

# High-Altitude, Long-Endurance UAVs vs. Satellites: Potential Benefits for U.S. Army Applications

by

William Everette Symolon  
Major, U.S. Army

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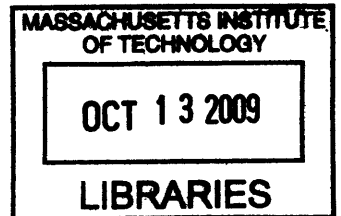
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William Everette Symolon, Major, U.S. Army

Submitted to the Department of Aeronautics and Astronautics on May 12, 2009 in Partial Fulfillment of the Requirements for the Degree of Master of Science in Aeronautics and Astronautics.

## ABSTRACT

Satellites have become a critical component of nearly every aspect of modern life. In addition to well-known civilian applications, military applications of space-based platforms include supporting mission operations through communications; intelligence, surveillance and reconnaissance (ISR); and position, navigation and timing (PN&T). While satellite applications are numerous and increasing technical achievements make satellites more capable, they do have several drawbacks. Satellites are expensive, they require long development times and they are difficult to replace. Since the successful Chinese anti-satellite (ASAT) missile test on January 11, 2006, U.S. military leaders have become increasingly concerned over this new vulnerability to critical space assets. In addition to efforts designed to improve operationally responsive space capabilities, military leaders have begun researching alternatives to space-based platforms. In November, 2006, the U.S. Army released the Army Space Master Plan (ASMP). In the unclassified extract of that plan, the Army identifies a list of eight topics for further investigation including the question, "Where should the Army invest in near-space and high-altitude, long-endurance [HALE] platforms as a lower cost, more responsive alternative to space platforms if they prove technically feasible?" This thesis discusses technical challenges associated with making HALE platforms feasible and explores the potential benefits of using these platforms to augment or enhance the three primary military applications of communications, ISR and PN&T including a detailed examination of current satellite-based military payload capabilities and limitations. Finally, this thesis discusses potential methods to integrate HALE capabilities into the current U.S. Army Space Operations doctrine and provides some suggestions for the potential role of Army Space Operations in the design, development, implementation and use of HALE systems. By demonstrating how the Army can use HALE platforms to reduce the capability gap and fulfill more of the users' requirements, this research will answer the question posed in the Army Space Master Plan.

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William E. Symolon, Major, U.S. Army  
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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MASTER OF SCIENCE IN AERONAUTICS AND ASTRONAUTICS

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Potential Benefits for U.S. Army Applications

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# Nomenclature

$\alpha$	Radiator Absorptivity
$\beta$	Angle Between the Sun and the Vector Normal to the Platform Face
$\beta_S$	Angle of the Sun Above the Orbit Plane
$\epsilon_r$	Radiator Emissivity
$\epsilon_s$	Minimum Elevation Angle in degrees
$\eta_b$	Transmission Efficiency Between the Battery and the Load
$\eta_{ant}$	Antenna Efficiency
$\eta_{nadir}$	Nadir Angle in degrees
$\eta_{sa}$	Solar Array Efficiency
$\frac{\Phi}{2}$	Half Rotation Angle Corresponding to Eclipse Duration
$\frac{E_b}{N_o}$	Ratio of Received Energy-per-Bit to Noise Density
$\lambda$	Carrier Wavelength ( $f = c/\lambda$ )
$\lambda_E$	Earth Central Angle in degrees
$Comm_{wt}$	Communications Payload Weight
$\rho$	Angular Radius of the Earth in degrees
$\rho_{albedo}$	Earth's Albedo
$\rho_{atm}$	Atmospheric Density in slugs per ft <sup>3</sup>
$\sigma$	Stefan-Boltzmann Constant ( $5.67051 \times 10^{-8} \text{ W/m}^2\text{K}^4$ )
$\tau$	Material Tensile Strength in psi
$\theta$	Antenna Half-Power Beamwidth
$\theta_i$	Angular Resolution of an Image
$\theta_r$	Rayleigh Limit of the Point Spread Function in radians

$A_i$	Required Aperture Diameter of Imaging Payload
$A_o$	Aperture Diameter of the Reference Imaging Payload
$A_p$	Surface Area of the Platform Face
$A_r$	Radiator Surface Area
$A_{sa}$	Solar Array Surface Area
$C$	Received Power
$c$	Velocity of Light in Free Space ( $\approx 3 \times 10^8$ m/s)
$C_r$	Battery Capacity
$D$	Aperture Diameter of an Optical Instrument
$d$	Imaging Pixel Size
$d'$	Diameter of the First Minimum of the Point Spread Function
$D_r$	Ground Receive Antenna Diameter in meters
$D_{ant}$	Diameter of a Parabolic Antenna in meters
$DoD$	Depth of Discharge
$e$	Antenna Pointing Error
$f$	Carrier Wave Frequency in Hertz
$f_l$	Focal Length
$F_r$	Sensor Footprint Radius in miles
$F_{albedo}$	Geometrical Factor Accounting for the Direction of the Radiator Relative to the Sun
$F_{EIR}$	Geometrical Factor Accounting for the Direction of the Radiator Relative to the Earth
$G_r$	Receive Antenna Gain
$G_t$	Transmit Antenna Gain
$H_p$	Platform Altitude
$I$	Current in Amperes
$I_d$	Inherent Degradation of Solar Cell Efficiency (Due to Design and Assembly Inefficiencies)
$I_{EIR}$	Intensity of the Earth IR Flux
$I_{solar}$	Intensity of the Solar Flux
$IA$	Incidence Angle = $90^\circ - \epsilon_s$



$k$	Boltzmann's constant ( $1.380658 \times 10^{-23}$ J/K)
$K_{solar}$	Solar Constant in the Vicinity of the Earth (1367 W/m <sup>2</sup> )
$L_a$	Transmission Path Loss
$L_d$	Life Degradation of the Solar Array
$L_i$	Scaled Payload Linear Dimension
$L_l$	Transmitter to Antenna Line Loss
$L_o$	Reference Payload Linear Dimension
$L_s$	Space Loss
$L_{pr}$	Antenna Pointing Loss
$M_b$	Battery Mass in kg
$M_i$	Scaled Payload Mass
$M_o$	Reference Payload Mass
$M_{sa}$	Solar Array Mass in kg
$N_{aS}$	Sodium-Sulfur
$N_b$	Number of Batteries in the Power Subsystem
$N_iH$	Nickel-Hydrogen
$P$	Orbit Period
$p$	Atmospheric Pressure in lbs/ft <sup>2</sup>
$P(\alpha)$	Probability that Signal Attenuation, $\alpha$ is Exceeded
$P_d$	Platform Power Requirements During Daylight
$P_e$	Platform Power Requirements During Eclipse
$P_i$	Scaled Payload Power
$P_o$	Reference Payload Power
$P_t$	Transmitter Power
$P_{BOL}$	Beginning-of-Life Power Generated
$P_{EOL}$	End-of-Life Power Generated
$P_{ideal}$	Ideal Solar Cell Power Output
$P_{sa}$	Power Generation Requirement of the Solar Arrays During Daylight

$P_{wr}$  Power Measured in Watts  
 $Q$  Image Quality Factor  
 $Q_r$  Radiative Power  
 $q_{albedo}$  Heat Input from the Earth's Albedo  
 $q_{backload}$  Radiative Backload from Other Platform Surfaces  
 $q_{EarthIR}$  Absorbed Earth IR Heat Load per Unit Area  
 $Q_{external}$  Environmental Heat Absorbed  
 $q_{external}$  External Environmental Heat Load on the Radiator per Unit Area  
 $Q_{internal}$  Power Dissipation of Onboard Electronic Components  
 $Q_{MLI}$  Heat Loss Through Multi-layer Insulation on the Platform  
 $Q_{radiator}$  Heat Rejected from the Platform's Primary Radiator Surfaces  
 $q_{solar}$  Incident Solar Energy on the Face of a Platform  
 $R$  Data Rate  
 $R_E$  Radius of the Earth (3963.16 miles)  
 $R_s$  Slant Range to Target  
 $R_{scale}$  Payload Scaling Ratio  
 $S$  Transmission Path Length (m)  
 $S_w$  Swath Width in degrees  
 $T$  Ambient Atmospheric Temperature in °F  
 $T_d$  Duration of Daylight Period (minutes)  
 $T_e$  Duration of Eclipse Period (minutes)  
 $T_r$  Absolute Radiator Temperature in K  
 $T_s$  System Noise Temperature  
 $V$  Potential Difference in Volts  
 $X$  Ground Pixel Size  
 $X'$  Ground Resolution  
 $X_d$  Efficiency of the Path Directly from the Solar Arrays to the Loads  
 $X_e$  Efficiency of the Paths from the Solar Arrays Through the Batteries to the Loads

$X_{max}$  Maximum Cross-Track Pixel Resolution  
 $Y_{max}$  Maximum Along-Track Sampling Distance  
 $Z_c$  Number of Cross-Track Pixels  
ABM Anti-Ballistic Missile  
ACR Armored Cavalry Regiment  
ACTD Advanced Concept Technology Demonstration  
AFRL Air Force Research Laboratory  
AFSPC Air Force Space Command  
Amp-hr Ampere-hour  
AMTI Air Moving Target Indicator  
AO Area of Operations  
APL Applied Physics Laboratory  
ASAT Anti-Satellite Weapon  
ASMP Army Space Master Plan  
AU Astronomical Unit (1 AU = 149,597,870,691 meters)  
BDA Battle Damage Assessment  
BER Bit Error Rate  
BFT Blue Force Tracker  
BLOS Beyond Line-of-Sight  
BOL Beginning-of-Life  
BOS Battlefield Operating Systems  
bpp Bits per Pixel  
C2 Command and Control  
CBRN Chemical, Biological, Radiological and Nuclear  
CCD Charge Coupled Device  
CCP Concept Capability Plan  
CDMA Code Division Multiple Access  
CER Cost Estimating Relationship

CNO Computer Network Operations

CONOPS Concept of Operations

CONUS Continental United States

DAGR Defense Advanced GPS Receiver

DARPA Defense Advanced Research Projects Agency

DET Direct-Energy-Transfer System

DGPS Differential GPS

DOD Department of Defense

DOP Dilution of Precision

DOT Department of Transportation

DOTMLPF Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel and Facilities

DRMS Distance Root Mean Square

DSCA Dielectric-loaded Slotted-Cylinder Antenna

DSCS Defense Satellite Communications System

EC Electrochemical Cell

EIRP Effective Isotropic Radiated Power

EMPRS En-route Mission Planning and Rehearsal System

EOL End-of-Life

EPLRS Enhanced Position Location Reporting System

EPS Electrical Power Subsystem

ERP Effective Radiated Power

EW Electronic Warfare

FBCB2 Force XXI Battle Command, Brigade and Below

FDMA Frequency Division Multiple Access

FM Field Manual

FOR Field of Regard

fW femto-watt ( $10^{-15}$ )

FY Fiscal Year

Gbps Gigabits per Second

GBS Global Broadcast System

GCS Ground Control Station

GEO Geosynchronous Earth Orbit (35,786km altitude)

GLONASS Global Navigation Satellite System (Russian)

GMTI Ground Moving Target Indicator

GNSS Global Navigation Satellite System

GPS Global Positioning System

GUI Graphical User Interface

HA-ECA High-Altitude Enabled Capabilities Assessment

HAA High Altitude Airship

HALE High-Altitude, Long-Endurance

HALL High-Altitude, Long-Loiter

HATBS High Altitude Tethered Balloon System

HPT High-Priority Target

HTA Heavier-than-Air

IED Improvised Explosive Device

IFOV Instantaneous Field of View

INS Inertial Navigation Systems

IO Information Operations

IR Infrared

ISR Intelligence, Surveillance and Reconnaissance

ITU International Telecommunications Union

JCTD Joint Concept Technology Demonstration

JP Joint Publication

JSTARS Joint Surveillance Target Attack Radar System

kW kilowatt

LEO Low Earth Orbit (200km to 2,000km altitude)  
LIDAR Light Detection and Ranging  
LTA Lighter-than-Air  
MDA Missile Defense Agency  
MEDEVAC Medical Evacuation  
MEO Medium Earth Orbit (2,000km to 35,786km altitude)  
MILDEC Military Deception  
MUAR Military Utility Assessment Report  
NASA National Aeronautics and Space Administration  
NGA National Geospatial-Intelligence Agency  
NOAA National Oceanic and Atmospheric Administration  
NSA National Security Agency  
OODA Observe, Orient, Decide and Act  
OPSEC Operations Security  
ORS Operationally Responsive Space  
PA Power Amplifier  
PLGR Precision Lightweight GPS Receiver  
PN&T Position, Navigation and Timing  
PPS Precise Positioning Service  
PPS-SM Precise Positioning Service - Security Module  
PPT Peak Power Tracker  
psi Pounds per Square Inch  
PSYOP Psychological Operations  
PVNT Position, Velocity, Navigation and Timing  
pW pico-watt ( $10^{-12}$ )  
QPSK Quadriphased Phase Shift Keying  
RF Radio Frequency  
RFC Regenerative Fuel Cells

RFI Radio Frequency Interference  
RSTA Reconnaissance, Surveillance and Target Acquisition  
RTK Real-Time Kinematic  
Rx Receiver  
SA Selective Availability  
SAASM Selective Availability/Anti-Spoofing Module  
SAM Surface-to-Air Missile  
SAR Synthetic Aperture Radar  
SATCOM Satellite Communications  
SINCGARS Single Channel Ground and Airborne Radio System  
SLEP Service Life Enhancement Package  
SMAD Space Mission Analysis and Design, 3d Edition  
SMDC Space and Missile Defense Command  
SPS Standard Positioning Service  
Tbps Terra-Bits per Second  
TCDL Tactical Common Data Link  
TCS Thermal Control System  
TDMA Time Division Multiple Access  
TDOA Time Difference Of Arrival  
TRADOC U.S. Army Training and Doctrine Command  
TST Time-Sensitive Target  
TTFF Time to First Fix  
TTSF Time to Subsequent Fix  
Tx Transmitter  
UAS Unmanned Aircraft System  
UAV Unmanned Aerial Vehicle  
UERE User Equivalent Range Error  
URFC Reversible (Unitized) Regenerative Fuel Cell

USAF SAB U.S. Air Force Scientific Advisory Board

USCM Unmanned Space Vehicle Cost Model

W-hr Watt-hour

WAAS Wide Area Augmentation System

WGS Wide-band Global SATCOM System

WTEM Weather, Terrain and Environmental Monitoring



# Chapter 1

## Introduction

### 1.1 Background & Motivation

Satellites have become a critical component of nearly every aspect of modern life. In addition to well-known civilian applications, military applications of space-based platforms include supporting mission operations through communications; intelligence, surveillance and reconnaissance (ISR); and position, navigation and timing (PN&T) or position, velocity, navigation and timing (PVNT). While satellite applications are numerous and increasing technical achievements make satellites more capable, they do have several drawbacks. Satellites are expensive, they require long development times and they are difficult to replace.

Since the successful Chinese anti-satellite (ASAT) missile test on January 11, 2006, U.S. military leaders have become increasingly concerned over this new vulnerability to critical space assets. In addition to efforts designed to improve operationally responsive space (ORS) capabilities, military leaders have begun researching alternatives to space-based platforms.

In November, 2006, the U.S. Army released the Army Space Master Plan (ASMP). In the unclassified extract of that plan, the Army "identifies roles and capabilities to guide the development of space capabilities as key enablers in support of ground maneuver force operations." [1] The ASMP extract concludes with a list of eight topics for further investigation and decision making. Second in that list of eight topics is the question, "Where should the Army invest in near-space and high-altitude, long-endurance platforms as a lower cost, more responsive alternative to space platforms if they prove technically feasible?" [1]

Also in November, 2006 and accompanying the ASMP, the U.S. Army Training and Doctrine Command (TRADOC) released TRADOC Pamphlet 525-7-4: The United States Army's Concept Capability Plan (CCP) Space Operations 2015-2024. The CCP "concentrates on the growing importance and dependence of Army operations on space-based systems and space-enabled functions, processes and information. The Army Space Operations CCP is intended to focus the Army's efforts to exploit . . . space and describe the required space-enabled capabilities

needed to realize the objectives of our joint and Army concepts." [2] The CCP is designed to achieve four imperatives:

- Facilitate the integration of space capabilities across the full spectrum of Army and joint operations.
- Improve the Army's ability to exploit existing space capabilities.
- Deliver space capabilities that address Army needs (capability requirements) and priorities by influencing the design of space-based systems and payloads.
- Systematically and deliberately evolve Army space support operations over time to provide dedicated, responsive, theater-focused support to operational and tactical commanders.

This thesis will attempt to provide input into the third bullet item by answering the question posed in the ASMP.

For the past several decades, military and commercial agencies have been capable of launching short duration, high-altitude platforms into the lower stratosphere (36,000 feet to 82,000 feet) for the purposes of atmospheric monitoring and beyond line-of-sight (BLOS) communications relay. These platforms have traditionally been free flying, non-steerable lighter-than-air (LTA) balloons that are launched from a location which allows the prevailing winds to blow the platform over the area of interest. Persistent coverage with these types of platforms can only be achieved by continually launching balloons for as long as coverage is required. Additionally, changes in wind direction necessitate changes in the launch locations which can be time consuming and cause service delays. New research in controllable airships will allow persistent coverage with a single long-endurance platform.

With the renewed focus on the near-space region of the earth's atmosphere that lies between 65,000 ft (20 km) and 325,000 ft (100 km) in altitude, the U.S. Air Force Scientific Advisory Board (USAF SAB) conducted a study on the subject of persistence at near space altitudes from March 2005 to June 2005. In that study, the authors determined that

"in order to persist at high altitudes, a fixed wing aircraft requires an extremely large wingspan, and a balloon or airship requires an extremely large volume ... the study found that a notional "near space" platform operating well above 100,000 feet altitude is not technologically feasible in the foreseeable future. On the other hand, if one limits one's focus in "near space" to the regime between 65,000-100,000 feet in altitude, there are viable options for such operation, even in the near-term." [3]

## 1.2 Lighter-than-Air Platforms

Previous research exists regarding the technical challenges and potential benefits associated with using high-altitude, long-endurance (HALE) or high-altitude, long-loiter (HALL) platforms in general and specifically in regard to support of U.S. military operations. Notably, the Rand Center technical report titled "High Altitude Airships for the Future Force Army"[4] outlines the comparative advantages and limitations of the use of LTA airships. The Rand study specifically focuses on LTA dirigibles and considers their use for communications and surveillance payloads.

In Fiscal Year (FY) 2003, the Department of Defense (DOD) Missile Defense Agency (MDA) initiated a High Altitude Airship (HAA) Advanced Concept Technology Demonstration (ACTD) designed to develop a multi-purpose platform to support the joint warfighter.[5] This ACTD outlined the following specifications for the HAA dirigible:

- Unmanned & Untethered
- Endurance: 30 days
- Geo-Stationary: ~65,000 ft MSL
- Semi-Autonomous Station Keeping
- Nominal Payload: 4000 lbs
- Nominal Payload Power: ~10 kW
- Length/Width: ~500ft/150ft

The HAA ACTD focused on multi-mission platforms for operational missions including but not limited to communications relay, ISR, PN&T and battlespace environmental monitoring with the goal of proving the technology for follow-on applications, demonstrating payload integration capabilities and validating operational concepts. The results of the ACTD were detailed in a Military Utility Assessment Report (MUAR) which intended to address the issues of support effectiveness, ease of operator training and interoperability with a joint battlespace environment.

Technical challenges associated with LTA platforms include all the normal flight control and avionics requirements for conventional unmanned aerial vehicles (UAV) including the ability to transit conventional (manned) airspace but have the additional requirements of lift gas pressure control, ballast control, gas envelope material design and more stringent ascent and descent environmental constraints.[6] Additional technical challenges to overcome include the following concerns.[4]

- Unpredictable structural and control responses to wind gusts

- No industrial base; limited institutional knowledge/memory
- Hull fabric degradation due to high altitude UV radiation (current UV barriers may be inadequate)
- High altitude control system is less effective at lower altitudes due to stronger winds
- Maximum latitude limitations due to solar power availability ( $\pm 45^\circ$  north/south latitudes (worst case)) limit global coverage capability

The additional subsystems necessarily increase the complexity of an LTA platform which increases the likelihood of failure modes and reduces the overall reliability and thus availability of the system.

A further subset of the LTA class of HALE platforms are tethered high-altitude balloons. Tethers offer the advantage of providing "hard line" communications connections to the ground station via an embedded fiber optic cable to facilitate telemetry and command as well as providing a potential source of continuous power for the airship and the payload. Using a tether for telemetry, command and power supply allows a weight reduction of the airship which allows an increased payload mass margin. Disadvantages of the tether include: *a*) strength-to-weight requirements of the tether material; *b*) tether drag in high winds; *c*) tether ice accretion at altitude; *d*) conventional airspace clearance around the tether; *e*) tether insulation material (thermal and electrical) and *f*) ground station survivability.

The Johns Hopkins University Applied Physics Laboratory (APL) conducted a study on the High Altitude Tethered Balloon System (HATBS). In that study, which was conducted from 2003 to 2004, the APL determined that it is technically feasible to maintain a captive LTA platform at an altitude of 65,000 feet for extended periods. The program ended before any physical tests could be conducted. See figure 1.1 for an illustration of the HATBS concept.

### 1.3 Heavier-than-Air Platforms

The Air Force RQ-4 Global Hawk UAV (see figure 1.2 below) designed and built by Northrop Grumman under an ACTD is an operational prototype heavier-than-air (HTA) HALE platform capable of operating for twenty-eight hours at a ceiling of 65,000 feet.[7] Global Hawk has been used operationally to support military actions in Iraq, Afghanistan and the Horn of Africa[8] and, as of September 2004, has logged more than 4,800 flight hours in 375 missions (half of which were flown in combat).[9] The operational successes of Global Hawk demonstrate the technical feasibility of using HTA platforms for surveillance missions. Design extensions to include other military payloads (e.g., communications and PN&T) along with increased mission duration and

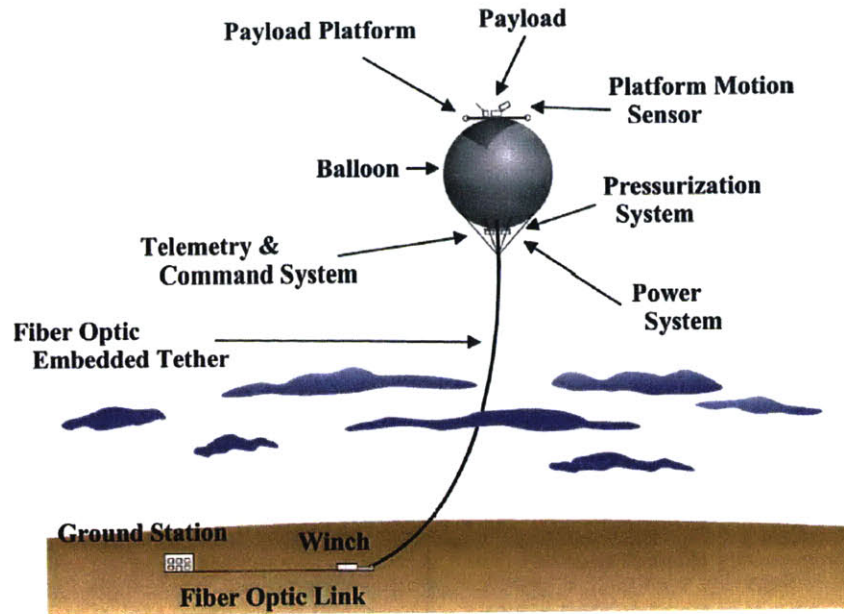


Figure 1.1: Diagram of the High Altitude Tethered Balloon System Concept; Source: John's Hopkins University/Applied Physics Lab

maximum altitude may make technologies like the Global Hawk an attractive substitute for orbiting satellites.

