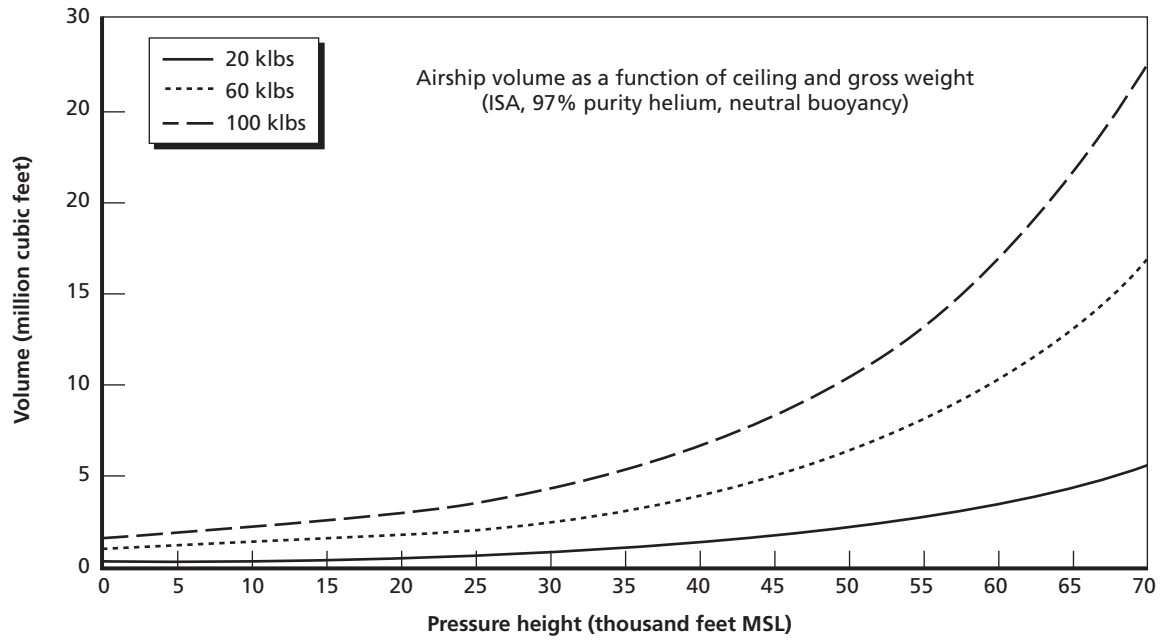
## The Tradeoff Between Airship Volume and Operating Altitude

This appendix illustrates a tradeoff that exists between airship volume and operating altitude. Specifically, the figures below show the airship volume required as a function of ceiling (specifically, “pressure height,” the altitude above which lifting gas must be vented) and total system weight. Note that volume increases exponentially with ceiling, and linearly with weight. For altitudes over 70,000 feet, airships become spectacularly large unless gross weight is low. This explains why only free balloons have ventured into this regime—without the penalties of aerodynamic shaping, tail surfaces, and propulsive means, their weight can be held down to reasonable levels.



Theoretical airship volume ( $V$ ) is simply total mass ( $m$ ) divided by the product of the atmospheric density ratio ( $\sigma$ ) and the density ( $\rho$ ) difference between helium and air. This is expressed as follows:  $V = m/(\sigma \cdot \rho_{\text{air}} - \rho_{\text{gas}})$ . This theoretical airship volume must then be increased in practice due to unavoidable impurities in the lifting gas. If the helium is 97 percent pure (a standard case), then the theoretical volume must be increased by a factor of  $(1/0.97)$  to arrive at a total volume. These calculations follow those described in Mueller,

Paluszek, and Zhao (2004), which provide a sufficient overview of the “aerostatics of airships.”





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