In June 2007, the Defense Advanced Research Projects Agency (DARPA) initiated a Joint Concept Technology Demonstration (JCTD) called the Vulture Project. Vulture focuses on developing an HTA platform that significantly extends the currently accepted capabilities of HTA aircraft. The four primary design goals of Vulture are: *a*) five year endurance; *b*) better than 99% time-on-station; *c*) 1000 pound payload capability and *d*) five kilowatt (kW) nominal payload power requirement.[8] A major design constraint of any successful Vulture proposal is that the aircraft will be able to operate independently of the selected, generic payload; Vulture designs must have independent avionics and navigation capabilities. In order to achieve the 99+% time-on-station requirement over the five year lifecycle, successful Vulture designs will likely be modular with the ability to detach and "fly home" defective components and/or have the ability to rendezvous with a tender aircraft for periodic servicing and replacement of failed components. Each event requiring the separation, docking and servicing of a Vulture design is an opportunity to introduce a failure mode. Increasing events necessarily increases complexity of the design which has the potential to reduce the overall reliability and thus availability of the system.



Figure 1.2: Air Force RQ-4 Global Hawk UAV; Image Source: [http://en.wikipedia.org/wiki/Global\\_Hawk](http://en.wikipedia.org/wiki/Global_Hawk)

## 1.4 Research Context & Thesis Outline

The research will conduct a detailed examination of current satellite-based military payloads, including capabilities and limitations, with specific focus on communications relay, ISR, GPS enhancement and multi-modal payloads.

The primary analysis tool will be MATLAB to develop and analyze mission-specific CONOPS for each of the applications. The basic assumptions behind HALE platforms are that they will be cheaper and more responsive than traditional satellites. This research will attempt to validate these assumptions for both HTA and LTA platforms and then develop parameters for the evaluation of space versus HALE platforms. The simulations will include both LTA and HTA platforms utilizing all current satellite payloads for military applications (modified for HALE platforms). The proposed steps in conducting the analysis are as follows:

1. Determine the technical challenges in using HALE to replace satellites.
2. Develop evaluation parameters and data mine suitable benchmark criteria from existing satellite specifications and capabilities.
3. Determine if there are particular missions/needs that require further study.

The goal of this research is to successfully evaluate HTA and LTA platforms against current

satellite capabilities to determine where and how HALE platforms can contribute to successful military operations by reducing the gap between current capabilities and user requirements (see figure 1.3 below).

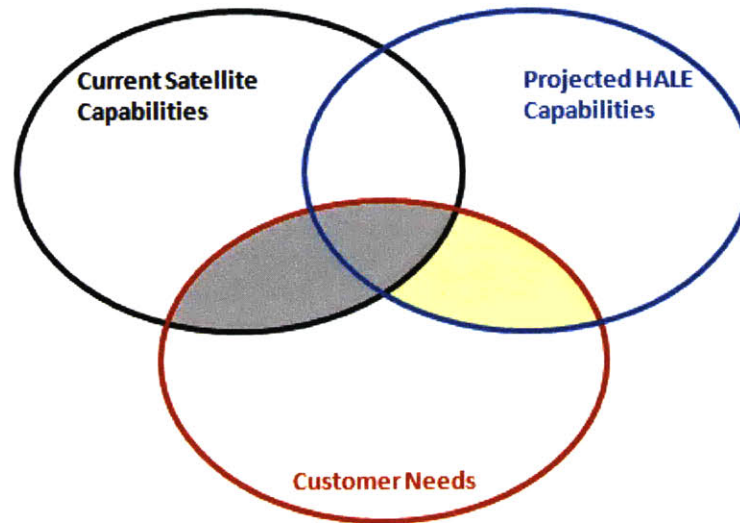


Figure 1.3: Ven Diagram of Current Capability Gaps between Satellites and Military User Requirements

By demonstrating how the Army can use HALE platforms to reduce the capability gap and fulfill more of the users' requirements, this research will answer the question posed in the Army Space Master Plan, dated November 2006: "Where should the Army invest in near-space and high-altitude, long-endurance platforms as a lower cost, more responsive alternative to space platforms if they prove technically feasible?"[1]

This thesis is organized as follows. Chapter 2 provides a discussion of the benefits and technical challenges associated with each platform type, an overview of the survivability considerations and concludes with a discussion of general concept of operations considerations. Chapter 3 is the first of four chapters outlining specific military applications with respect to communications relay payloads in terms of the link margin design and performance differences between HALE platforms and satellites. Chapter 4 discusses observation payload design and sizing for both optical and multi-spectral payloads. Chapter 5 provides a discussion of using HALE platforms for GPS enhancement in support of military operations. Chapter 6 represents a key contribution of this thesis and discusses potential methods to integrate HALE capabilities into the current Space Operations doctrine and provides some suggestions for the potential role of Army Space Operations in the design, development, implementation and use of HALE systems. Finally, Chapter 7 discusses the possibility of multi-modal payloads for multiple, simultaneous mission support, outlines known limitations in the preceding analysis, suggests avenues for future work and provides the thesis conclusions.

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## Chapter 2

# HALE Platform Overview

This chapter provides a discussion of the design drivers and engineering challenges associated with HALE platforms then moves to a discussion of the projected HALE platform capabilities, provides a platform sizing example to help scope the problem and concludes with some general concept of operations (CONOPS) considerations.

### 2.1 Design Drivers and Engineering Challenges

Successful long-duration airborne platforms, as with any complex system, must be designed with the ability to survive within the operating environment. Considerations for generic HALE platforms include climatology and winds aloft; power issues; thermal management issues; and materials selection criteria. Additionally, for military applications, survivable designs must consider the impact of dynamic and electronic attacks via ground-to-air and air-to-air engagements.

This section is not intended to be a detailed design analysis of each of the subsystems listed above. Rather, it is intended to acquaint the reader with some of the major survivability considerations for the implementation of HALE platforms. For the purposes of this thesis, it is assumed that the technological feasibility of HALE platforms has already been determined, citing the RQ-4 Global Hawk UAV[7] discussed in section 1.3 as an existence proof of the concept.

#### 2.1.1 Environmental Considerations

Figure 2.1 below, taken from the Rand Study "High Altitude Airships for the Future Force Army"[4] details the average annual winds aloft over Baghdad and clearly shows that stratospheric winds are most favorable for extended operations between the altitudes of 60,000 feet and 80,000 feet. This graph is intended for application to LTA platforms but one can draw similar conclusions for HTA platforms as well. Additionally, system design and site selection

considerations must include the annual frequency and severity of thunderstorms, lightning, hurricanes and tornadoes with respect to launch and recovery operations.

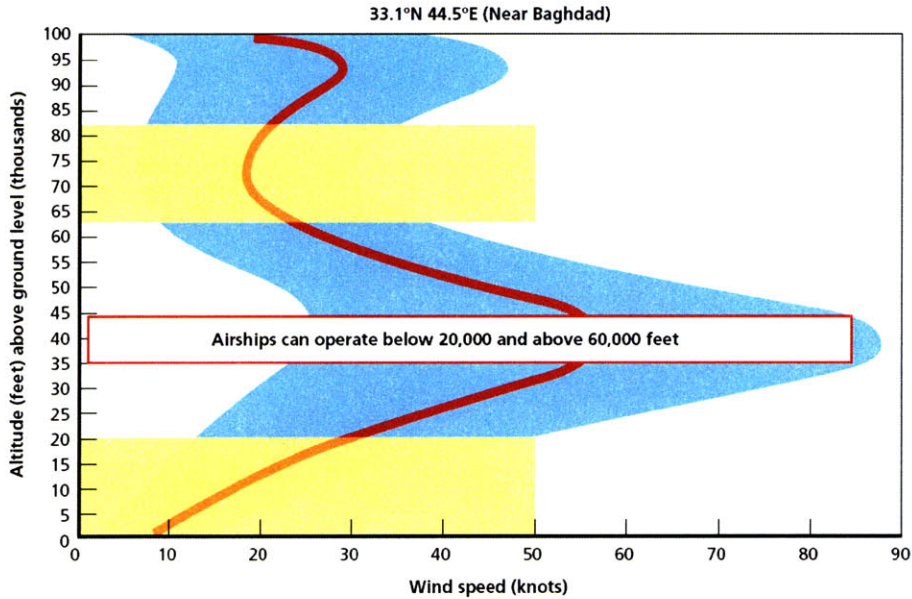


Figure 2.1: Annual Winds Aloft Near Baghdad; Source: "High-Altitude Airships for the Future Force Army," Jamison et al, Rand Corporation Study, 2005

Once at altitude, the platform will be above most natural threats. Wind and turbulence, as shown above, are typically not severe enough to affect performance, however, designing the platform to withstand jetstream winds at lower altitude and to negotiate those winds during ascent and descent will provide the platform with sufficient ability to maneuver at altitude. The other natural threat to HALE platforms are localized electrical discharges known as jets, sprites and elves which are generally concentrated above thunderstorms. Designing the platform for conventional lightning protection is sufficient to protect against these phenomena as they generally have less intensity than lightning. Since HALE platforms operate within the Earth's atmosphere and under 1g conditions, considerations applicable to conventional satellites such as operating in a vacuum or in micro-gravity do not apply.

Finally, one must consider the problem of ice accretion on a captive stratospheric airship. The HATBS study conducted by the Johns Hopkins University APL (section 1.2) briefly considered accretion rates, duration of icing conditions and possible mitigations. Possible mitigation techniques include avoidance, sheath coatings, deicing fluids and "crawlers" to traverse the tether and prevent ice build-up. Of these options, avoidance is the least desirable as this technique would require recovering the platform during icing conditions creating an interruption in service. "Crawlers" would mean added weight to the tether and could potentially create

unnecessary design complications. Deicing fluids appear to be a viable solution assuming an effective, lightweight delivery system. Given the two limiting factors of coverage requirements and weight limitations, hydrophobic sheath coatings appear to be the most viable option.

### 2.1.2 Power System Requirements

Satellites and HALE platforms have similar power requirements in terms of the necessity for renewable power sources. The extreme mission durations (months to years) being considered for HALE platforms eliminate the possibility of conventional, expendable fuel sources. Three possible long-duration power sources are nuclear reactors, fuel cells and solar arrays. Nuclear reactors are widely considered to be too dangerous and too heavy for implementation in HALE platforms operating within the Earth's atmosphere and existing fuel cells are not efficient enough to provide sustained power for several years. As a result, the primary focus of this section is on solar arrays. There are some emerging technologies involving regenerative fuel cells that may yield a viable alternative to solar arrays and are discussed at the end of this section.

With respect to captive stratospheric airships, such as APL's HATBS concept, the tether could potentially provide a continuous virtually unlimited power supply from the ground station. This concept has the advantage of reducing the onboard power subsystem requirements to a simple back-up battery supply in the event of a temporary power disruption from the ground station.

#### Solar Arrays

Figures 2.2 and 2.3 below outline some of the challenges associated with using solar power generation in HALE platforms. These figures show that, at latitudes closer to the poles, the angle of incidence of solar radiation to the solar arrays is such that there is a limited availability of solar power. It may be possible to take advantage of the large volume required for LTA platforms by mounting large solar arrays on the sides of the platform thus increasing the surface area for solar radiation absorption. Although HTA platforms must necessarily have large wingspans to operate at altitude, the increased surface area is not significant enough to offset the decreased angle of incidence. Another possibility for increasing the operational latitudes of an HTA HALE platform is to use panel-mounted, gimballed solar arrays instead of body-mounted arrays but this solution adds weight and complexity to the design. Pending the development of more efficient solar cells, the effective operational latitudes of some platforms may be limited, especially during the winter months.

The biggest difference between satellites and HALE platforms, with respect to solar power generation, is the duration of the eclipse time. For satellites in earth orbit, regardless of the orbit altitude, the eclipse time is a relatively small fraction of the total orbit period. The governing

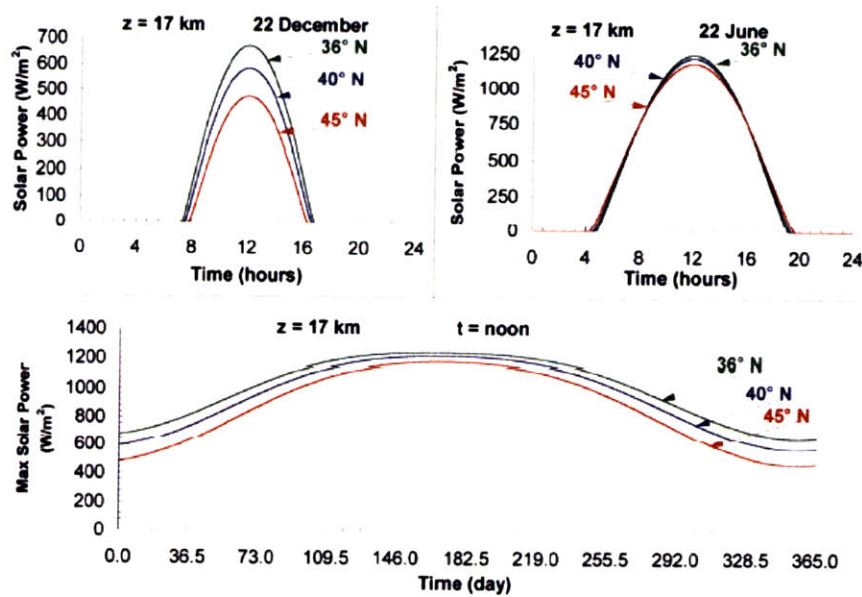


Figure 2.2: Daily and Yearly Solar Power Distribution at Several Latitudes; Source: Illustration courtesy Giulio Romeo, Turin Polytechnic University

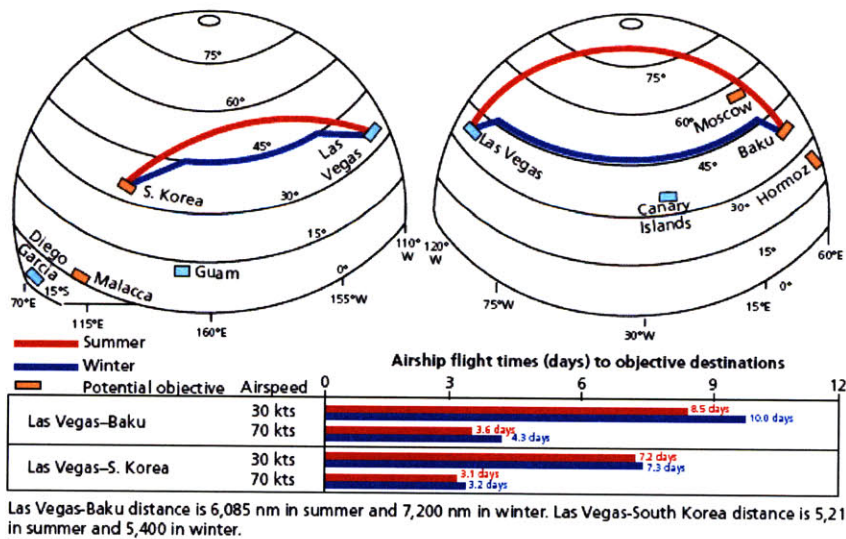


Figure 2.3: Deployment Flight Routes to Forward Destinations; Source: Rand Center technical report, "High Altitude Airships for the Future Force Army," 2005

equations for computing the eclipse fraction for any given sun angle are:[10]

$$\cos\left(\frac{\Phi}{2}\right) = \frac{\cos\rho}{\cos\beta_S} \quad (2.1)$$

The duration of the eclipse in a circular orbit,  $T_E$ , is then

$$T_E = P\left(\frac{\Phi}{360^\circ}\right) \quad (2.2)$$

Where  $\rho$  is the angular radius of the Earth,  $\beta_S$  is the angle of the sun above the orbit plane,  $\frac{\Phi}{2}$  is half of the rotation angle corresponding to the eclipse duration and  $P$  is the orbit period.[10] For satellites in Earth orbit, the eclipse time is measured in minutes and is usually on the order of 30% of the total orbit period for LEO satellites.

For HALE platforms, which are nearly stationary with respect to the area of interest on the ground and still operating within the Earth's atmosphere, the daily eclipse time has the same duration as the local night. Accounting for seasonal variations and operational latitude, the average annual eclipse duration is taken to be twelve hours. It is important to note, however, that the eclipse period approaches 24 hours or 100% of the duty cycle during the winter months in operational latitudes approaching 22° north/south thus significantly limiting the operational latitude ranges during certain months. This extended eclipse period translates to fewer charge/discharge cycles than required for conventional satellites. Spacecraft in low earth orbit (LEO) experience their maximum depth of discharge ( $DoD$  - percent of total battery capacity removed during a discharge period) approximately fifteen times per day while HALE platforms experience the maximum  $DoD$  only once per day. The reduced number of battery cycles afforded by HALE platforms allows for either lighter batteries or a deeper depth of discharge. Additionally, the reduced cycles prolong battery life facilitating a longer operational lifetime.

The expectation for power system sizing is that the smaller, lighter payloads possible on HALE platforms (discussed in the following Military Applications chapters) will require less power and therefore allow a lighter power subsystem. Further research is necessary to optimize HALE platform power systems in terms of size, mass and cost or to optimize the CONOPS by limiting operations at higher latitudes. As stated at the beginning of this section, subsystem optimization is beyond the scope of this thesis; however, the relevant governing equations are provided in Appendix A for further examination. This chapter will provide a power subsystem sizing example to outline the general requirements and feasibility of supporting a HALE platform.

### Regenerative Fuel Cells

As mentioned above, the efficiency of existing fuel cells is insufficient to provide sustained power for the multi-year missions planned for HALE platforms. Fuel cell efficiency is determined by

the amount of power drawn from the cell. The current drawn from a fuel cell is proportional to the amount of power drawn through the equation:

$$Pwr = VI \tag{2.3}$$

Where  $Pwr$  is the power in Watts,  $V$  is the potential difference in volts and  $I$  is the current in Amperes.

Drawing more power means drawing more current, which increases the losses in the fuel cell. As a general rule, the more power (current) drawn, the lower the efficiency. Most losses manifest themselves as a voltage drop in the cell, so the efficiency of a cell is almost proportional to its voltage. The affect of power draw on efficiency generally makes conventional fuel cells undesirable for use as a long term power source.

Fuel cells operate by electrochemical conversion through the consumption of a fuel and an oxidant which react in the presence of an electrolyte. The reactants consumed in the process must be replenished in order to maintain power output. This replenishment requirement is another major drawback to using fuel cells on HALE platforms.

Recent research in the area of regenerative fuel cells (RFC) suggests that it is possible to design a fuel cell that could consume waste products as reactants. The general operational principle is that, during daylight hours, a photovoltaic solar array generates all power requirements for the system electrical loads as well as power for a water electrolysis unit. In this configuration, hydrogen and oxygen are the two reactants consumed in the fuel cell power generation process. The water by-product of the electrolysis unit is collected, stored and then electrolyzed into its hydrogen and oxygen components during daylight for consumption during the following eclipse period (see figure 2.4 for a diagram of RFC system operations[11]).

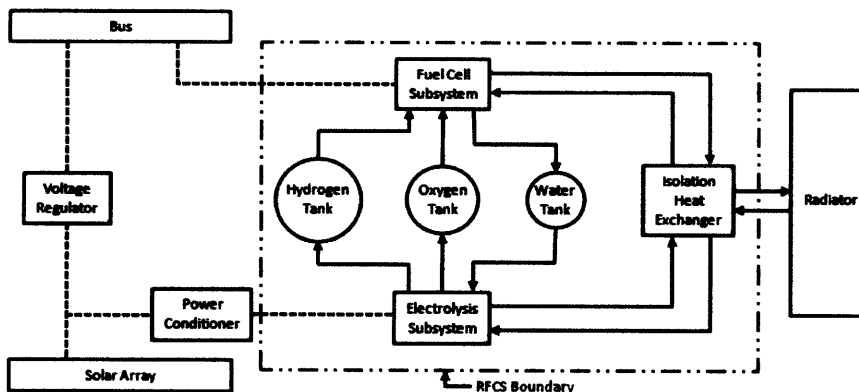


Figure 2.4: Diagram of a Regenerative Fuel Cell System; Source: Life Systems, Inc. Study Report, "Engineering Model System Study for a Regenerative Fuel Cell," 1984

Figure 2.5, taken from "The Fuel Cell in Space: Yesterday, Today and Tomorrow" by War-

shay and Prokopius,[12] shows the potential advantage of regenerative fuel cell energy storage versus conventional battery systems for long discharge applications. An important conclusion of figure 2.5 is that for a discharge time of twelve hours, an RFC system could potentially weigh one-quarter of the weight of a system using sodium-sulfur ( $NaS$ ) batteries or one-tenth that of a nickel-hydrogen ( $NiH$ ) battery powered system.

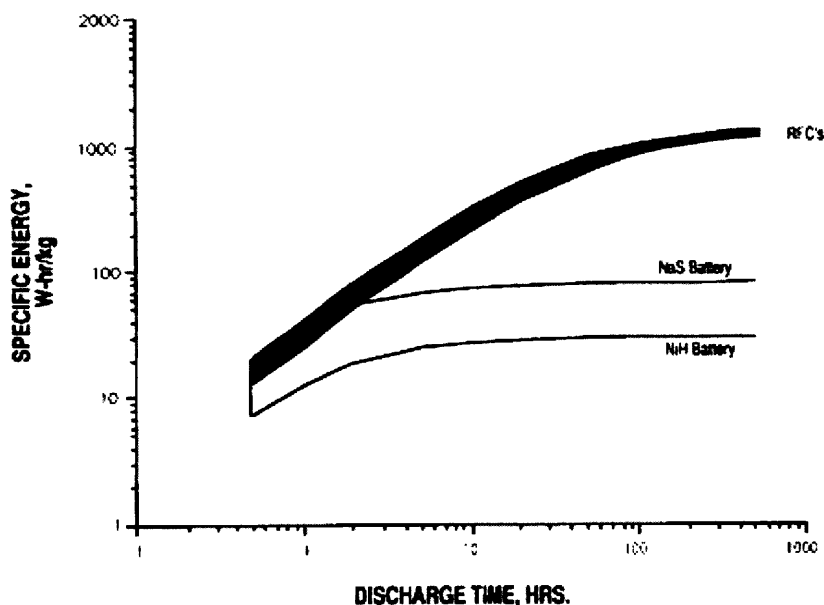


Figure 2.5: Advantage of Regenerative Fuel Cell Energy Storage versus Conventional Battery Systems for Long Discharge Applications; Source: NASA Technical Memorandum 102366, "The Fuel Cell in Space: Yesterday, Today and Tomorrow," 1989

According to Barbir et al, "The results suggest that high efficiency does not necessarily provide the highest specific energy, and that the highest specific energy of the energy storage subsystem does not result in the lowest mass of the entire power system. Figure 2.6 is extracted from Barbir et al[13] and shows the relationship between specific energy and total RFC mass as a function of the nominal fuel cell potential. This data is based on empirical studies of a specific regenerative  $H_2-O_2$  fuel cell and is not meant to provide a parametric relationship between specific energy and mass.

"Optimum cell voltage (in both fuel cell and electrolyzer modes) strongly depends on the duty cycle of the system as well as the fuel cell/electrolyzer polarization curves and hydrogen/oxygen storage characteristics." [13] Since research suggests that regenerative  $H_2-O_2$  fuel cells can achieve much higher specific energy densities than currently available batteries (Figure 2.5), these "systems may be used in applications where relatively large amounts of energy must be stored. These applications include ... high altitude long endurance solar rechargeable

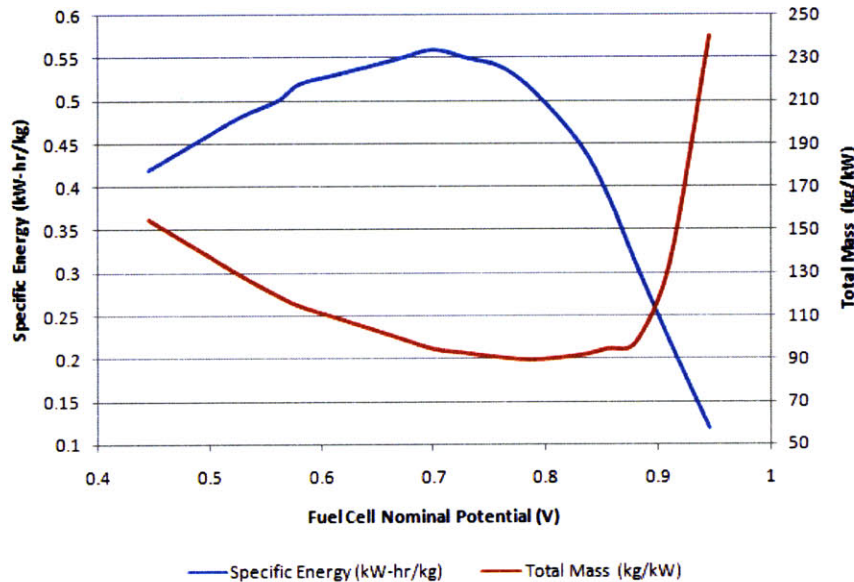


Figure 2.6: RFC Specific-Energy & Mass Relations as a Function of Fuel Cell Voltage; Source: IEEE A&E SYSTEMS MAGAZINE, "Regenerative Fuel Cells for Energy Storage: Efficiency and Weight Trade-offs," Barbir et al, 2005

aircraft." [13]

A further advantage of these hydrogen/oxygen RFCs is that they operate more efficiently on pure oxygen rather than an air mixture of oxygen and nitrogen. This characteristic is important in high altitude applications where atmospheric oxygen is limited (and critical in the vacuum of space). The pure oxygen by-product of electrolysis allows the system to operate more efficiently, be lighter as it would not require a device to pump air through the fuel cell (resulting in additional efficiency losses) and be a closed system with fewer failure modes.

Another existence proof of this concept is "Helios", a solar cell/regenerative fuel cell system powered unmanned air vehicle under development by AeroVironment. Helios is designed to "fly at 50,000-70,000 feet for months without landing and serve as a substitute satellite, a platform capable of supporting telecommunication, and military and civilian applications." [14] To date, a HALE UAV named "Pathfinder," designed and built by AeroVironment "flew to 80,000 feet setting a new world record for the highest flying propeller driven aircraft." [14]

Research to date indicates that  $H_2-O_2$  RFCs are a viable option for HALE platforms however, further research must be done to optimize the system design for specific applications (e.g., duration of charge/discharge cycles and various load profiles).



### 2.1.3 Thermal Management

Since HALE platforms operate within the Earth's atmosphere, temperature variations are not as extreme as those experienced by Earth orbiting satellites. However, temperatures in the near-space regime of the atmosphere still vary widely between daylight and nighttime hours. Thus successful HALE designs must include a thermal control system (TCS) to maintain all platform and payload components within their required upper and lower operating temperatures. Traditionally two temperature limits are defined: "operational limits that the component must remain within while operating and survival limits that the components must remain within at all times." [15] There are two broad categories of thermal control: passive, which uses materials, coatings, insulation and radiators; and active, which uses electrically powered heaters and coolers. Table 2.1 below is taken from chapter 11.5 of Space Mission Analysis and Design, 3d Edition (SMAD) written by Gilmore et al and provides examples of typical thermal requirements for spacecraft and payload components. In general, if the spacecraft components shown in the table can also be used on HALE platforms, the component will have similar operational and survival temperatures and can be used as design guidelines for HALE systems. While the difference in ambient temperatures between stratospheric and orbital altitudes will necessitate different thermal system requirements, the governing equations and design principles are the same and are discussed later.

Component	Typical Temperature Ranges (°C)	
	Operational	Survival
Batteries	0 to 15	-10 to 25
Power Box Baseplates	-10 to 50	-20 to 60
Reaction Wheels	-10 to 40	-20 to 50
Gyros/IMUs	0 to 40	-10 to 50
Star Trackers	0 to 30	-10 to 40
C&DH Box Baseplates	-20 to 60	-40 to 75
Hydrazine Tanks and Lines	15 to 40	5 to 50
Antenna Gimbals	-40 to 80	-50 to 90
Antennas	-100 to 100	-120 to 120
Solar Panels	-150 to 110	-200 to 130

Table 2.1: Examples of Typical Thermal Requirements for Spacecraft Components; Source: SMAD Chapter 11.5

In October 2007, while working under contract to the Missile Defense Agency, Charles Lavan gave a presentation entitled the High Altitude Long Endurance Primer [16] in which he outlined the basic design considerations and issues surrounding HALE platforms. In that presentation, Dr. Lavan provided several simple equations to determine the ambient temperature and atmospheric pressures at various altitudes. Those equations are summarized below:

For altitudes in the upper stratosphere ( $H_p \geq 82345$  feet):

$$\begin{aligned} T &= -205.05 + 0.00164H_p \\ p &= 51.97 * \left[ \frac{T + 459.7}{389.98} \right]^{-11.388} \end{aligned} \quad (2.4)$$

For altitudes in the lower stratosphere ( $36152 \leq H_p < 82345$  feet):

$$\begin{aligned} T &= -70 \\ p &= 473.1 * e^{(1.73 - 0.000048H_p)} \end{aligned} \quad (2.5)$$

For altitudes in the troposphere ( $H_p < 36152$  feet):

$$\begin{aligned} T &= 59 - 0.00356H_p \\ p &= 2116 * \left[ \frac{T + 459.7}{518.6} \right]^{5.526} \end{aligned} \quad (2.6)$$

In all cases, atmospheric density ( $\rho_{atm}$ ) is a function of pressure as follows:

$$\rho_{atm} = \frac{p}{1718 * (T + 459.7)} \quad (2.7)$$

Where  $H_p$  is the platform altitude in feet,  $T$  is the ambient temperature in °F,  $p$  is the atmospheric pressure in lbs/sq ft and  $\rho_{atm}$  is measured in slugs/cu ft.

Based on the USAF SAB study discussed in section 1.1, we are primarily interested in HALE uses in the near space regime between 65,000 ft (20 km) and 100,000 ft (30.5 km), therefore; we will restrict our consideration to equations (2.4), (2.5) and (2.7). Applying those equations, we obtain the atmospheric temperature/density profile shown in figure 2.7.

Knowing the external temperatures at various altitudes allows us to calculate the required heat balance for proper system operation. According to Gilmore et al,[15] "for most spacecraft, heat balance on radiators is the dominant factor in the thermal design." We will apply this same consideration to HALE platforms in a generalized heat balance equation:

$$Q_{external} + Q_{internal} = Q_{radiator} + Q_{MLI} + Q_{convective} \quad (2.8)$$

Where  $Q_{external}$  is the environmental heat absorbed,  $Q_{internal}$  is the power dissipation of on-board electronic components,  $Q_{radiator}$  is the heat rejected from the platform's primary radiator surfaces,  $Q_{MLI}$  is the heat lost through multi-layer insulation on the platform and  $Q_{convective}$  is the heat lost through convection. For the purposes of this section, it is assumed that the primary means of heat elimination is radiative since the low atmospheric density makes convective heating and cooling impractical. Therefore, we will ignore the  $Q_{convective}$  term.

Appendix A contains the other governing equations relevant to determining the solutions

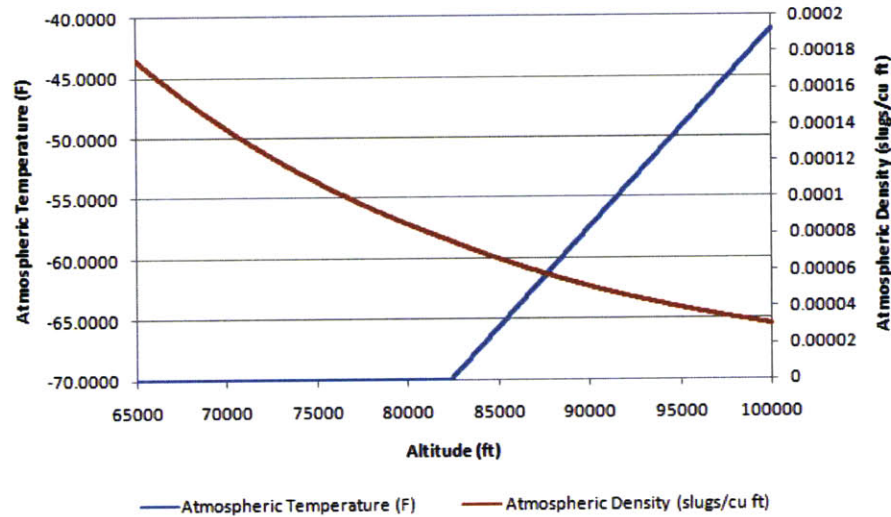


Figure 2.7: Near-Space Atmospheric Temperature and Density Profile; Source: Charles Lavan, Personal Communication, April 2009

to the heat balance equation, including some simplifications of equation 2.8. For the scope of this chapter, it is sufficient to say that heat absorbed must equal heat dissipated and that the mean and excursion temperatures must remain within the operational and survival limits of all onboard components.

Effective thermal management requires the careful balancing of heat input and heat output to maintain components within their acceptable temperature ranges. Several advantages apply to HALE platforms over spacecraft in that the environmental temperatures in the stratosphere do not vary as widely as those encountered by spacecraft; specifically, the range of temperatures between night and day is much less extreme. This reduced variation simplifies the thermal control requirements. Additionally, since HALE platforms operate under 1g conditions and within the Earth's atmosphere, the problems associated with the microgravity and vacuum of spaceflight such as outgassing and mechanical adhesion to the substrate don't apply, making a wider range of insulating materials and surface finishes available for use.

#### 2.1.4 Materials Selection

As mentioned previously in section 1.1, the USAF SAB study of high altitude persistence found that the operational altitude has a direct correlation to the required volume of an LTA platform and the wingspan of an HTA platform. In another study conducted jointly by the Air Force Space Command (AFSPC) and the Air Force Research Laboratory (AFRL), it was determined that "as altitude increases, an LTA platform grows exponentially and UAV endurance drops exponentially,"[17] (or, conversely, UAV wingspan increases asymptotically). Figure 2.8 taken

from that study illustrates this phenomenon.

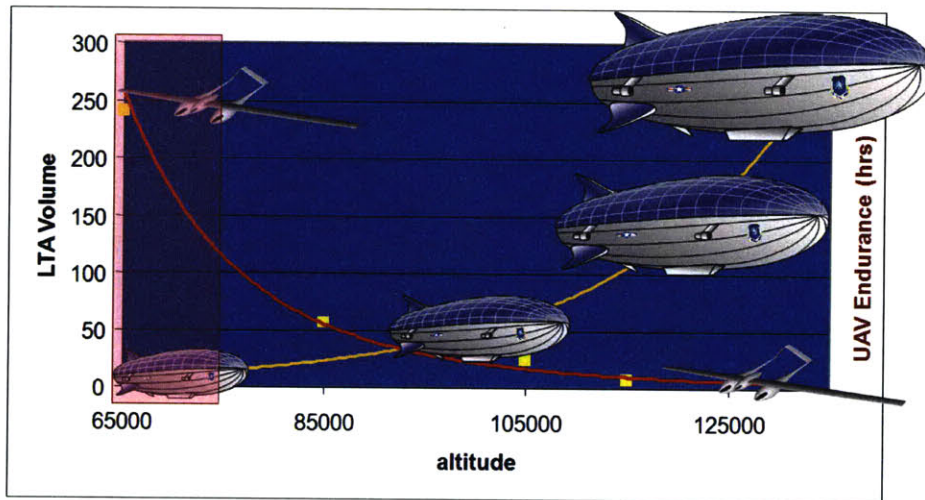


Figure 2.8: Altitude Density Effects on Near Space Carriers; Source: AFSPC/AFRL Study, "Near Space Study: Approach/Findings and Conclusions - Outbrief," 2005

As a result of the effect of atmospheric density on both HTA and LTA platform performance, material selection is a critical consideration in successful designs. Key considerations in the design of the platform structure include "optional materials, types of structure and methods of construction. To select from these options, we do trade studies to compare weight, cost and risk." [18] Materials used in the structure and gas envelope, for LTA platforms, must have high strength-to-weight ratios and a typical structure will include both metallic and nonmetallic materials. According to SMAD v3,

"the core body structure ... typically accounts for 10% to 20% of a spacecraft's dry weight. ... We should also add approximately 25% for weight growth to account for program additions, underestimating and inadequate understanding of requirements. ... The spacecraft item most often underestimated or neglected is electronic wiring, sometimes approaching 10% of a spacecraft's dry weight." [18]

A typical spacecraft experiences very high inertial loads during launch, however, these load factors are short-duration and once the spacecraft is in orbit, it experiences very little inertial loading. HALE platforms experience less extreme variations in inertial load factors throughout its lifetime and will experience the highest inertial loading due to turbulence especially while transiting the jetstream (see figure 2.1 for a description of typical wind velocities by altitude). However, since the platform remains subject to 1g conditions for the duration of its lifetime, the load factors are continuous and require a structure capable of supporting and, in the case of HTA platforms, lifting the vehicle throughout its lifetime. Materials with sufficient strength to

withstand the inertial loads due to the jetstream will be strong enough to support the vehicle through the range of inertial loads experienced during operation. Generally speaking, structural materials for HALE platforms will account for a larger percentage of the platform dry weight, on the order of 40% of the total weight.[19]

In a study conducted by the Naval Ordnance Laboratory in 1975, the authors discuss several considerations germane to LTA platforms.

"Fabric selection will be determined by environmental conditions as well as by weight, strength, and other basic parameters of the material. ... The ideal hull fabric should be very strong, extremely light, insensitive to extremes of temperature, impervious to ultraviolet radiation, ozone and bombardment with charged particles, have limited elasticity and no creep, and be impenetrable to helium or hydrogen. For ease of manufacture the material should be easy to cut, seam, and seal, and be readily available and cheap. In addition it should be insensitive to folding and creasing, and have a storage life of several years under the poorest of conditions." [19]

The two most important considerations in this rather extensive list are arguably the material's resistance to temperature fluctuations and ultraviolet radiation since exposure to sunlight is magnified and thermal coupling to the atmosphere is reduced at higher altitudes thus increasing exposure to ultraviolet radiation.[19]

While it is beyond the scope of this thesis to select actual candidate materials for HALE platforms, it is important to identify some key parameters upon which material selection depends most strongly. To this end, two parameters are offered for the reader's consideration: material tensile strength,  $\tau$ , and resistance to inelastic deformation. Tensile strength is important in determining the material's strength-to-weight ratio and the material's resistance to inelastic deformation is critical with respect to the material's ability to retain its shape and lift properties through the cyclic and continuous stresses over the extreme mission durations being considered for HALE applications.

In general, HALE platforms benefit from a wider range of available materials than does a spacecraft. The materials available are not exotic and do not require space qualification. Therefore, while material selection is a critical component of a successful design, it is not likely to be the significant factor in the overall technical feasibility of the HALE concept.

### 2.1.5 Dynamic and Electronic Attacks

Predictability is undoubtedly the issue at the crux of a platform's ability to survive dynamic and electronic attacks via both ground-to-air and air-to-air engagements. In the military applications discussed here: communications relay, ISR, and GPS enhancement, predictability is

essential in order to maximize the performance of the platform. On the other hand, a platform's predictability is the key factor that would enable engagement by an enemy force.

A study commissioned by the AFRL conducted an analysis of HALE platform survivability and concluded that there are several advantages working in favor of a platform's ability to survive an attack. First and foremost, HALE platforms, while operating at altitude, are out of range for most conventional weapon systems. The exception to this rule is a radio frequency (RF) terminally guided medium to long-range missile.[20] Table 2.2 outlines the capabilities of currently available medium/long-range surface-to-air missiles (SAM). A further limiting factor on platform vulnerability is the fact that medium/long-range SAMs are not highly proliferated due to their inherent high cost.

Country	Designation	Range	Flight Alt.	Guidance
Russia	SA-2	28km	66 kft	3 GHz Track/Engage Radar
	SA-5	>300km	130 kft	Active RF Terminal Seeker
	SA-10 (SA-10C)	200km	82 kft	RF Terminal Seeker
China	KS-1	40km	79 kft	Phased Array Radar
France	MASURCA	23km	75 kft	Semi-active Radar

Table 2.2: Medium/Long-Range SAM Capabilities; Source: [www.wikipedia.com](http://www.wikipedia.com), accessed March 2009

The AFRL study also considered vulnerability to weapon systems operating in the infrared (IR) and visible spectrums. In both cases, the study concluded that HALE platform does not have any significant vulnerability to these types of attack.[16] The key contributing factor to low IR vulnerability is the fact that the vehicle's IR signature is very large (spatially) and highly distributed with no significant "hot spots" for terminal lock-on. Based on an unclassified review of threat literature, it is sufficient to say that IR terminally guided munitions are not capable of detecting HALE platforms.

Vulnerability in the visible spectrum depends on the range, relative brightness and atmospheric clarity. HALE platforms are beyond the range of visually targeted hand held weapons and the low target contrast with the background sky means even high-altitude visually targeted weapons will not be able to detect the platform. It is valid to argue that HALE platforms are vulnerable to visually targeted weapon systems during ascent and descent. In this case, alternate means of protection must be considered and are discussed later.

Further contributing factors to HALE survivability include the fact that these platforms are maneuverable and, given sufficient warning, can be moved out of range of SAM attacks. A nominal operating altitude of 85,000 feet places the platform out of range of all threat SAMs except the SA-5. Additionally HALE platforms can be equipped with conventional counter-measure devices that alter the electromagnetic, acoustic or radio frequency (RF) signature of

the platform and/or jettison decoys such as chaff and flares. It is important to note that altering or modifying the platform's RF signature will not work for communications and GPS payloads which depend on their RF signatures for mission accomplishment. Finally, the U.S. Army's MIM-104 Patriot missile system, operating in its primary role as an anti-ballistic missile (ABM) platform, could intercept and destroy any inbound missile threat.

Having safely achieved the operating altitude, one must now consider the platform's vulnerability during ascent and descent; several options exist to offset potential threats. First, the U.S. Army always assumes air superiority in any confrontation. Assigning USAF fighter jets to patrol the vicinity of the HALE platforms ascent and descent will afford the necessary protection against most conventional attacks. The Patriot missile system could also be employed to protect the platform during this period of increased vulnerability. Deploying the platform from within the United States and then moving the platform to the area of operations under its own power and thus avoiding ascent and descent over hostile territory is another way to mitigate platform vulnerability. Finally, the vulnerability during ascent and descent can be mitigated by not operating the payload until the platform has reached its operational altitude thus eliminating a large percentage of platform emissions during the most vulnerable times.

One admitted limitation to the AFRL study is that it does not consider the properties of the payload in the survivability calculations. One key example is that, while the platform may have a small radar cross-section, a communications relay payload would essentially act as a beacon for RF terminally guided munitions. This limitation is offset by the fact that a communications payload will only be operational once on station. The communications payload vulnerability example requires significant design upgrades to ensure platform survivability.

## 2.2 Projected HALE Capabilities

HALE platforms have the capability to significantly improve many aspects of military operations. A commander's situational understanding on the battlefield relies on rapid, relevant information. Space-based assets are currently able to satisfy these requirements to a limited extent but they are difficult to retask, require significant operational resources and usually cannot be accessed below the National Command Authority level. Sufficient numbers of HALE platforms have the potential to provide commanders with dedicated pseudo-satellite capabilities at a fraction of the cost of conventional satellites. Dedicated support would allow the combatant commander to specify the platform's tasks and retask the platform to higher priority missions with virtually no time-lag.

A simple example can clearly demonstrate the potential effectiveness of HALE platforms. Consider a HALE platform with a generic mission payload. Equation (2.9) shows the calculation

for a sensor coverage area.

$$F_r = R_E * \cos^{-1} \left( \frac{R_E}{R_E + H_p} \right) \quad (2.9)$$

Where  $F_r$  is the sensor footprint radius in miles,  $R_E$  is the radius of the Earth (3963.16 miles) and  $H_p$  is the platform altitude in miles.

Equation (2.9) assumes a zero degree elevation angle (i.e., the sensor can see all the way to the horizon). While this assumption may be true for a communications payload operating over the flat Iraqi desert, it is not a valid assumption for platforms operating over mountainous or urban terrain or for imaging payloads which cannot detect usable images at the horizon. Therefore, the sensor coverage equation must be modified to include the elevation angle. The calculations that follow reference the angular relationships shown in figure 2.9 adapted from SMAD chapter 5.[21]

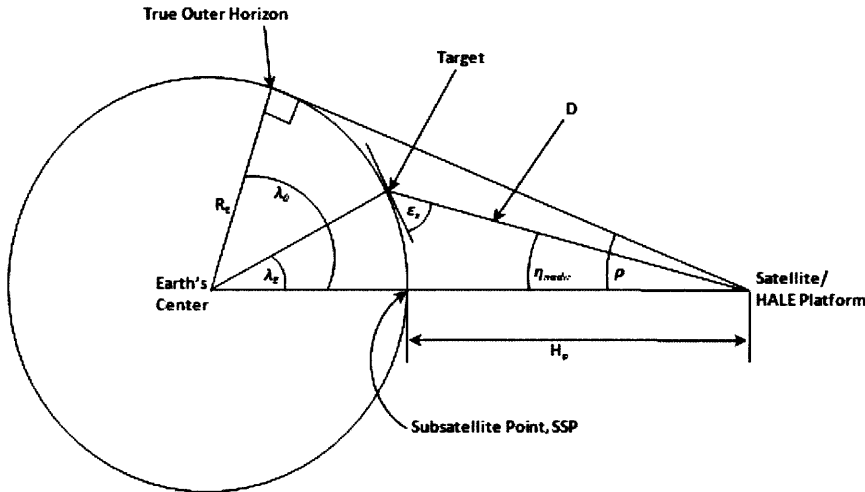


Figure 2.9: Definition of Angular Relationships between Satellite, Target and Earth Center; Source: SMAD Chapter 5, Figure 5-13

First calculate the angular radius of the earth,  $\rho$ , from equation (2.10).

$$\sin \rho = \frac{R_E}{R_E + H_p} \quad (2.10)$$

Then set the desired elevation angle,  $\epsilon_s$ , and determine the nadir angle,  $\eta_{madir}$ , as follows:

$$\sin \eta_{madir} = \cos \epsilon_s \sin \rho \quad (2.11)$$

Finally, find the Earth central angle,  $\lambda_E$ , through the relation given in equation (2.12) and multiply  $\lambda_E$  by the number of miles per degree on the Earth's surface to determine the radius



of the sensor footprint.

$$\eta_{nadir} + \lambda_E + \epsilon_s = 90^\circ \tag{2.12}$$

$$F_r = \lambda_E \left( \frac{2\pi R_E}{360^\circ} \right) \tag{2.13}$$

Applying equations (2.10) through (2.13) for altitudes from 10,000 to 100,000 feet, we get the sensor coverage area profile shown in figure 2.10. This figure shows sensor coverage areas for 0, 5, 10 and 15 degree elevation angles. It is clear that imposing any elevation angle significantly impacts the available coverage area, however, at a nominal altitude of 85,000 feet, an elevation angle of 15 degrees still allows a coverage area of more than 115 miles which is a significant improvement over current ground-based sensor capabilities. The final elevation angle, and thus the coverage area, chosen will depend on specific payload capabilities.

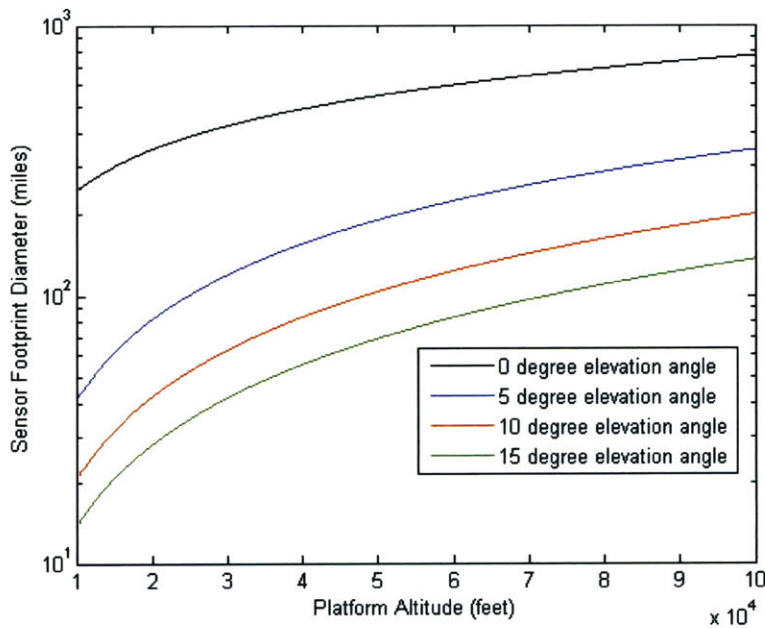


Figure 2.10: HALE Platform Sensor Coverage Profile; Source: U.S. Army Space & Missile Defense Command

In a further extension of this example, figure 2.11 shows that a HALE platform operating at 70,000 feet with a zero degree elevation angle can cover an area nearly the size of Afghanistan. Even accounting for performance losses at the horizon and interference by the country’s mountains, this coverage area is a significant benefit to the combatant commander at any level.

Other advantages of HALE platforms over satellites are shorter transmission distances for



Figure 2.11: Example HALE Footprint Coverage (647 mile diameter from 70,000 feet); Source: Rand Study, "High Altitude Airships for the Future Force Army"

relying ground-based communications and shorter ranges for sensor surveillance of the battlefield and acquisition of ground targets. Persistent coverage of an area of interest allows for continuous BLOS communication and terrain comparison analysis can highlight changes over time. The detection, by HALE supported sensors, of changes such as freshly turned dirt along a roadway where bombs have been emplaced would provide significant survival advantages to Soldiers operating in hostile areas.

## 2.3 Platform Sizing Example

It is necessary to provide some general sizing information as a means of scoping the HALE problem. In this section, we will first explore the physical size requirements of the platform itself and describe how the reduced atmospheric density, as an inverse function of altitude, affects the volume of an LTA vehicle and the wingspan of an HTA vehicle. Following the physical size discussion, we will size the power subsystem, including energy storage, power distribution and power regulation requirements as a representative example of subsystem sizing calculations.

### 2.3.1 Platform Physical Sizing

The USAF SAB study on persistence at near space altitudes provides some excellent examples of the size requirements imposed on both LTA and HTA platforms as a function of the reduction of

atmospheric density with increased altitude. Figure 2.12 demonstrates the increased radius for increased altitude with respect to a vented helium-filled balloon carrying a 1,000 pound payload assuming a very lightweight envelope material (on the order of 50 gm/m<sup>2</sup> or 1.5 oz/yd<sup>2</sup>).

According to the study, "at 40,000 ft in altitude, a balloon with a 30 ft radius is required to lift a 1000 lb payload ... at about 90,000 ft in altitude, this balloon must be twice its original radius to lift the [same] payload. By the time the balloon reaches 180,000 ft in altitude, the balloon must be 540 ft in diameter, with a volume of 82 million ft<sup>3</sup>, almost 2.3 times the volume of Houston Astrodome. Simply on the basis of the atmospheric density reduction, a high altitude balloon becomes impractical at such high altitudes." [3] Beyond the need to provide sufficient buoyant lift in a low density environment, the increased volume of a stratospheric airship is necessary to allow room for the lifting gas (in the case of the SAB study, helium) to expand. Without this pressure relief method, a gas envelope capable of withstanding the high internal pressure loads would be prohibitively heavy. [3]

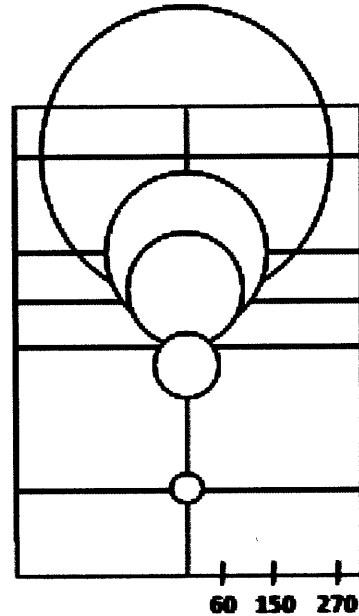


Figure 2.12: Changes in LTA Radius (ft) for 1000 lb Payload; Source: USAF SAB Study, "Persistence at Near Space Altitudes," 2005

In a further example, the SAB study analyzed the LTA radii required for three different payload weights (500, 1,000 and 2,000 pounds) again assuming the same lightweight envelope material as above with a payload mass margin of 25%. The study also analyzed the LTA volume required for two different payload fractions (1% and 10%). Figure 2.13 shows a comparison of the radii of a vented helium-filled balloon as altitude increases and figure 2.14 shows a comparison of the volume of a vented helium-filled balloon for two different payload fractions (1% and 10%) as altitude increases.

The analysis in figure 2.13 shows that increasing the altitude from 45,000 feet to 150,000 feet requires the balloon volume to increase by more than 100 times. "At 135,000 feet, the diameter of the balloon diameter will approach the length of the Boeing 747 fuselage ... at 150,000 feet, the balloon volume is nearly half that of the Houston Astrodome. To the unaided human eye from sea level, the balloon would appear to be about 25% of the size of the moon." [3]

Figure 2.14 demonstrates the relative size of a stratospheric airship as compared to the Goodyear Blimp which is designed to operate below 10,000 feet. Additionally, this figure shows the extreme sensitivity to payload fraction, "at 1% payload fraction, it is difficult to close on an airship design that can operate at stratospheric altitudes. ... At a 10% payload fraction, stratospheric altitudes (somewhat above 65,000 ft) could be achieved with an airship sized at

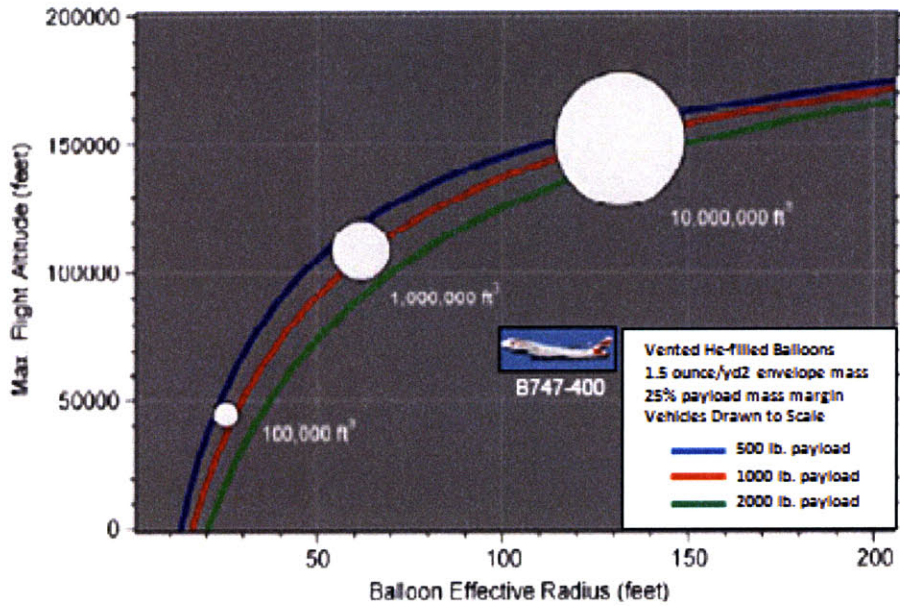


Figure 2.13: Comparison of the Radii of a Vented Helium-filled Balloon as a Function of Increased Altitude with Varying Payload Weights; Source: USAF SAB Study, "Persistence at Near Space Altitudes," 2005

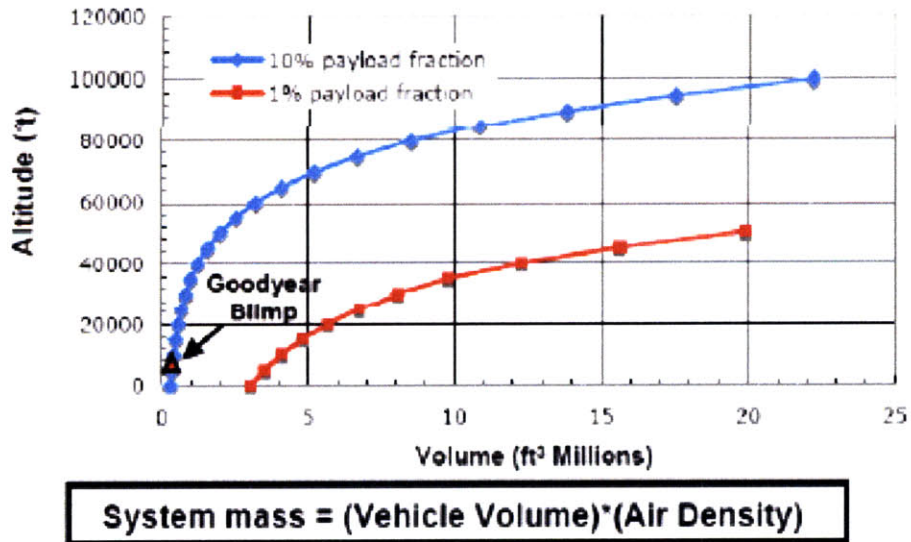


Figure 2.14: Comparison of the Volume of a Vented Helium-filled Balloon as a Function of Increased Altitude with Varying Payload Fractions; Source: USAF SAB Study, "Persistence at Near Space Altitudes," 2005

about 5 [million] cubic feet." [3]

In sizing an HTA platform, the primary consideration is the wingspan necessary to provide lift and maneuverability at stratospheric altitudes. Figure 2.15 shows the variation of an HTA platform wingspan as a function of altitude. The SAB study assumes a fixed payload of 2,000 pounds and a fixed aspect wing ratio of twenty. The two payload fractions considered are 1% and 10% as in the LTA example in figure 2.14.

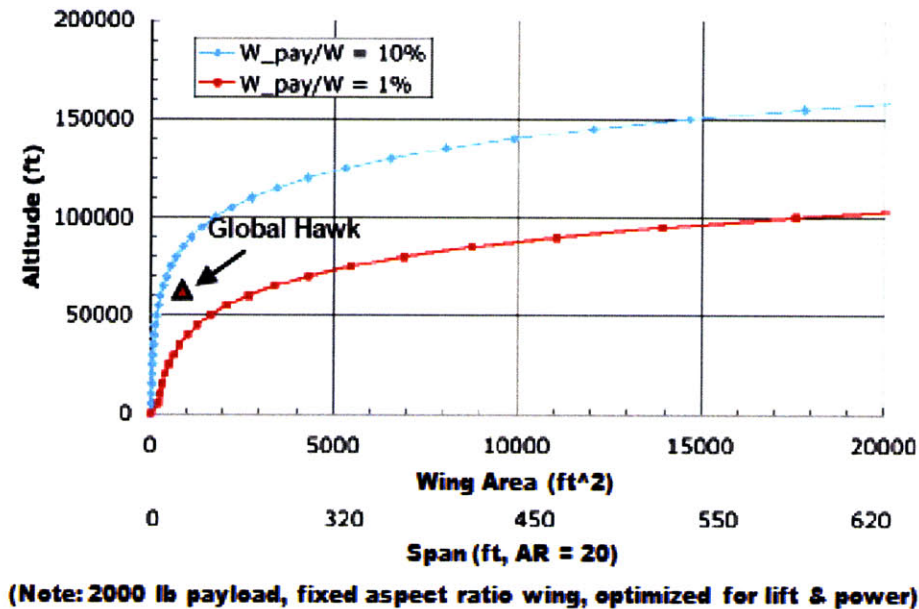


Figure 2.15: Comparison of the Wingspan of an HTA UAV as a Function of Increased Altitude with Varying Payload Fractions; Source: USAF SAB Study, "Persistence at Near Space Altitudes," 2005

"Realistically speaking, an aircraft wingspan of 300 ft is about the largest that would be practical for a single vehicle. One could operate such a vehicle above 65,000 ft if the payload fraction could be increased via advanced materials and other platform optimization." [3]

Based on the threat analysis in section 2.1.5 and the analysis conducted by the SAB study, we assume the following characteristics of a HALE platform: a) nominal 85,000 feet operational altitude; b) 2,000 payload weight and c) 10% payload fraction. Table 2.3 then provides the size requirements for both an LTA and an HTA vehicle. These characteristics will be carried forward and incorporated into future payload sizing calculations as appropriate.

For reference, the Boeing 747-400 commercial aircraft has a wingspan of 211 feet and a wing area of 5,825 square feet. [22] Therefore, the dimensions proposed for an HTA HALE platform are reasonable.

---

<b>Platform Type</b>	<b>Diameter</b>	<b>Volume</b>
LTA	96 ft	5.5 million ft <sup>3</sup>
<b>Platform Type</b>	<b>Wingspan</b>	<b>Wing Area</b>
HTA	64 ft	1,000 ft <sup>2</sup>

---

Table 2.3: HALE Platform Size Requirements for Given Operational Characteristics; Source: USAF SAB Study, "Persistence at Near Space Altitudes," 2005

### 2.3.2 Power Sub-system Sizing

Subsequent chapters will analyze HALE platform performance with respect the three primary military applications identified in section 1.4: communications, ISR and navigation. As the reader will see later, the maximum payload power requirement for the three discussed applications is 113 watts which is the requirement for an earth observation payload operating in both the visible and infrared spectrums. We will use this power value to determine the required subsystem size in terms of the hardware, software and interfaces for each.

The detailed governing equations for power sub-system design and sizing are outlined in appendix A.1 and are referenced here. As discussed in appendix A.1, it is necessary to size the power subsystem based on the end-of-life (EOL) requirements in order to account for solar cell degradation over time. Additionally, the 113 watt power requirement is the average payload power. It is necessary to multiply the average power by a factor of 2 or 3 to determine the peak power requirements for attitude control, thermal management and electrical power subsystem (EPS) while charging the batteries in addition to the payload requirements.[23] Generally, the solar arrays are sized to provide the average power requirement and any additional power requirements, up to the peak power, are serviced by the batteries – even during daylight hours. This method is possible because not all systems will require peak power at the same time and peak requirements are short-duration.

Table 2.4[24] shows a comparison of the most common spacecraft power sources. This analysis will focus on solar arrays as the more mature power generation technology available and because solar arrays offer the highest specific power (W/kg) and lower specific cost (\$/W) than other power sources.

Having identified the average power requirements of the platform, the next step is to calculate the amount of power,  $P_{sa}$ , that the solar arrays must produce. The formula is provided in equation (2.14). As discussed in section 2.1.2, the average eclipse time (discounting seasonal variations and operational latitudes) is taken to be 12 hours (720 minutes). For this analysis, we will assume an array to battery to load efficiency,  $X_e$ , of 0.6 and an array to load efficiency,  $X_d$ , of 0.8, assuming a peak power tracking regulation scheme; daylight and eclipse power

EPS Design Parameters	Solar Photovoltaic	Solar Thermal Dynamic	Radio-isotope	Nuclear Reactor	Fuel Cell
Power Range (kW)	0.2-200	5-300	0.2-10	5-300	0.2-50
Specific Power (W/kg)	25-200	9-15	5-20	2-40	275
Specific Cost (\$/W)	800-3,000	1,000-2,000	16K-200K	400K-700K	Unknown
Stability and Maneuverability	Low	Med	High	High	High
Degradation Over Life	Med	Med	Low	Low	Low
Storage Required for Solar Eclipse	Yes	Yes	No	No	No
Sensitivity to Sun Angle	Med	High	N/A	N/A	N/A
Fuel Availability	Unlimited	Unlimited	V. Low	V. Low	Med
IR Signature	Low	Med	Med	High	Med

Table 2.4: Comparison of Common Spacecraft Power Sources; Source: SMAD Chapter 11.4, Table 11-33 (excerpt)

requirements ( $P_d$  and  $P_e$ , respectively) are assumed to be equal and set to 113 watts.

$$P_{sa} = \frac{\left(\frac{P_e T_e}{X_e} + \frac{P_d T_d}{X_d}\right)}{T_d} = \frac{\left(\frac{113 \cdot 720}{0.6} + \frac{113 \cdot 720}{0.8}\right)}{720} = 330 \text{ watts} \quad (2.14)$$

The next step in sizing the solar array is to calculate the required surface area of the array through equation (2.15).

$$A_{sa} = \frac{P_{sa}}{P_{EOL}} = \frac{330}{113} = 2.92 \text{ m}^2 = 31.43 \text{ ft}^2 \quad (2.15)$$

Referring to table 2.3, it is clear that either an HTA or an LTA platform designed to operate at 85,000 feet will have sufficient surface area to support body-mounted solar arrays. Therefore, using power subsystem sizing requirements as the sole metric, there is no significant advantage of one platform type over another.

Note that since we already know the average end of life power requirements to be 113 watts, there is no need to calculate the beginning of life (BOL) power requirement in this sizing example. However, should it be necessary, the reader would use equations (A.2) through (A.5) and tables A.1 and A.2 to calculate the correct value for BOL power.

Having calculated the surface area of the solar array, the next step is to estimate the mass of the array,  $M_{sa}$ , using equation (2.16).[25] In this case, we will assume a specific power of 25 W/kg as a conservative estimate, since the solar array must be able to support itself and

operate in a 1g environment.

$$M_{sa} = \frac{1}{\text{Specific Power (W/kg)}} * P_{sa} = \frac{1}{25} * 330 = 13.2 \text{ kg} = 29 \text{ lbs} \quad (2.16)$$

Given that our initial lifting capacity of the platform was estimated at 2,000 pounds (section 2.3.1), the platform can easily support the weight of the solar cells. However, designers must keep in mind the weight budget for the entire system including the weights of the payload and the other platform subsystems; it is easy to see how the total platform weight can quickly approach the upper limit. Clearly, current solar cell technology is sufficient to make HALE platforms a practical alternative to satellites or conventional aerial platforms.

The final step in sizing the power subsystem is to calculate the battery capacity required to support platform operations during eclipse periods. Batteries have one of two uses, primary and secondary. Primary batteries convert chemical energy into electrical energy and cannot be recharged. Therefore they only apply to short duration missions or low-power, long-term tasks such as memory backup. This analysis will focus on secondary batteries which can be recharged (via the solar array) and are used to provide power during eclipse periods or to provide backup power in the event of solar cell failure. Table 2.5 provides the specific energy densities (W-hr/kg) for some common secondary batteries. In general, secondary batteries have a much lower specific energy density than primary batteries but that limitation is offset by their ability to be recharged.

Battery Couple	Specific Energy Density (W-hr/kg)	Comments
Nickel-Cadmium	25-30	Space-qualified, Extensive database
Nickel-Hydrogen (Individual †)	35-43	Space-qualified, Good database
Nickel-Hydrogen (Common †)	40-56	Space-qualified for GEO and Planetary
Nickel-Hydrogen (Single †)	43-57	Space-qualified
Lithium-Ion	70-110	Under development
Sodium-Sulfur	140-210	Under development

† Various Types of Pressure Vessel Designs

Table 2.5: Characteristics of Common Secondary Batteries; Source: SMAD Chapter 11.4.2, Table 11-39

Since HALE platforms experience relatively few eclipse periods (365 per year), we will assume the use of nickel-hydrogen common pressure vessel design batteries. These batteries



are commonly used on satellites in GEO orbit, experience fewer charge/discharge cycles and thus are designed to tolerate a high depth of discharge, approximately 50%. [24] Conversely, LEO satellite batteries experience approximately 5,000 charge/discharge cycles per year with an average *DoD* of 15-25%. Thus, GEO applications are much more similar to HALE platform operations than those platforms designed to operate in LEO.

Figure 2.16 shows the common charge/discharge profile of secondary batteries and the affect of depth-of-discharge on battery life. Here, we will assume an operating lifetime of five years. We therefore know that the platform will experience 1,825 eclipse periods. Figure 2.16(b) then tells us that a nickel-hydrogen battery can support a depth-of-discharge of approximately 40% over the life of the batteries.

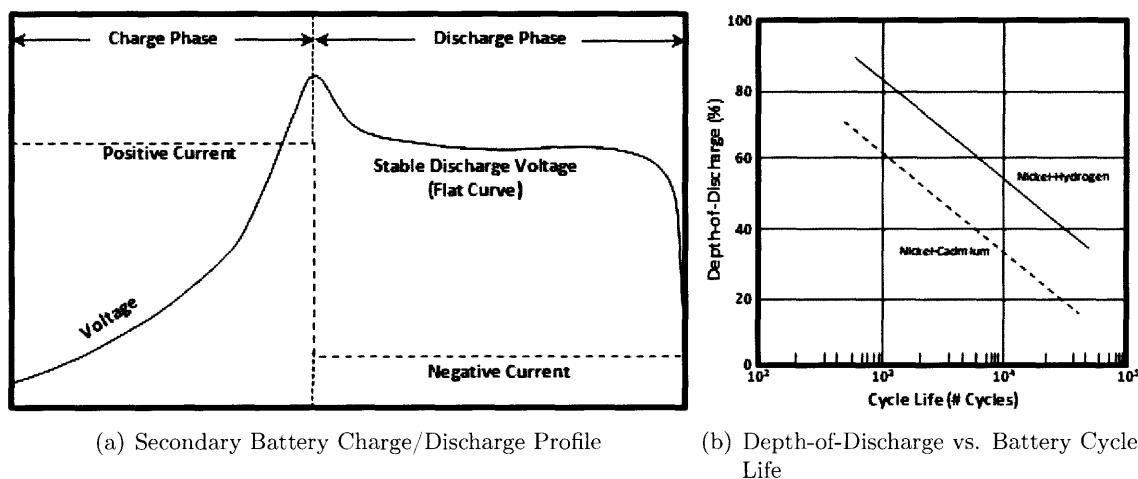


Figure 2.16: Charge/Discharge Profile and Battery Life Characteristics for Secondary Batteries; Source: SMAD Chapter 11.4.2, Figures 11-10 and 11-11

In order to determine the required battery capacity,  $C_r$ , we use equation (2.17) and initially set  $N_b$  equal to 1. In this equation,  $N_b$  is the number of batteries in the system,  $\eta_b$  is the transmission efficiency between the battery and the load, *DoD* is the depth of discharge,  $C_r$  is measured in Watt-hours,  $P_e$  is the average eclipse load and  $T_e$  is the duration of the eclipse in minutes. In this case, we will assume a battery to load efficiency,  $\eta_b$ , of 90%.

$$C_r = \frac{P_e T_e}{(DoD) N_b \eta_b} = \frac{125 * 720}{0.4 * 1 * 0.9} = 2.3 \times 10^5 \text{ W-hr} \quad (2.17)$$

According to McDermott, "two to five batteries are typical. We must have at least two (unless the battery uses redundant cells) because the [platform] needs redundant operation with one unit failed. But more than five batteries requires complex components for recharging." [24] In this case, we will conservatively assume the maximum of five batteries. Then the new battery

capacity is shown in equation (2.18)

$$C_r = \frac{P_e T_e}{(DoD)N_b \eta_b} = \frac{125 * 720}{0.4 * 5 * 0.9} = 4.5 \times 10^4 \text{ W-hr} \quad (2.18)$$

From table 2.5, we will take the average specific energy density for a nickel-hydrogen, common pressure vessel design which is 48 W-hr/kg, then equation (2.19) gives us the expected mass,  $M_b$ , of the batteries.

$$M_b = \frac{C_r}{\text{Specific Energy Density}} = \frac{5.0 \times 10^4}{48} = 942 \text{ kg} = 2,076 \text{ pounds} \quad (2.19)$$

Battery specific energy densities have improved since SMAD version 3 was published in 1999. For example, a lithium iron phosphate  $LiFePO_4$  battery is capable of specific energy densities between 80 and 120 W-hr/kg can are capable of handling more than 2,000 cycles.[26] Using the average specific energy density of 100 W-hr/kg, the new battery mass requirement is shown in equation (2.20).

$$M_b = \frac{C_r}{\text{Specific Energy Density}} = \frac{5.0 \times 10^4}{100} = 452 \text{ kg} = 997 \text{ pounds} \quad (2.20)$$

While this new battery mass is an improvement, it still requires a significant portion of the platform weight budget. Therefore, we will look at possible alternatives to conventional batteries. Section 2.1.2 discusses some of the ongoing research in regenerative fuel cell technology and table 2.6[27] summarizes the parameters of some current RFC designs.

Stack Type	System Weight (kg)	Specific Energy (W-hr/kg)	Comments
1 URFC	130	431	Not redundant, Lightweight
2 URFCs	135	415	Redundant, Favored
3 URFCs	151	370	Redundant, Heavy
1 FC/1 EC	190	295	Not redundant, Heavy
2 FCs/1 EC	221	253	Partly redundant, Heavy
3 FCs/3 ECs	258	217	Redundant, Heavy

Table 2.6: Specific Energy of RFC Designs; "Regenerative Fuel Cell Systems," Mitlitsky et al, Table 2 (excerpt)

Here, we will assume the optimum 2 URFC stack favored in the analysis conducted by Mitlitsky et al. Additionally, we will assume the average power requirement of 113 watts per hour for a twelve-hour eclipse period giving a total power requirement of 1,356 watt-hours. Then from table 2.6, we find that we need four stacks to provide the required average power for a total mass of 540 kg (1,190 pounds). Clearly, the required RFC mass is no improvement over the mass of secondary batteries alone. Note that if we are willing to accept the risk of

a non-redundant power supply and assume the 1 URFC stack, we would still need four stacks and a mass of 520 kg (1,146 lbs) to achieve the required power.

Based on the assumptions used above, table 2.7 summarizes the sizing requirements for the power subsystem.

Parameter	Requirement
Solar Array Power	330 watts
Solar Array Area	2.92 m <sup>2</sup> (31.43 ft <sup>2</sup> )
Solar Array Mass	13.2 kg (29 lbs)
Battery Capacity	4.5 × 10 <sup>4</sup> W-hr
Battery Mass	452 kg (997 lbs)
URFC Specific Energy	1,660 W-hr/kg
URFC Mass	540 kg (1,190 lbs)
Total Subsystem Mass w/ Batteries	465 kg (1,025 lbs)
Total Subsystem Mass w/ URFCs	553 kg (1,219 lbs)

Table 2.7: Summary of Power Subsystem Sizing Requirements

Clearly, the solar array requirements are supportable by our estimated HALE platform capabilities. The requirements for either secondary batteries or RFCs are also feasible but require a significant portion of our available payload weight in order to provide sufficient power. Both secondary batteries and RFCs require significant technological development before they can be used effectively on proposed HALE platforms. While subsequent chapters will show that HALE platforms have the potential to offer significant performance improvements over satellite capabilities, designers must first develop technologies to allow these designs to be realized. Ongoing research in available power sources, including more efficient solar cells, batteries with higher specific energy densities and regenerative fuel cell technology is an important step toward making HALE platforms viable.

## 2.4 General CONOPS

General (non-mission specific) CONOPS considerations for HALE applications include deployment times, operational altitudes, control system considerations, the number of platforms per theater, repair/maintenance schedules and route planning considerations.

According to the Rand Study by Jamison et al, "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." [4] See figure 2.3 for an illustration of the flight routes described. The limitation of the 45° north latitude is imposed by the angle of incidence

of solar radiation. This limitation could be avoided through the use of alternate power sources discussed in section 2.1.2. Deployment times aside, once the asset was in place, it could loiter almost indefinitely providing support as needed to the combatant commander.

Section 2.1.5 outlines survivability concerns against dynamic and electronic attacks; specifically table 2.2 highlights the five conventional weapon systems that can threaten HALE platforms. Setting a nominal operational altitude of 80,000 feet places the platform out of range for all but two of the long-range SAMs listed in table 2.2 and an operational altitude of 85,000 feet would place the platform out of range of all but the SA-5 SAM.

Another general CONOPS consideration is the platform control system. The main decision is whether the platform should be fully autonomous or human-in-the-loop controlled via a ground station. Fully autonomous flight control allows the platform to operate indefinitely while significantly reducing the operational costs associated with platform performance. Two key drawbacks to a fully autonomous system are the difficulty of responding to dynamic or electronic attacks as detailed in section 2.1.5 and reduced operational flexibility to meet the changing requirements of the combatant commander. It is likely that successful designs will incorporate some measure of both autonomous and human-in-the-loop control, allowing the platform to deploy itself to the required theater and monitor general flight control operations while maintaining the flexibility to rapidly respond to changing ground conditions and contingency operations.

Platform cost will likely have the most direct impact on the number of platforms operating per theater. Subsequent chapters will demonstrate that HALE platforms can provide equivalent performance as current satellite payloads but at a fraction of the cost. In order to take advantage of the projected HALE capabilities outlined in section 2.2, it is expected that at least one platform will operate in each of the Army's major theaters of operation. Ideally, funding will be available to provide dedicated HALE platforms to each of the brigade-level commanders in theater. In the case of Iraq and Afghanistan, this means approximately twenty platforms operating over Southwest Asia alone.

This thesis assumes that HALE platforms will operate as pseudo-satellite platforms for operational lifetimes of up to five years. This being the case, HALE platforms should be designed to be maintained as if they were satellites, relying on platform telemetry to diagnose and repair all malfunctions. One significant advantage of HALE platforms over satellites is that they can be recovered in the event of a catastrophic failure that cannot be repaired by any other means. It is expected, however, that recovering the platform for repair will be the last resort and will only occur to avoid total platform loss.

Route planning considerations are critical to the success of any HALE platform. Two areas for consideration are flight plan deconfliction with other HALE platforms operating in theater and overflight of sovereign airspace. As mentioned above, if each brigade-level commander in

Southwest Asia received a dedicated platform, there would be twenty platforms operating in close proximity and careful flight planning would be required to avoid collisions. Figure 2.3 outlines two possible deployment flight routes to forward destinations. Observe that the route from Las Vegas to Baku requires the platform to fly almost directly over Moscow. The key consideration in this case is international law which currently recognizes sovereign airspace up to an altitude of 65,000 feet and then is not regulated again until 330,000 feet which is the legal definition of space.[28] The area between 65,000 feet and 330,000 feet is currently in a legal "gray area." Until this legal issue is resolved, deployment route planning will continue to require the avoidance of hostile airspace.

## 2.5 Chapter Summary

At this point it is appropriate to revisit the question posed by the Army Space Master Plan, "Where should the Army invest in near-space and high-altitude, long-endurance platforms as a lower cost, more responsive alternative to space platforms if they prove technically feasible?"[1] This chapter has demonstrated, in very general terms, the technical feasibility of designing and operating a HALE platform in the "near space" regime between 65,000-100,000 feet in altitude. It remains to be determined whether or not HALE payloads can provide the necessary performance requirements when compared to currently existing satellite payloads.

In a conversation with personnel at the U.S. Army Space and Missile Defense Command (SMDC), Mr. William Coffey and MAJ Timothy Tubergen identified some key user needs that could potentially be filled by HALE platforms. These capability gaps include persistent BLOS communications in all terrain and command and control on-the-move, the need for increased bandwidth (network expansion) in operational theaters, persistent ISR capability and the need to reduce the latency associated with Blue Force Tracking (BFT) and Force XXI Battle Command, Brigade and Below (FBCB2) transmissions. According to MAJ Tubergen, SMDC, there are no current capability gaps in GPS navigation service, however, the U.S. Army is not currently engaged in a navigation war. MAJ Tubergen agreed that stronger GPS signals to allow increased functionality in complex (i.e., urban and mountainous) terrain would be valuable under any circumstances.

With respect to persistent BLOS communications, U.S. Army forces in Iraq are currently using the RIPR network which is essentially communications over telephone lines. Additionally the U.S. Air Force E-8 Joint Surveillance Target Attack Radar System (JSTARS) is capable of providing short duration radio retransmission capability but it does not provide a very large footprint, communications relay is not the platform's primary mission and use of the system is prohibitively expensive for routine communications. The Army is also looking to improve BLOS communications to small mobile antennas. Currently, the only spacecraft capable of providing this service are communications satellites in geosynchronous orbit (GEO). In order

for a small antenna to receive transmissions from a GEO orbiting satellite at an altitude of 35,786 km (22,236 mi), the satellite must be equipped with a powerful transmitter and a very large transmitting antenna. A large antenna focuses the beamwidth into a small diameter on the Earth's surface. Thus persistent coverage of an area the size of Iraq requires many large antennas on GEO satellites - a requirement severely limited both by cost and by space availability in the GEO belt. HALE communications relay platforms could potentially provide the same service but at a fraction of the power and antenna size requirements imposed by the extreme GEO altitude. Additionally, the U.S. Army is continually fielding new technologies in Iraq (on the order of thirty to forty new systems per week)[28] each of which requires bandwidth to operate. HALE platforms equipped with communications relay payloads may be capable of providing both large-footprint BLOS communications and network expansion for new technologies. HALE communication payload capabilities will be outlined and analyzed in chapter 3.

Current ISR satellites must operate in low earth orbit (LEO) in order to achieve a useful target resolution. The physics governing LEO orbits limit the coverage capability to approximately six minutes every nine hours, an insufficient amount of time in a rapidly evolving battlefield like Iraq. A constellation of LEO ISR satellites improves the percent coverage of the Earth's surface but, by definition, increases the number of satellites and thus the cost of the mission. A HALE platform, being nearly stationary with respect to the area of interest on the ground, is capable of providing continuous coverage from a much lower altitude. The lower altitude also has the advantage of providing better resolution as will be demonstrated in chapter 4.

Finally, while GPS navigation coverage is admittedly not a key capability gap for current operations, experts do not question the advantages of stronger, more reliable GPS signals. The Army relies on GPS dependent automation for more than simple navigation. BFT and FBCB2 both combine location (derived from GPS signals) and unit status (input by the user) information into a consolidated report for units to send to their higher headquarters. FBCB2 uses transponder frequencies in the L-band and transmits via the non-satellite based Enhanced Position Location Reporting System (EPLRS), a line-of-sight secure radio system. BFT transponders transmit information via a satellite network and frequently experience latency ranging from eight minutes to eight hours. Even for routine operations in a combat zone, an eight minute latency is too long and emergency situations require an immediate response. Potential improvements to both line-of-sight EPLRS communications and BFT latency through the use of HALE platforms are discussed in chapter 5.

Having identified several key user needs not satisfied by current satellite service to the military, we return our attention to the ven diagram introduced in figure 1.3 and fill in some areas for further development. Figure 2.17 summarizes the focus of the rest of this thesis with the goal of evaluating HALE payloads against current satellite capabilities for communications relay, ISR and GPS to determine where and how HALE platforms can contribute to successful

military operations.

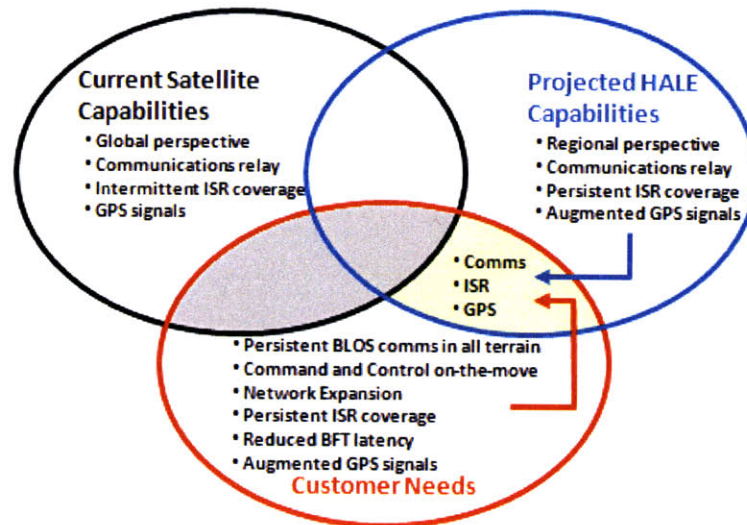


Figure 2.17: Expanded Ven Diagram of Current Capability Gaps between Satellites and Military User Requirements

By demonstrating how the Army can use HALE platforms to reduce the capability gap and fulfill more of the users' requirements, this research will answer the question posed by the Army Space Master Plan.

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## Chapter 3

# Military Applications — Communications Payload

There are two types of communications to consider in the treatment of the general subject of communications: broadcast and relay. Communications broadcasting refers to the distribution of communications signals over a wide area or to a large number of customers and communications relay sends signals on a point-to-point basis. Broadcast signals are typically transmitted from a fixed location to either fixed or mobile receivers while relayed signals are capable of transmitting and receiving from either fixed or mobile antennas. The vast majority of military communications involve relaying signals to and from a unit headquarters to units in the field; thus this chapter will focus on communications relay systems in the following analysis.

This chapter begins with a discussion of the link margin governing equations followed by an analysis of the performance of communications payloads with respect to both satellites and HALE platforms and will conclude with a discussion of some of the communications mission-specific CONOPS considerations. The baseline satellite communications (SATCOM) payload used in the analysis is the Wide-band Global SATCOM System (WGS).

For reference, table 3.1, taken from SMAD, outlines the various frequency band ranges and uses as established by the International Telecommunications Union (ITU). The calculations and comparisons in this chapter will be based on the center frequencies of the bands listed below.

WGS, which was designed and built by Boeing Satellite Systems and launched in 2007, is specifically for DOD use which makes it an ideal candidate for this analysis. WGS operates in the X- and Ka-band frequency ranges from a geosynchronous orbit and is intended to replace DOD wideband satellite communication services formerly provided by the Defense Satellite Communications System (DSCS) (X-band) and Global Broadcast System (GBS) (Ka-band) satellites. Figure 3.1 shows a diagram of the WGS satellite transmit and receive antennas[29] and table 3.2 provides additional WGS technical specifications from the Air Force Space Command website.[30]

Frequency Band	Frequency Range (GHz)		Service
	Uplink	Downlink	
UHF	0.2 - 0.45	0.2 - 0.45	Military
L	1.635 - 1.66	1.535 - 1.56	Maritime/Nav, Telephone
S	2.65 - 2.69	2.5 - 2.54	Broadcast, Telephone
C	5.9 - 6.4	3.7 - 4.2	Domestic, Comsat
X	7.9 - 8.4	7.25 - 7.75	Military, Comsat
Ku	14.0 - 14.5	12.5 - 12.75	Domestic, Comsat
Ka	27.5 - 31.0	17.7 - 19.7	Domestic, Comsat
SHF/EHF	43.5 - 45.5	19.7 - 20.7	Military, Comsat
SHF/EHF	49	38	Internet Data, Telephone, Trunking
V		~60	Satellite Crosslinks

Table 3.1: Limitations on Frequency Band Ranges & Uses as Established by the ITU; Source: SMAD Chapter 13.3, Table 13-12

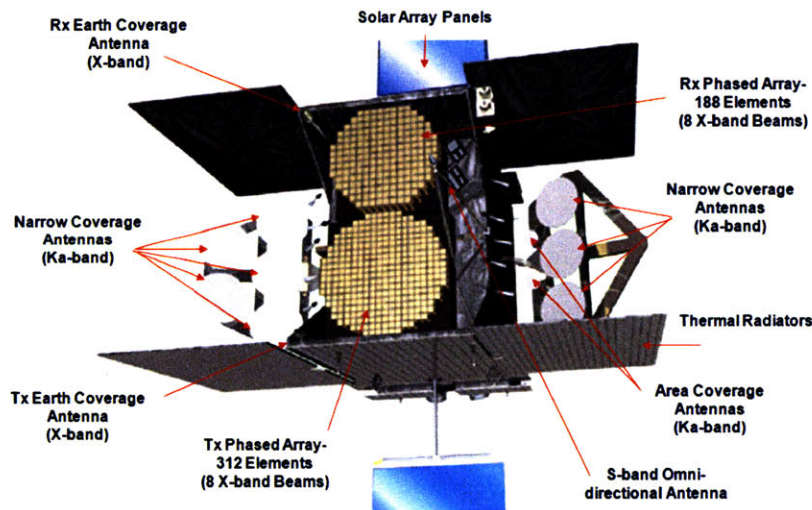


Figure 3.1: Wideband Global SATCOM Diagram; Source: SMDC/ARSTRAT, Wideband Global SATCOM (WGS) System Utilization Plan & Integrated Operations; WGS Block II SDRU, Daniel Hannan

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<b>Component</b>	<b>Characteristic</b>
Primary Function	High-capacity military communications satellite
Satellite Bus	Boeing 702
Weight	~13,000 lbs (at launch), 7,600 lbs (on orbit)
Orbit Altitude	22,300 mi (GEO)
Payload	Transponded, cross-banded X- and Ka-band communications suite
Antennas	8 X-band Phased Arrays, 10 Ka-band gimbaled dishes, 1 X-band Earth coverage
Capability	39 125-MHz Channels
Unit Cost	~\$300 million

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Table 3.2: WGS Technical Specifications; Source: Air Force Space Command, <http://www.afspc.af.mil/library/factsheets/factsheet.asp?id=5582>

WGS offers several advantages over previously used SATCOM systems not least of which is the fact that, "each WGS can supply more than 10 times the capacity of a DSCS III Service Life Enhancement Program (SLEP) satellite." [31] Additionally, WGS is fully compatible with currently used ground station terminals [29] thus eliminating the need for additional ground infrastructure costs.

Bandwidth is the key limiting factor in almost any satellite-based communication system. As noted by Military Information Technology Online, "Current military satellite capacity is expected to grow to four gigabits per second (Gbps) when the Wideband Gapfiller satellite system becomes operational [in 2005] . . . a Joint Chiefs of Staff document that estimates that satcom bandwidth requirements for theater-of-war capability will be 14 Gbps by 2010." [32] Thus it is critical to continue exploring methods of increasing bandwidth for military applications.

Military Information Technology Online further states that, even with the addition of WGS capability, "military-owned satellite capacity will still fall substantially short of projected demand. The solution is commercial satcom services. . . Commercial systems provided approximately 60 percent of satellite communications (satcom) capability in Operation Enduring Freedom, and the percentage rose to 80 percent during Operation Iraqi Freedom." [32] While purchasing commercial satellite bandwidth is the currently accepted solution to increasing DOD demand, it is not a cost-effective method especially since procurement regulations and mission uncertainty prevent the DOD from leasing these capabilities on long-term (more than twelve month) contracts. [32] HALE platforms potentially provide a cost-effective means of increasing bandwidth while eliminating the need to lease expensive commercial satellite time.

This research will show that the lower operating altitude afforded by HALE platforms will allow for smaller, lighter, cheaper communications payloads while still affording BLOS communications capability.

### 3.1 Link Margin Governing Equations

In beginning the analysis of the communications link equation, the primary sizing equation used relates all of the link parameters to the signal-to-noise ratio and is given in equation (3.1) below:[33]

$$\frac{E_b}{N_o} = \frac{P_t L_l G_t L_s L_a G_r}{k T_s R} \quad (3.1)$$

Where  $E_b/N_o$  is the ratio of received energy-per-bit to noise density,  $P_t$  is the transmitter power,  $L_l$  is the transmitter to antenna line loss,  $G_t$  is the transmit (Tx) antenna gain,  $L_s$  is the free space loss,  $L_a$  is the atmospheric transmission path loss,  $G_r$  is the receive (Rx) antenna gain,  $k$  is Boltzmann's constant ( $1.380658 \times 10^{-23}$  J/K),  $T_s$  is the system noise temperature and  $R$  is the data rate in bps.

Equation (3.1) can be rewritten in decibel notation as follows:

$$E_b/N_o = P_t + L_l + G_t + L_{pr} + L_s + L_a + G_r + 228.6 - 10 \log T_s - 10 \log R \quad (3.2)$$

Where  $E_b/N_o$ ,  $L_l$ ,  $G_t$ ,  $L_s$ ,  $L_a$ ,  $L_{pr}$  and  $G_r$  are in dB,  $P_t$  is in dBW,  $T_s$  is in K,  $R$  is in bps and  $10 \log k = -228.60$  dBW/Hz · K. Note that equation (3.2) contains one additional term,  $L_{pr}$ , that is not included in equation (3.1). This additional term is the receive antenna pointing loss, which accounts for imperfect antenna alignment, and will be discussed later.

For the purpose of this thesis, we want to solve equation (3.1) (or equation (3.2), depending on preference) for  $P_t$  and then use parametric relations to determine payload mass and cost from the transmitter power. Thus it is necessary first to determine all the remaining parameters in the equation.

The energy-to-noise ratio,  $E_b/N_o$ , can be estimated from figure 3.2 (taken from SMAD, chapter 13) after selecting an appropriate bit error rate (BER) and modulation scheme.

A common bit error rate for communications payloads is between  $10^{-5}$  and  $10^{-6}$ ; in this case, we will use the more stringent standard of  $10^{-6}$ . Modulation is the process of varying the RF carrier wave characteristics of the input signal. Quadriphased phase shift keying (QPSK) is the modulation technique used by WGS and "takes two bits at a time to define one of four symbols. Each symbol corresponds to one of four carrier phases: 0 deg, 90 deg, 180 deg or 270 deg." [33] Thus using QPSK modulation and a BER of  $10^{-6}$ , figure 3.2 gives the required energy-to-noise ratio of:

$$\boxed{\frac{E_b}{N_o} = 10.5 \text{ dB}} \quad (3.3)$$

Note that we could improve the energy-to-noise ratio by employing coding techniques such as Viterbi or Reed-Solomon (also shown in figure 3.2) thus gaining at least a 3dB reduction in

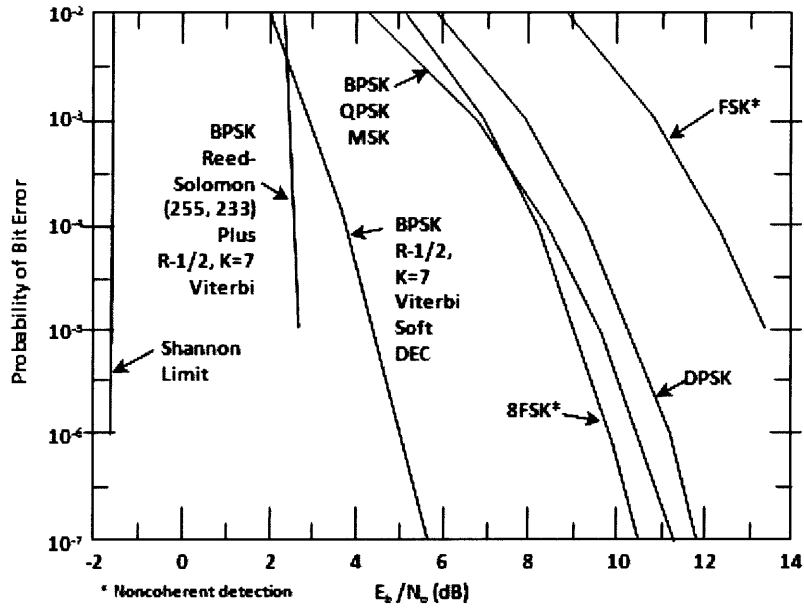


Figure 3.2: Bit Error Probability as a Function of  $E_b/N_o$ ; Source: SMAD Chapter 13.3, Figure 13-9

$E_b/N_o$ . Any reduction gained in the energy-to-noise ratio would directly correspond to an equal reduction in the required amplifier power; in the conservative estimate, 3dB or half the power. However, even assuming we employ some coding method, we will still use the estimate of 10.5 dB in order to allow design margin in the link equation.

The next parameters to define are the losses due to free space,  $L_s$ , and transmission path loss attenuation by the Earth's atmosphere,  $L_a$ . The free space loss is a function of the carrier frequency,  $f$ , and the transmission path length,  $S$ , as shown in equations (3.4) and (3.5), and the transmission path loss is a function of frequency as shown in figure 3.3.

$$L_s = \left( \frac{\lambda}{4\pi S} \right)^2 = \left( \frac{c}{4\pi S f} \right)^2 \quad (3.4)$$

Or in decibel notation:

$$L_s = 147.55 - 20 \log S - 20 \log f \quad (3.5)$$

Where  $S$  is measured in meters,  $f$  is in Hertz,  $\lambda$  is the carrier wavelength, in meters, defined by the relationship  $f = c/\lambda$  and  $c$  is the velocity of light in free space  $\approx 3 \times 10^8$  m/s.

Based on the nominal operating altitude of 85,000 ft (25,908 m) determined in section 2.3 and taking the center uplink frequencies of the X- and Ka-bands used by the WGS system (from table 3.1), the space loss parameters of the link equation are given in equations (3.6) and (3.7).

For the X-band:

$$L_s (\text{X-band}) = 147.55 - 20 \log 25,908 - 20 \log (8.15 \times 10^9) \quad (3.6)$$

$$L_s (\text{X-band}) = -138.94 \text{ dB}$$

For the Ka-band:

$$L_s (\text{Ka-band}) = 147.55 - 20 \log 25,908 - 20 \log (29.25 \times 10^9) \quad (3.7)$$

$$L_s (\text{Ka-band}) = -150.04 \text{ dB}$$

It is important to note that the space loss calculations above use the platform altitude as the transmission path length. This assumption is valid for communications with ground stations directly below the platform (nadir), however, communicating with ground stations operating at the edge of the coverage area will require a longer transmission path. For the purposes of this analysis, we will use the edge of the coverage area as the worst-case scenario. Again referring to the angular relationships shown in figure 2.9, where  $D$  is the distance from the platform to the target and is the same as the transmission path length, equation (3.8) shows the calculation of the worst-case transmission path length.

$$D = S = R_E \left( \frac{\sin \lambda_E}{\sin \eta_{\text{nadir}}} \right) \quad (3.8)$$

For a nominal altitude of 85,000 feet, the transmission path length to the edge of the coverage area (assuming a 15 degree elevation angle) is 319,649 feet (97,429 m). Applying equations (2.10) through (2.13) to find the associated angular relationships and equation (3.5) for the new transmission path length, we get the following results for the space loss.

For the X-band:

$$L_s (\text{X-band}) = 147.55 - 20 \log 97,429 - 20 \log (8.15 \times 10^9) \quad (3.9)$$

$$L_s (\text{X-band}) = -150.45 \text{ dB}$$

For the Ka-band:

$$L_s (\text{Ka-band}) = 147.55 - 20 \log 97,429 - 20 \log (29.25 \times 10^9) \quad (3.10)$$

$$L_s (\text{Ka-band}) = -161.55 \text{ dB}$$

The primary source of signal attenuation within the Earth's atmosphere is rainfall due to the absorption and scattering effects on the signal beam.[34] According to Gagliardi, "rain effects become most severe at wavelengths approaching the water drop size . . . thus rainfall effects can become extremely severe at frequencies at X-band and above." [35] The path loss,  $L_a$ , due to

rain attenuation is a difficult parameter to quantify as one must account for the size and rate of the rain drops as well as the frequency of storms and all of these factors vary according to the climate of a given operational area. Due to the uncertainty associated with predicting rain attenuation, it is common to consider the percentage of time a certain attenuation level will be exceeded. If  $P(\alpha)$  is the probability that an attenuation,  $\alpha$ , is exceeded, then  $1 - P(\alpha)$  is the percent availability of the link. Probability curves are much more useful in allowing for sufficient design margin while preventing link overdesign.[35] According to the WGS System Utilization Plan developed by the U.S. Army Space and Missile Defense command, "the X-band is comparatively robust in the presence of weather [whereas] the Ka-band is less robust and will result in outages  $\sim 3\%$  of the time, depending on rain region." [29] Figure 3.3 shows predicted rain attenuation for a climate typical of the northern United States.

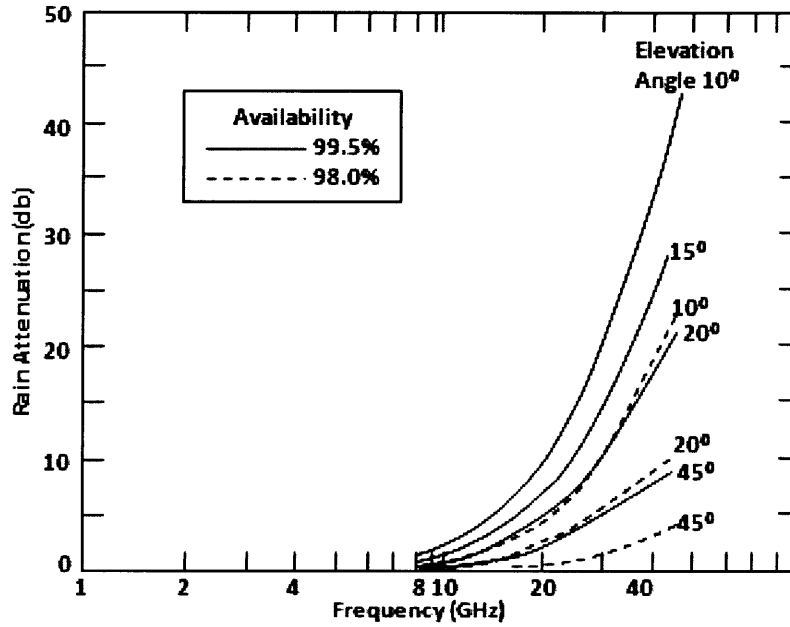


Figure 3.3: Rain Attenuation as a Function of Frequency for Rain Climate Typical of the Northern United States; Source: SMAD Chapter 13.3, Figure 13-11

Assuming that the rain climate of the northern United States is representative of the typical climates of current operational areas, a conservative estimate for countries such as Iraq and Afghanistan, figure 3.3 provides an estimate of the path loss. Assuming 99.5% link availability, a 15 degree elevation angle and the mean uplink frequencies of the X and Ka-bands used above then the atmospheric path losses,  $L_a$ , are shown below.

For the X-band:

$$\boxed{L_a \text{ (X-band)} = 2 \text{ dB}} \quad (3.11)$$

For the Ka-band:

$$\boxed{L_a \text{ (Ka-band)} = 7 \text{ dB}} \quad (3.12)$$

The next parameters to define are the transmitter to antenna line loss,  $L_l$ , and the system noise temperature,  $T_s$ . The line loss is a function of the efficiencies of the connections and wires and is determined from the time the payload is built. The system noise temperature is the sum of several contributing sources both in the antenna aperture and in the space between the transmitter and the receiver. Sources of system noise include *a*) galactic noise; *b*) noise radiated by clouds and rain in the propagation path; *c*) solar noise; *d*) noise radiated by the Earth; *e*) man-made noise; *f*) contribution of nearby objects, buildings, etc and *g*) temperature of blockage items in the subsystem such as booms and feeds.[33] Typical system noise temperatures for communications systems using uncooled receivers are shown in table 3.3; we will use the line loss (dB) and system noise (K) values in subsequent calculations.

Noise Temperature	Frequency (GHz)					
	Downlink		Crosslink		Uplink	
	0.2	2-12	20	60	0.2-20	40
Antenna Noise (K)	150	25	100	20	290	290
Line Loss (dB)	0.5	0.5	0.5	0.5	0.5	0.5
Line Loss Noise (K)	35	35	35	35	35	35
Receiver Noise Figure (dB)	0.5	1.0	3.0	5.0	3.0	4.0
Receiver Noise (K)	36	75	289	627	289	438
System Noise (K)	221	135	424	682	614	763
System Noise (dB-K)	23.4	21.3	26.3	28.3	27.9	28.8

Table 3.3: Typical System Noise Temperatures in Satellite Communications Links in Clear Weather; Source: SMAD Chapter 13.3, Table 13-10

The gains of the transmit,  $G_t$ , and receive,  $G_r$ , antennas are a function of the diameter,  $D_{ant}$ , of the parabolic antenna, the carrier frequency,  $f$ , and the antenna efficiency,  $\eta_{ant}$ , as shown in equations (3.13) and (3.14). The antenna efficiency is a figure of merit between 0 and 1 and is a function of various antenna imperfections. A typical efficiency value for parabolic antennas is 0.55[33] and we will use this value as a conservative estimate in future calculations. For an omni-directional antenna, the gain is assumed to be 1 (0 dB) and is the worse-case scenario for antenna gain; any other directional antenna will have improved gain.

$$G = \frac{\pi^2 D_{ant}^2 \eta_{ant}}{\lambda^2} \quad (3.13)$$

Or in decibel notation:

$$G = -159.59 + 20 \log D_{ant} + 20 \log f + 10 \log \eta_{ant} \quad (3.14)$$



Where  $D_{ant}$  is measured in meters and  $f$  is in Hertz.

Finally, we return to the antenna pointing loss which is a result of the receive antenna not pointing at the center of the transmitted beam and manifests as a loss in gain of the receive antenna (subtracted from  $G_r$  prior to the calculation of equation (3.1)). Small antenna pointing errors, introduced by wind gusts on the ground or platform stabilization errors, become more significant contributors as the beamwidth becomes more narrow.[33] The antenna pointing loss is calculated through equation (3.15).

$$L_{pr} = -12 \left( \frac{e}{\theta} \right)^2 \quad (3.15)$$

Where  $e$  is the pointing error and  $\theta$  is the antenna half-power beamwidth (calculated below in equation (3.17)).

For the purposes of this thesis, we will assume that the HALE platform is operating directly overhead and the beamwidth covers the ground area of operations; thus there is no need to point the platform antenna. Rather, all users within the coverage area will be able transmit to and receive from the platform. In order to accomplish this coverage, we will assume that the pointing error,  $e$ , is equal to half of  $\theta$ . Substituting this pointing error into equation (3.15), we get the following relationship for the antenna pointing loss:

$$L_{pr} = -12 \left( \frac{\frac{\theta}{2}}{\theta} \right)^2 = -12 \left( \frac{1}{2} \right)^2 = -3 \text{ dB} \quad (3.16)$$

The typical methodology for determining the link budget requirements is first to determine the required footprint size or beamwidth necessary to cover the area of operations. Once the footprint radius is known, use the angular relationships shown in figure 2.9 and discussed in equations (2.10) and (2.11) to determine the required nadir angle,  $\eta_{nadir}$ . The nadir angle is the same as the half-power beamwidth,  $\theta$ , or the angle at which the signal strength is half (3 dB) of the transmitted signal strength. The beamwidth can then be used to find the required transmit antenna diameter (through the relationship shown in equation (3.17)) and the transmit antenna gain (equations (3.13) and (3.14)).

$$\theta = \frac{21}{f D_{ant}} \quad (3.17)$$

Where  $f$  is the carrier frequency in GHz and  $D_{ant}$  is the antenna diameter in meters.

The next step is to determine the ground receive antenna diameter,  $D_r$ , and efficiency,  $\eta_{ant}$ , which then yield the receive antenna gain,  $G_r$ , through the relationships shown in equations (3.13) and (3.14). Then substitute these factors into the link equation, (3.1) or (3.2), along with the previously defined losses to determine the required transmitter power.

In defining the relationship between data rate and bandwidth, we refer to C.E. Shannon's

paper, A Mathematical Theory of Communication, published in 1948 in which he stated "Theorem 22: The rate for a white noise source of power,  $Q$ , and band  $W$  relative to [a root mean square] measure of fidelity is:  $R = W \log_2 (Q/N)$ ." [36] Where  $N$  is the allowed mean square error between original and recovered messages and the log is base 2. Rewriting Shannon's equation in terms of the variables used in this section, we get equation (3.18).

$$R = BW * \log_2 \left( \frac{P_t}{BER} \right) \quad (3.18)$$

Where  $R$  is the data rate in bps,  $BW$  is the bandwidth in hertz,  $P_t$  is the transmit power in watts and BER is the bit error rate all as previously defined. Then solving for  $BW$  we find:

$$BW = \frac{R}{\log_2 \left( \frac{P_t}{BER} \right)} \quad (3.19)$$

Section 3.4 will recommend frequency division multiple access as an appropriate interference mitigation technique. In order to determine the number of independent channels the link is able to support, we will use the bandwidth determined above and the operating ranges of the frequencies. Therefore, the required transmitter power and the number of channels will be the two primary metrics with which we evaluate performance.

Subsequent sections of this chapter will analyze the performance delta between a WGS payload at GEO altitude and a WGS payload at the nominal HALE altitude of 85,000 feet. Following that, we will size a communications payload, with equivalent WGS performance, for a HALE platform and compare the resultant mass and cost.

## 3.2 Communications Satellite Performance Analysis

This section will use the analysis conducted in section 3.1 to develop the performance analysis of a WGS satellite for communications relay. For reference, figure 3.4 shows a simple block diagram of the WGS payload. [37]

Since we are primarily concerned with the power requirements onboard the WGS platform, we will restrict our analysis to the downlink (satellite to ground) portion of the link equation. According to the WGS System Utilization Plan, the WGS downlink frequency ranges are "X-band: 7250.135 to 7750.135 MHz [500 MHz range] and Ka-band: 20199.865 to 21199.865 MHz [1 GHz range]." [29] We will use the center frequencies of these X-band and Ka-band ranges in subsequent calculations.

Based on the WGS System Utilization Plan developed by the U.S. Army Space and Missile Defense command, "the best-fit [ground] terminal antenna diameter is 2.4 meters and above at X-band and 1 meter at Ka-band. WGS supports smaller terminal antennas by using a disproportionate amount of power to "close" [the link]." [29] For the purposes of this analysis,

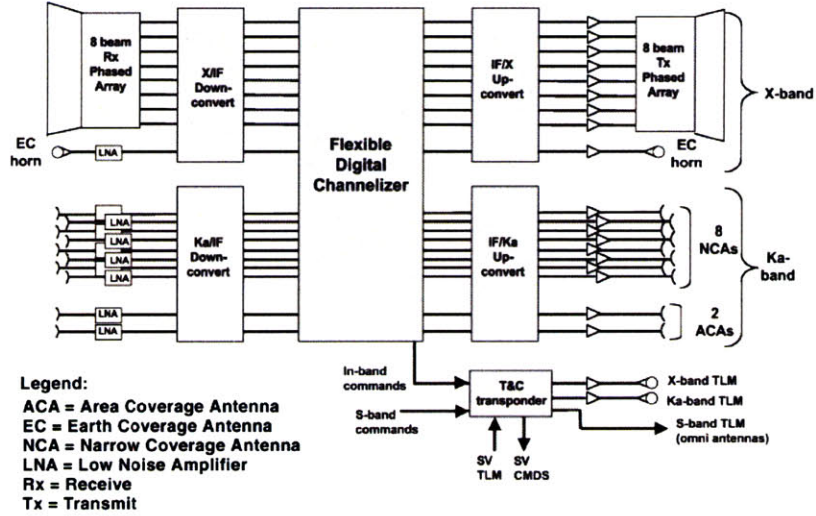


Figure 3.4: Simplified WGS Payload Block Diagram; Source: Boeing Satellites, Transformational Wideband Communication Capabilities for the Warfighter, [http://www.boeing.com/defense-space/space/bss/factsheets/702/wgs/wgs\\_factsheet.html](http://www.boeing.com/defense-space/space/bss/factsheets/702/wgs/wgs_factsheet.html)

we will assume ground transmit and receive antenna diameters with the above specifications and assume an antenna efficiency of 0.55 as discussed in the link equation analysis of section 3.1.

In determining the transmit antenna diameter of the WGS X- and Ka-band antennas, we use the methodology introduced at the end of section 3.1. From the WGS System utilization plan, we know that five WGS satellites can provide world wide coverage (excluding the polar regions).[29] From the table of Earth Satellite Parameters on the inside back cover of SMAD, we know that a single satellite in GEO orbit, using an earth coverage antenna, has an instantaneous access area of  $134.93 \times 10^6$  square kilometers ( $1.35 \times 10^{14}$  square meters), assuming a twenty degree elevation angle.[38] From table 3.2, each satellite has nine X-band antennas and ten Ka-band antennas; therefore each X-band antenna covers  $1.5 \times 10^{13}$  square meters and each Ka-band antenna covers  $1.35 \times 10^{13}$  square meters. Then, using the angular relationships shown in figure 2.9, and standard geometric relationships for the area of a circle and the tangent of an angle, we can determine the nadir angle,  $\eta_{nadir}$ , and thus the beamwidth,  $\theta$ , from equation (3.20).

$$\eta_{nadir} = \theta = \tan^{-1} \left( \frac{F_r}{H_p} \right) \quad (3.20)$$

Since the nadir angle is the same as the beamwidth, we have calculated the beamwidth for each X- and Ka-band antenna which are shown below:

Beamwidth for one X-band antenna:

$$\theta_{\text{X-band}} = 3.49^\circ \quad (3.21)$$

Beamwidth for one Ka-band antenna:

$$\theta_{\text{Ka-band}} = 3.32^\circ \quad (3.22)$$

Then using the center frequencies for the X- and Ka- band ranges and the relationship shown in equation (3.17), we can determine the WGS transmit antenna diameters shown below:

X-band antenna diameter:

$$D_t (\text{X-band}) = 0.8 \text{ meter} \quad (3.23)$$

Ka-band antenna diameter:

$$D_t (\text{Ka-band}) = 0.3 \text{ meter} \quad (3.24)$$

Taking the center frequencies of the X-band and Ka-band ranges, the baseline ground receive antenna diameters and satellite transmit antenna diameters just calculated, we can determine the gain of each antenna based on the parameters in equation (3.14), shown below. In all cases, the antenna efficiency is assumed to be 0.55.

Receiver gain for the X-band:

$$G_r (\text{X-band}) = 39.1 \text{ dBi} \quad (3.25)$$

Transmitter gain for the X-band:

$$G_t (\text{X-band}) = 34.4 \text{ dBi} \quad (3.26)$$

Receiver gain for the Ka-band:

$$G_r (\text{Ka-band}) = 44.1 \text{ dBi} \quad (3.27)$$

Transmitter gain for the Ka-band:

$$G_t (\text{Ka-band}) = 39.0 \text{ dBi} \quad (3.28)$$

Applying the resulting transmit and receive antenna gains shown above to the link equation (3.2), using the losses determined in section 3.1 (WGS space loss values for the X- and Ka-band are -202.03 dBW and -210.85 dBW, respectively) and taking the WGS data rate to be 2.1 Gbps[37], we determine the required X-band and Ka-band transmitter powers as follows: 39 watts for each X-band antenna and 29 watts for each Ka band antenna. Multiplying by the number of antennas gives the total power requirements shown below.

Transmit power for the X-band:

$$\boxed{P_t (\text{X-band}) = 143.4 \text{ dBW} = 353 \text{ W}} \quad (3.29)$$

Transmit power for the Ka-band:

$$\boxed{P_t (\text{Ka-band}) = 146.1 \text{ dBW} = 289 \text{ W}} \quad (3.30)$$

One can see from equations (3.29) and (3.30) that the lower frequency X-band requires more power to close the link with the ground station. This power increase is due primarily to the decreased transmit and receive antenna gains apparent in the lower frequency antennas. This difference in gains offsets the increased free space signal scattering and signal path absorption losses which occur at higher frequencies.

Referring to equation (3.19) we can estimate the available bandwidth for each of the frequency bands as follows.

WGS X-band Bandwidth:

$$BW = \frac{R}{\log_2 \frac{P_t}{BER}} = \frac{2.1e9}{\log_2 \frac{144}{10^{-8}}} = 8.8 \times 10^7 \text{ Hz} = 88 \text{ MHz} \quad (3.31)$$

WGS Ka-band Bandwidth:

$$BW = \frac{R}{\log_2 \frac{P_t}{BER}} = \frac{2.1e9}{\log_2 \frac{89.78}{10^{-8}}} = 9.1 \times 10^7 \text{ Hz} = 91 \text{ MHz} \quad (3.32)$$

Then, dividing the frequency range of each band by the associated bandwidth, we find that the X-band is able to support five channels and the Ka-band can support eleven channels.

It is possible to parametrically estimate the cost of the communications payload from the subsystem weight and power requirement using the cost estimating relationship (CER) shown in equation (3.33) taken from the Unmanned Space Vehicle Cost Model (USCM).[39]

$$\text{Cost} = (4574.25 + (0.19 * (\text{Comm}_{\text{wt}} * P_t))) + (2798.12 + 0.066 * \text{Comm}_{\text{wt}} * P_t) \quad (3.33)$$

Where the first term is the non-recurring cost in \$K, the second term is the recurring cost in \$K,  $\text{Comm}_{\text{wt}}$  is in pounds and  $P_t$  is in watts. Both the non-recurring and recurring costs are in FY00 dollars; multiply the result by an inflation factor of 1.199 to get the cost in FY09 dollars.[38]

The weight of the subsystem can be found from the diameters of the Tx and Rx antennas using the using the curve fit shown in figure 3.5, extrapolated from SMAD chapter 13.[33]

Applying the antenna diameter to payload weight relation in figure 3.5 and the CER in equation (3.33), we get the following value for the total communications payload system cost.

$$\text{Total WGS Communications P/L Cost} = \$2.5279 \times 10^7 = \$25,279,000 \text{ (FY09)}$$

The next section will demonstrate that HALE platforms are capable of achieving comparable WGS performance at significantly lower power and cost requirements.

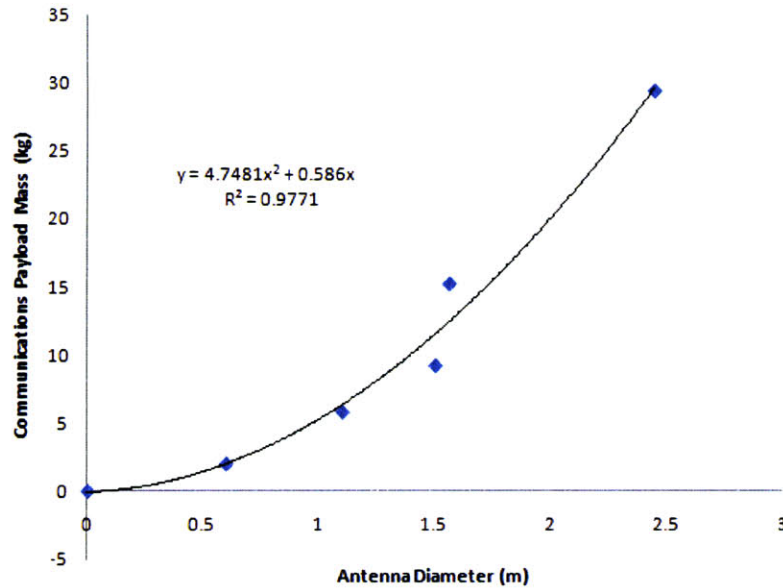


Figure 3.5: Communications Payload Antenna Diameter to Mass Relationship; Source: SMAD Chapter 13.4, Table 13-16

### 3.3 HALE Platform Performance Analysis - Communications Payload

This section will use the analysis conducted in section 3.1 to develop the performance analysis of a HALE communications payload and determine what, if any, specific advantages apply to using HALE platforms for communications relay.

It is not appropriate to place the WGS communications payload directly onto a HALE platform since the WGS antennas are sized for Earth coverage from geosynchronous altitude. The resultant beamwidths,  $3.49^\circ$  for X-band and  $3.32^\circ$  for Ka-band (equations (3.21) and (3.22)), operating from 85,000 feet (25,908 meters) would illuminate an area only  $7.84 \times 10^6$  square meters (3 square miles) for the X-band and  $7.1 \times 10^6$  square meters (2.7 square miles) for the Ka-band. Since simple, commercial hand-held radios (not to mention currently available military radios)[40] are capable of covering larger areas than the WGS payload from 85,000 feet, we will instead focus on achieving comparable WGS performance from a HALE platform and evaluate the resultant power requirements and use CERs to determine the payload cost from the power.

The first step in sizing the HALE communications payload is to determine the footprint coverage area required. In this example, we will use Iraq as the basis for sizing the design. Iraq covers an area of 168,754 square miles and is currently divided into four multi-national divisions with a total of approximately twenty brigade-level units operating at any given time. For the

### 3.3. HALE Platform Performance Analysis - Communications Payload

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purposes of this analysis, we will use the area of operations (AO) assigned to the 3d Armored Cavalry Regiment (ACR) (of which the author was a part) in Northwestern Iraq from May 2005 through February 2006. During this time, the 3d ACR's area of operations comprised an area of 3,861 square miles; assuming a circular area of operations, the diameter of the AO was seventy miles. Figure 2.10 shows that a HALE platform operating at 85,000 feet with an elevation angle of fifteen degrees is capable of achieving a footprint diameter of 116 miles. Therefore, the 3d ACR's AO was well within the established capabilities of a HALE communications payload.

Taking the footprint radius of thirty-five miles and the nominal operating altitude of 85,000 feet, then equation (3.20) yields the required communications beamwidth to be 65.4°. Next, using the center frequencies for the X- and Ka- band ranges and the relationship shown in equation (3.17), we can determine the HALE platform transmit antenna diameters as shown below.

X-band transmit antenna diameter:

Ka-band transmit antenna diameter:

$$D_t (\text{X-band}) = 0.04 \text{ meter} \quad (3.34)$$

$$D_t (\text{Ka-band}) = 0.02 \text{ meter} \quad (3.35)$$

Taking the transmitting antenna efficiencies to be 0.55 as in previous calculations, the gains of the transmitting antennas, for X- and Ka-band are 22 dBi and 27.5 dBi, respectively. Then, assuming the same ground receive antenna diameters (2.4 meters for the X-band and 1 meter for the Ka-band) and gains used in section 3.2 (and shown in equations (3.25) and (3.27)), along with the associated link losses calculated in section 3.1 and a comparable WGS data rate of 2.1 Gbps, then the required transmitter power for a HALE communications payload operating at 85,000 feet are shown below.

Platform transmit power for the X-band:

Platform transmit power for the Ka-band:

$$\boxed{P_t (\text{X-band}) = -17.02 \text{ dBW} = 0.019 \text{ W}} \quad (3.36)$$

$$\boxed{P_t (\text{Ka-band}) = -17.68 \text{ dBW} = 0.017 \text{ W}} \quad (3.37)$$

Clearly, the reduced altitude afforded by a HALE platform allows for significantly reduced transmitter power and, again, the X-band requires slightly more power than the Ka-band. This power advantage can be translated into subsystem cost, using figure 3.5 and equation (3.33), as shown below.

$$\text{Total HALE Communications P/L Cost} = \$1.7679 \times 10^7 = \$17,679,000 \text{ (FY09)}$$

Again referring to equation (3.19) we estimate the available bandwidth for each of the frequency bands as follows.

HALE X-band Bandwidth:

$$BW = \frac{R}{\log_2 \frac{P_t}{BER}} = \frac{2.1e9}{\log_2 \frac{0.019}{10^{-6}}} = 1.93 \times 10^8 \text{ Hz} = 193 \text{ MHz} \quad (3.38)$$

HALE Ka-band Bandwidth:

$$BW = \frac{R}{\log_2 \frac{P_t}{BER}} = \frac{2.1e9}{\log_2 \frac{0.017}{10^{-6}}} = 1.96 \times 10^8 \text{ Hz} = 196 \text{ MHz} \quad (3.39)$$

The above calculations show that the low operating altitude of a HALE platform allows for significantly reduced power requirements. These reduced transmit powers result in increased bandwidth and a corresponding decrease in the number of available channels (two channels for the X-band and five for the Ka-band). Subsequent analysis will show that it is possible to increase the number of channels to bring HALE platforms in-line with WGS capabilities.

While these reduced power requirements do translate to a lower system cost, the HALE cost is not as low as expected (a savings of about \$8 million). The primary reason for this discrepancy is that the HALE cost was calculated using satellite CERs obtained from the USCM rather than aircraft CERs which were not available to the author at the time of this analysis. Using the appropriate cost model will undoubtedly result in even lower system costs.

There is one further step to take in this analysis. The above calculations use the best fit ground receive antennas taken from the WGS System Utilization Plan. However, as noted in section 2.5, one of the key capability gaps is BLOS communications on-the-move which is not possible with antenna dishes of the size used above. Therefore, we must consider the use of an omnidirectional ground receive antenna and determine the required platform transmit power to enable mobile communications. Note that this next step will not change the established platform antenna diameters or gains (equations (3.34) and (3.35)). Rather, it changes the ground receive terminals from directional, parabolic antennas sized for the WGS link to an omnidirectional ground receive antenna.

It is important to note that the ideal omnidirectional antenna is an isotropic antenna which radiates equally in all directions. While an isotropic antenna is the simplest reference antenna model, it cannot be built, "as isotropic radiation is incompatible with the transverse character of electromagnetic waves." [34] Due to this limitation most omnidirectional antennas are, in reality, only capable of transmitting in two-dimensions rather than three. In spite of the directional limitations, certain antenna configurations allow for wider beamwidths than others. Figure 3.6, taken from a 2008 study conducted by Ando et al [41] shows an existence proof of one such antenna.

The figure shows a dielectric-loaded slotted-cylinder antenna (DSCA) configuration that allows wide beamwidth communications in the X-Y plane. While this antenna was mounted on a rooftop for the purposes of the study, figure 3.6(a) shows that the antenna is small enough



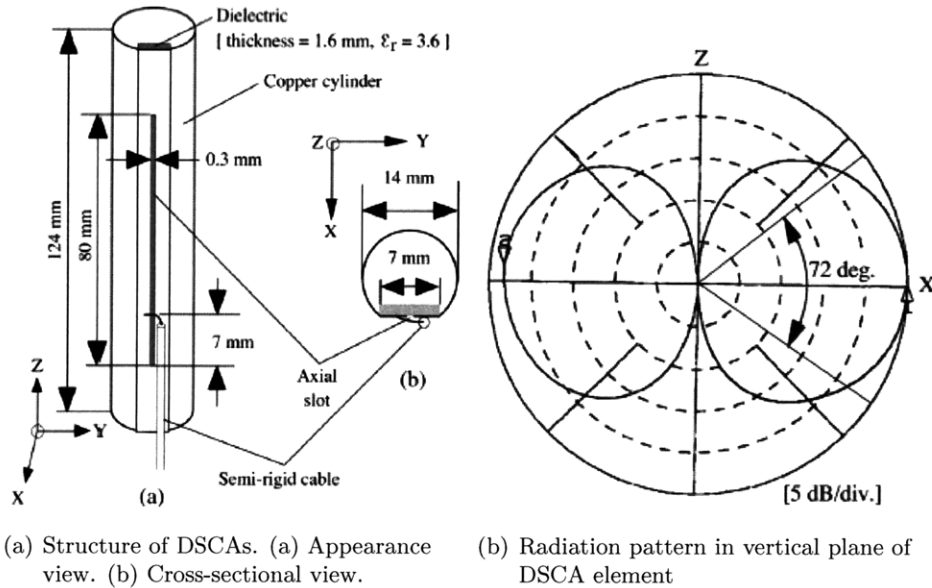


Figure 3.6: DSCA Structure and Radiation Pattern; Source: "A Study of Radio Zone Length of Dual-Polarized Omnidirectional Antennas Mounted on Rooftop for Personal Handy-Phone System," Atsuya Ando, Akira Kondo and Shuji Kubota, IEEE Transactions on Vehicular Technology

(fewer than five inches long) to be mounted on a vehicle. As shown in figure 3.6(b), this antenna, mounted horizontally, allows nearly hemispherical coverage and thus satisfies the requirement for an omnidirectional antenna.

According to the study by Ando et al, "The peak gain of the DSCA array is about 8 dBi,"[41] and we will use this gain in the following calculations. Applying the new ground receive antenna gain to equation (3.2) yields the following transmit power requirements.

Transmit power with ground omni receive antenna for the X-band:

$$P_t (X\text{-band}) = 14.02 \text{ dBW} = 18.4 \text{ W} \tag{3.40}$$

Transmit power with ground omni receive antenna for the Ka-band:

$$P_t (Ka\text{-band}) = 18.4 \text{ dBW} = 69.1 \text{ W} \tag{3.41}$$

In the case of the omnidirectional antenna, it is clear that the higher frequency Ka-band now requires more power to close the link than does the X-band. This reversal of power requirements is due to the fact that the receive antenna gain is fixed for both frequency bands which no longer offsets the increased free space signal scattering and signal path absorption losses which occur at higher frequencies.

Determining the available bandwidth for an omnidirectional receive antenna, we find that

the X-band power allows a bandwidth of 100 MHz and the Ka-band allows for 92 MHz (from equation (3.19)). These values are comparable to the WGS bandwidth capabilities (higher for the X-band and slightly higher for the Ka-band). Therefore, HALE platforms transmitting to omnidirectional ground receive antennas are capable of supporting five X-band channels and ten Ka-band channels. This channel capability proves that HALE communications capabilities are nearly as good as those of the WGS and the reduced systems cost allows for more platforms to provide service to the warfighter.

Having demonstrated comparable performance capability at significantly reduced power and cost requirements, we now turn our attention to a trade study. To determine how the transmit antenna size affects the required transmit power, we will fix the operational altitude at 85,000 feet and the elevation angle at fifteen degrees and vary the size of the coverage area. According to the Single Channel Ground and Airborne Radio System (SINCGARS) technical manual[40] the range of a vehicle mounted radio with power amplifier (PA) is 40 kilometers (24.8 miles). Therefore, the lower bound of this trade study is chosen to provide BLOS communications capability and the upper bound is based on the field of view limitations imposed by the operating altitude and the elevation angle (figure 2.10). Thus, in this study, we will assume circular coverage areas and vary the footprint radius from 25 to 115 miles, based on the upper and lower bounds just established. This trade study will vary the HALE platform antenna diameters and corresponding gains based on the varying coverage area. Figure 3.7 outlines the resulting power requirements for both X- and Ka-band center frequencies, again using the omnidirectional ground receive antenna necessary for communications on-the-move.

One can see from the figure that a larger coverage area requires a larger beam which translates into a smaller antenna size. Smaller antennas have less gain and therefore require more power to close the link. Even so, the maximum power required for the transmitter is still only 87 watts, significantly lower than the 353 watts required by the WGS payload. Additionally, the power requirements for a WGS satellite to close the link with an omnidirectional ground receive antenna are prohibitively high (228,640 watts and 594,670 watts for the X- and Ka-bands, respectively). Clearly, a HALE platform provides superior performance for BLOS communications on-the-move.

### 3.4 Communications Mission Specific CONOPS

In considering methods for the employment of communications payloads on HALE platforms, the key question is how to avoid interference between multiple platforms. Consider the Iraq example discussed in section 3.3 in which as many as twenty platforms may be supporting ground operations at any one time. If all twenty platforms are operating at the same frequencies, each signal will jam the surrounding signals and none of the links will function properly. There are several methods to overcome the problem of interference each with their own advantages and

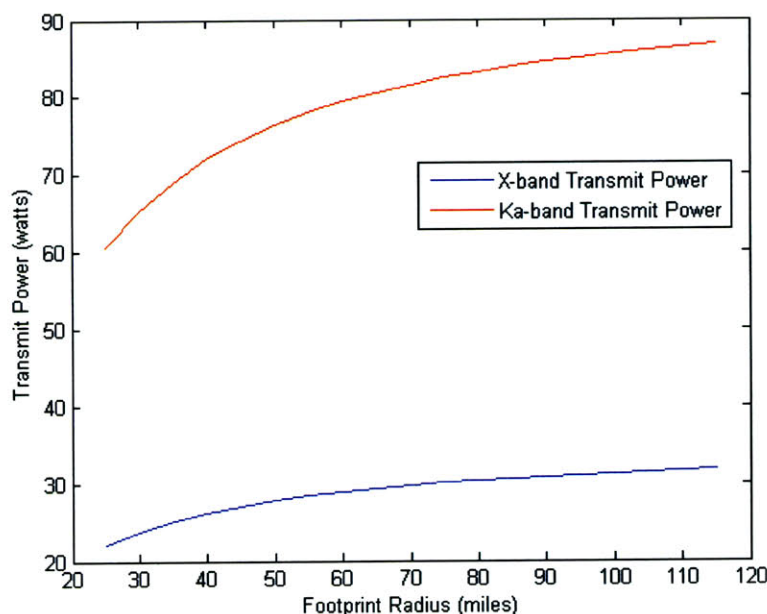


Figure 3.7: HALE Transmit Power versus Antenna Size Trade Study

disadvantages. These methods are shown in figure 3.8 and discussed below.

Code division multiple access (CDMA) is a multiplexing scheme in which each transmitter is allocated a specific code to allow multiple users to be multiplexed over the same physical channel or frequency. This method has the advantage of not dividing the available spectrum into smaller channels as is required by FDMA (discussed later) and users can transmit at any desired time[35], however, CDMA requires data packaging, more complicated receiver equipment to carry out the code selection and is especially vulnerable to the near-far problem.

The near-far problem relates to the interference created by two transmitters and one receiver in which one of the transmitters is closer to the receiver than the other. If both transmitters transmit simultaneously and at equal powers then, due to the inverse square law, the receiver will receive more power from the nearer transmitter and the far transmitter signal may be interpreted as background noise and filtered out, effectively jamming the signal transmitted from farther away. This problem is commonly solved by dynamically adjusting the transmitting power so that the near transmitter uses less power than the far transmitter causing both signals to arrive at the receiver with similar power. Dynamic power adjustment is subject to power control runaway in which near transmitters increase power in high-noise situations requiring an even higher transmit power from the station farther away. This cycle perpetuates until the far transmitter reaches its power output limit and is unable to maintain a usable SNR and drops from the network. Limitations to available platform transmitter power make CDMA an unlikely

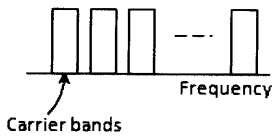
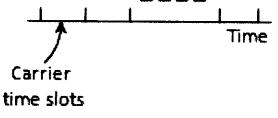
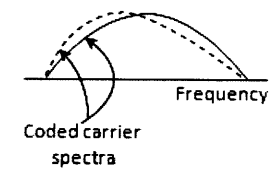
Multiple-access Format	Designation	Characteristic
Frequency-division multiple-access	FDMA	<p>Frequency separation</p> 
Time-division multiple-access	TDMA	<p>Time separation</p> 
Code-division multiple-access (spread-spectrum Multiple access)	CDMA (SSMA)	<p>Waveform separation</p> 

Figure 3.8: Multiple Access Formats; Source: "Satellite Communications," Robert M. Gagliardi, Table 1-4

choice for military communication applications.

In time division multiple access (TDMA), each transmitting station is assigned a specific time slot in which to transmit data[35] with users transmitting in rapid succession. Like CDMA, time division allows the users full access to the frequency spectrum but requires data packaging, short burst communications and precise time synchronization among all users. According to Gagliardi, "TDMA is primarily applicable to special purpose systems involving relatively few earth stations,"[35] and is thus not likely to be the best choice for military communication applications.

Frequency division multiple access (FDMA) is the simplest format to implement[35] and functions by allocating smaller frequency bands or channels within the available spectrum and is the access scheme employed by WGS.[29] FDMA allocates a pre-determined frequency that is always available to the assigned user which facilitates streaming data rather than requiring packetized data as do other multiple access schemes. Three disadvantages of this method are that it requires high performance filters to separate the frequencies, it is susceptible to station cross-talk and intercarrier interference and it reduces the bandwidth available to users. FDMA has the additional benefit of flexibility, either to service multiple users through channel allocation or to support protected communications by synchronized hopping through a range

of frequencies. Therefore, FDMA is likely to be the best choice for military communication applications.

As discussed in section 3.1 we are assuming that the HALE platform is operating directly overhead with a beamwidth sufficient to cover the entire field of view and thus does not require platform antenna pointing. Should it be necessary to point the antenna, "it is common to have a pointing accuracy of 10% to 20% of the field of view diameter." [21] In the case of communications payloads, the field of view *radius* is the half-power beamwidth,  $\theta$ . If we assume the mean pointing accuracy of 15%, then  $e = 2\theta / 15$  and equation (3.42) shows the relationship for the antenna pointing loss.

$$L_{pr} = -12 \left( \frac{2\theta}{15} \right)^2 = -12 \left( \frac{\theta}{15} \right)^2 \quad (3.42)$$

Note that pointing the platform antenna toward a specific ground terminal will change the coverage area and prevent communications access to users located outside the antenna pattern. Therefore, designers must give careful consideration to user impact when deciding to employ antenna pointing.

### 3.5 Chapter Summary

This chapter has demonstrated that HALE platforms are capable of providing communications performance comparable to that of the WGS satellites with significantly reduced power requirements due to the shortened path length. These power savings consequently result in a lower system cost although the resultant cost savings were not as high as anticipated.

The main drawback of the HALE platform compared to the WGS is the reduced field of view of the onboard communications system. However, since this thesis is attempting to develop the feasibility of using HALE platforms to support operations at the brigade-level, the available footprint is still more than sufficient to cover the size of the area of operations in question.

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## Chapter 4

# Military Applications — ISR Payload

Resolution is the key performance metric in the design of observation payloads. Astronomical observations define resolving power in terms of angular resolution, or the angular separation between two objects of interest. In earth observation, the key is be able to resolve fine detail on the surface, therefore, the resolution is expressed in terms of the size of an object that is distinguishable from the background.[42] This chapter will focus on earth observation and thus will use ground resolution as the primary evaluation metric.

This chapter will begin with an overview of the equations governing observation payload design followed by an analysis of the performance of observation payloads with respect to both satellites and HALE platforms and will conclude with a discussion of observation mission-specific CONOPS considerations. This analysis will use the newly commissioned GeoEye commercial imaging satellite as the baseline for ground resolution performance comparisons.

The GeoEye-1 satellite was designed and built by General Dynamics Advanced Information Systems and launched in September 2008 aboard a Boeing Delta II rocket. While GeoEye is a commercial satellite, it provides imaging services to government agencies as well including the National Geospatial-Intelligence Agency (NGA) and the National Oceanic and Atmospheric Administration (NOAA). Section 4.2 will discuss the GeoEye-1 satellite capabilities in more detail.

### 4.1 ISR Payload Design and Sizing

As mentioned previously, ground resolution is the primary performance metric and is dependent upon four factors: distance to the target ( $R_s$ ), focal length ( $f_l$ ), wavelength ( $\lambda$ ) and aperture size ( $D$ ). Figure 4.1 shows the optical characteristics of a refractive imaging system.

The fundamental resolution limitation is diffraction, the bending of light that occurs at the edge of the optical system.[42] Diffraction causes a point source of light to appear as a series of concentric circles getting successively dimmer away from the center; a pattern known as the

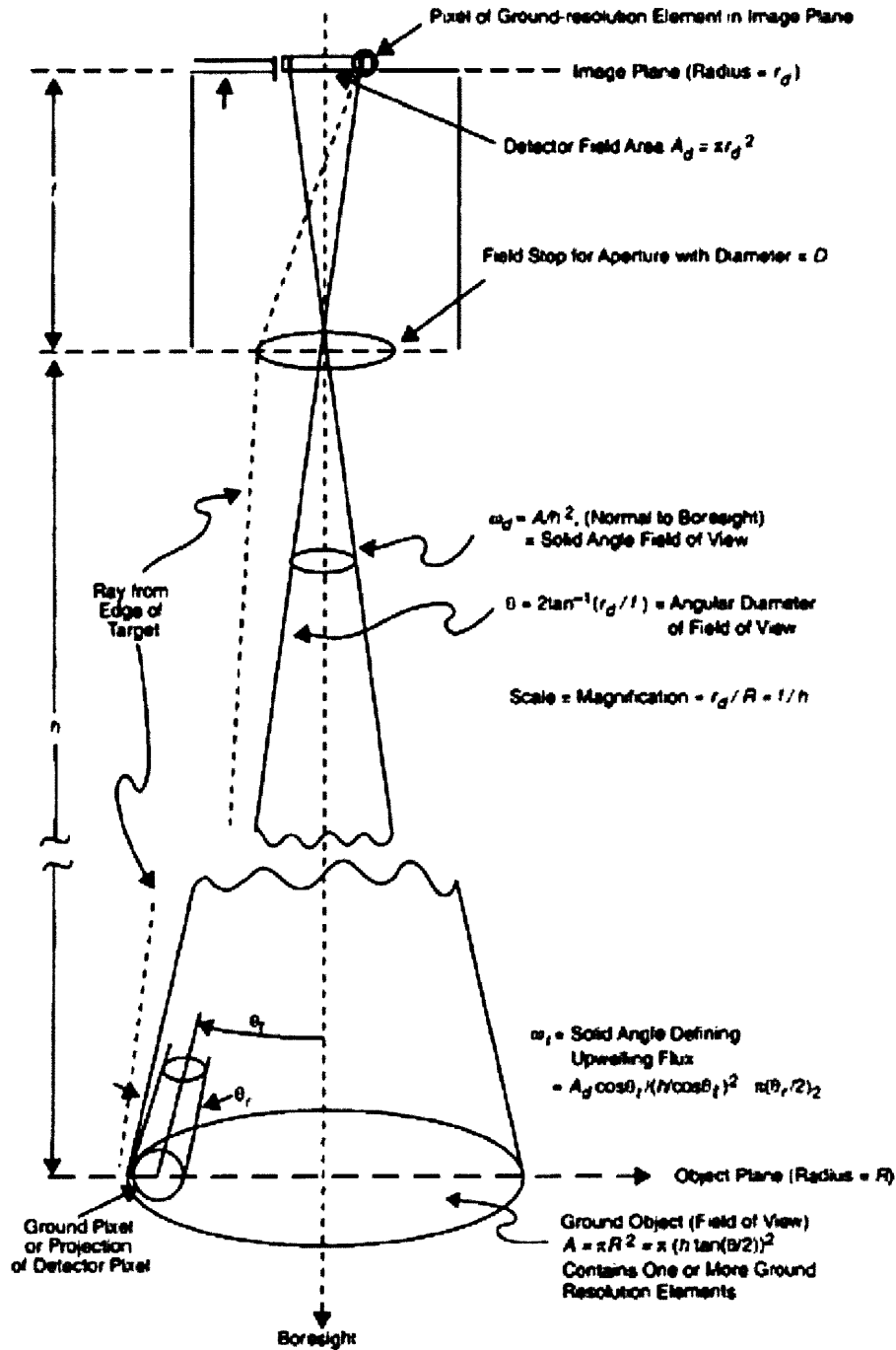


Figure 4.1: Optical Characteristics of a Refractive Imaging System; Source: SMAD Chapter 9.3, Figure 9-8



point spread function as shown in figure 4.2.

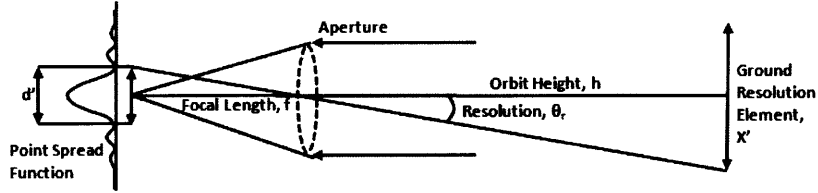


Figure 4.2: Point Spread Function for Imaging System with Diffraction; Source: SMAD Chapter 9.3, Figure 9-11

The angular distance,  $\theta_r$ , from the maximum at the center of the image to the first dark interference ring, called the Rayleigh limit is given in equation (4.1).[42]

$$\theta_r = \frac{1.22\lambda}{D} \tag{4.1}$$

Where  $\lambda$  is the wavelength,  $D$  is the aperture diameter of the optical instrument and  $\theta_r$  is expressed in radians.

For a satellite, or HALE platform at altitude,  $H_p$ , the ground resolution is shown in equation (4.2).

$$x' = \frac{2.44H_p\lambda}{D} \tag{4.2}$$

Equation (4.2) is valid for objects located at nadir, however,  $H_p$  can be replaced by the slant range,  $R_s$ , to determine the resolution away from nadir. Here  $R_s$  is the same as  $S$  in equation (3.8) and refers to the angular relationships shown in figure 2.9. Table 4.1, taken from SMAD chapter 9, provides some possible resolutions from various altitudes for common aperture sizes.

<b>Ground Resolution = 2.44 h <math>\lambda</math>/D</b>				
<b>Altitude</b>	<b>Aperture Size, D</b>	<b>Visible [<math>\lambda = 0.5 \mu\text{m}</math>]</b>	<b>IR [<math>\lambda = 3 \mu\text{m}</math>]</b>	<b>Microwave [<math>\lambda = 3 \text{ cm}</math>]</b>
900 km (LEO)	1 m	1.1 m	6.59 m	65.9 km
	3 m	0.366 m	2.2 m	22 km
35,800 km (GEO)	1 m	43.7 m	262 m	2,620 km
	3 m	14.6 m	87.4 m	874 km
20 km (SR-71)	0.3 m	0.081 m	0.488 m	4.88 km

Table 4.1: Diffraction-Limited Resolution: Source: SMAD Chapter 9.3, Table 9-9

There is one additional design parameter to consider in the design of optical detector arrays: the quality factor,  $Q$ . The quality factor is defined as the ratio of the pixel size ( $d$ ) to the diameter

of the first minimum of the point spread function ( $d'$ ) as shown in equation (4.3).

$$Q \equiv \frac{d}{d'} = \frac{X}{X'} \tag{4.3}$$

Where  $d'$  is twice the Rayleigh limit,  $\theta_r$ ,  $X$  is the ground pixel size and  $X'$  is the ground resolution. The quality factor typically ranges from 0.5 to 2. For  $Q < 1$ , the pixels are smaller than the point spread function and resolution is limited by diffraction in the optics; for  $Q > 1$ , resolution is limited by the pixel size.[42] Generally speaking, the smaller the quality factor, the better the resolution for a given aperture.

Remote sensing has its basis in electromagnetic radiation resulting from energy transference from one form to another. Generally speaking there are four primary types of spectral radiation that apply to spacecraft and HALE remote sensing: visible, infrared, microwave and radar. Table 4.2 outlines the relative advantages and disadvantages of measuring each type of radiation.

Spectral Type	Wavelength	Advantages	Disadvantages
Visible	0.3 $\mu\text{m}$ - 0.75 $\mu\text{m}$	High Resolution	Limited to daylight
Infrared	1 $\mu\text{m}$ - 100 $\mu\text{m}$	Operate day & night	Limited atmospheric windows
Microwave	1.5 mm - 15 mm	Unique information Covers large areas	Worst resolution Extensive calibration
Radar	50mm - 3.7 cm	Penetrate atmosphere Self-illumination	Poor resolution

Table 4.2: Comparison of Spectral Types for Remote Sensing Systems; Source: SMAD Chapter 9.4

Table 4.2 references the limited atmospheric transmission windows associated with infrared imaging systems. Figure 4.3 shows the transmission characteristics of the Earth’s atmosphere. One can see that it is possible to view objects on the surface with infrared remote sensing provided designers select a wavelength with a high percentage of atmospheric transmission.

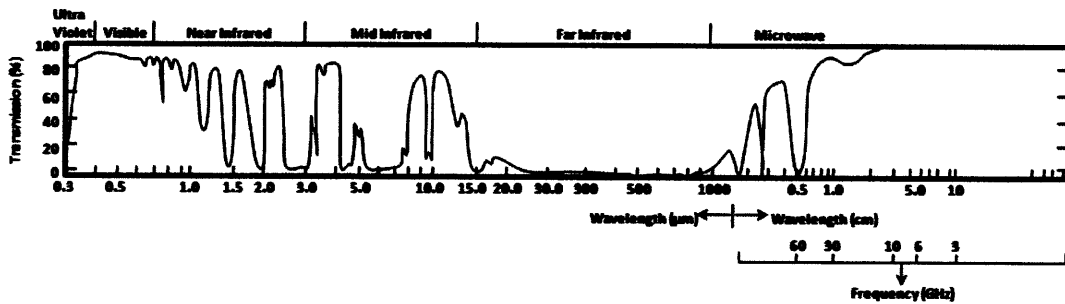


Figure 4.3: Transmission Characteristics of the Earth’s Atmosphere; Source: SMAD Chapter 9.3, Figure 9-6

The final consideration in optical payload design is the configuration of the pixels in the sensor. There are four main scanning techniques (shown in figure 4.4): whiskbroom sensor (both single- and multi-element), push broom sensor and matrix. In all cases, each detector element corresponds to one pixel on the ground and the integration time is determined by the ground pixel size and the velocity of the sub-spacecraft point.[42]

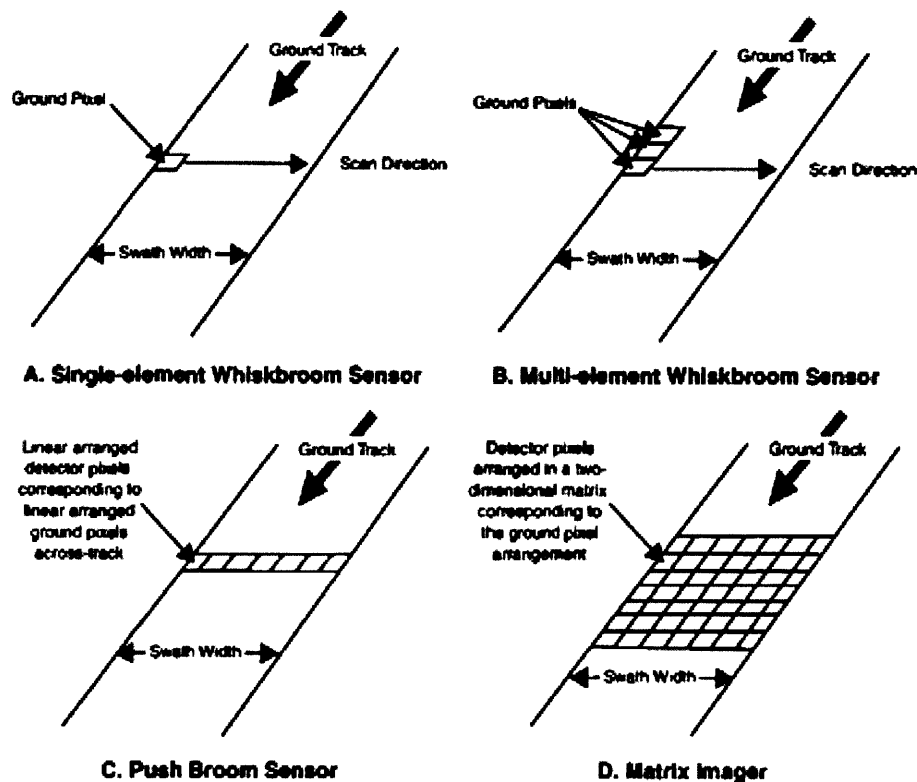


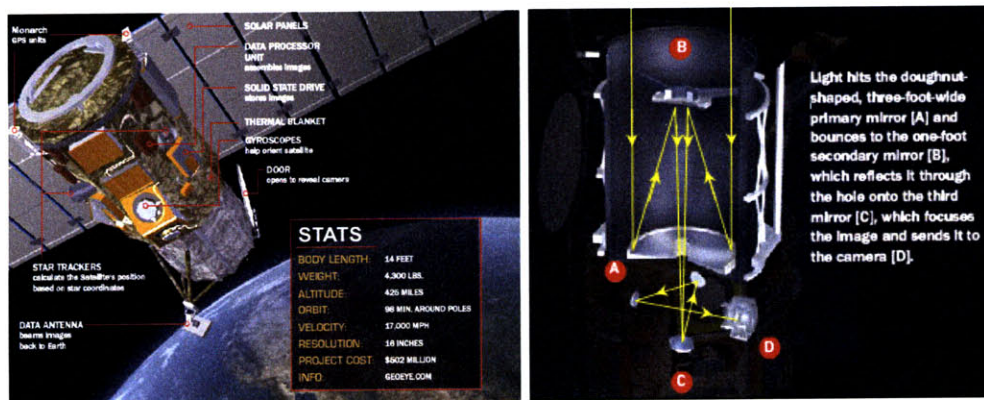
Figure 4.4: Scanning Techniques for Electro-Optical Instruments; Source: SMAD Chapter 9.4, Figure 9-14

The motion of the sub-spacecraft point replaces one of the scan dimensions so, in the case of whiskbroom sensors, the scanning system only needs to perform a one-dimensional scan in the cross-track direction.[42] In the case of HALE systems that remain nearly stationary relative to the area of interest, a matrix imager is the best choice in order to avoid excessive scanning requirements.

## 4.2 ISR Satellite Performance Analysis

The GeoEye-1 satellite orbits at 425 miles and has a ground resolution capability of 0.41 meters (1.3 feet) in panchromatic (black and white) mode at nadir targets and 1.65 meters / 5.4 feet in multi-spectral (color) mode at nadir targets.[43] This panchromatic resolution means that

GeoEye will be able to discern objects measuring 41 centimeters (16 inches) in size, roughly the size of home plate on a baseball diamond.[44] Additionally, GeoEye has the ability to precisely map objects on the ground to within nine feet of the true location. This mapping accuracy is accomplished through the use of high precision star trackers and military-grade GPS signals; GeoEye is the first commercial satellite with access to military GPS signals.[45] Figure 4.5(a) shows the GeoEye-1 Satellite configuration and statistics and figure 4.5(b) shows the path of light through the satellite optical system.



(a) GeoEye-1 Satellite Configuration

(b) GeoEye-1 Satellite Optics

Figure 4.5: GeoEye-1 Satellite Configuration and Optics Functionality; Source: "How It Works: The Best View From Space Yet," Bjorn Carey, Popular Science Online, March 2008, <http://www.popsci.com/node/19968>

There can be no doubt that the GeoEye-1 satellite represents a tremendous step forward in the state of the art of orbital remote sensing, however there are some disadvantages inherent in the system that make it undesirable for use in military applications. These disadvantages include the fact that it operates in the visible range of the electromagnetic spectrum meaning that it can only function when the target is illuminated by daylight. The other main disadvantage is that there is currently only one satellite in orbit meaning that the revisit time ranges from two to eight days depending on the target latitude.[43] Both of these limitations mean that GeoEye cannot satisfy the requirement for persistent military observation. We will show in the next section that placing an observation payload capable of operating in both the visible and infrared ranges of the spectrum aboard a HALE platform that can remain stationary relative to the target area of interest will overcome both of these limitations.

### 4.3 HALE Platform Performance Analysis - ISR Payload

Having determined the relevant governing equations, spectral types and sensor configurations, we will now select a baseline optical system for HALE platform performance analysis. In this

section, we will use a multi-spectral imaging system using both the visible and infrared ranges of the electromagnetic spectrum with sensor pixels configured in a matrix imager. As in previous analyses, we will assume a nominal operating altitude of 85,000 feet and an elevation angle of fifteen degrees. Based on equation (3.8), the maximum slant range,  $R_s$ , then becomes 319,649 feet (97,429 meters). We will use this slant range to determine the worst case ground resolution possible

In this analysis, we will vary the aperture diameter from 0.3 meters (equivalent to the sensor on an SR-71 Blackbird) to one meter (approximately equivalent to the GeoEye-1 satellite aperture). Figure 4.6 shows the resulting ground resolution for the given aperture range.

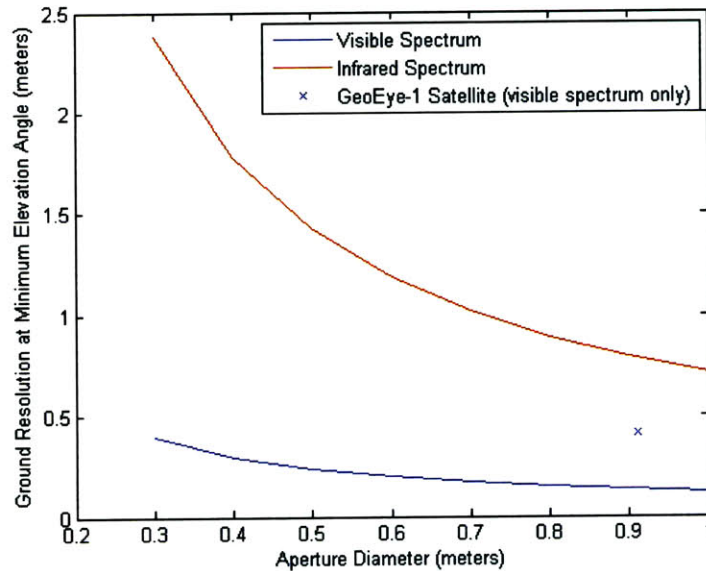


Figure 4.6: HALE Platform Remote Sensor Ground Resolutions at the Minimum Elevation Angle (15 degrees) for the Visible and Infrared Spectrums

One can see from figure 4.6 that an aperture diameter of 0.3 meters allows a ground resolution of 0.39 meters; the HALE platform already outperforms the GeoEye-1 satellite. As the aperture diameter approaches one meter, the ground resolution in the visible spectrum is 0.12 meters. For perspective, a resolution of 0.01 meters is sufficient to distinguish a large newspaper headline.[42] Any resolution in this range of aperture diameters is sufficient to observe human activity on the surface. Activities such as the emplacement of improvised explosive devices (IEDs) in Iraq or Afghanistan are of particular concern for military operations. It is important to note that these resolution values are for the maximum slant range for a 15 degree elevation angle. At nadir, the resolution is even better as shown in figure 4.7. At an aperture diameter of one meter, the nadir ground resolution is approximately 0.03 meters.

In order to calculate the design parameters of the optical system, we must begin with swath

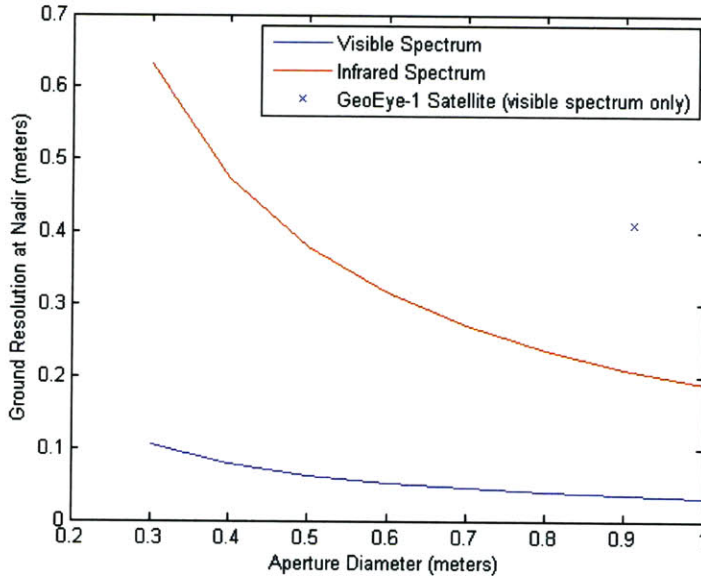


Figure 4.7: HALE Platform Remote Sensor Ground Resolutions at Nadir for the Visible and Infrared Spectrums

width,  $S_w$ , which is simply twice the Earth Central Angle,  $\lambda_E$ , (calculated in equation (2.12)). Next, we must determine the maximum cross-track pixel resolution,  $X_{max}$ , at the Earth Central Angle. In this case, we will assume a median aperture diameter of 0.7 meters from the above calculations and an optical system operating in the visible spectrum. From figure 4.6, we find a resolution of 0.17 meters at the minimum elevation angle; this then becomes the maximum cross-track pixel resolution,  $X_{max}$ . Equation (4.4) shows the relationship between the cross-track resolution and the along-track sampling distance,  $Y_{max}$ .

$$X_{max} = \frac{Y_{max}}{\cos(IA)} \quad (4.4)$$

Where  $IA$  is the incidence angle and is defined as  $IA = 90^\circ - \epsilon_s$ . Then, equation (4.5) determines the Instantaneous Field of View, (IFOV). The IFOV is also defined as the width of one pixel and, for simplicity, we will assume square pixels in this analysis.

$$IFOV = \frac{Y_{max}}{R_s} \frac{180^\circ}{\pi} \quad (4.5)$$

Therefore, for a HALE platform operating at 85,000 feet with a minimum elevation angle of 15 degrees, and aperture diameter of 0.7 meters and a ground resolution at the edge of the coverage area of 0.17 meters, the IFOV is  $2.59 \times 10^{-5}$  degrees.

Next, we determine the number of cross-track pixels,  $Z_c$ , required to cover the swath width

as shown in equation (4.6).

$$Z_c = \frac{2\eta_{nadir}}{IFOV} = 5.73 \times 10^6 \text{ pixels} \quad (4.6)$$

Since HALE platforms remain relatively stationary with respect to the ground, we will assume a matrix imager (from figure 4.4) and, for simplicity, we will assume a square matrix. Therefore, the total number of pixels required is  $Z_c^2 = 3.29 \times 10^{13}$  pixels.

Next, we must determine the number of bits used to encode each pixel. The number of bits used is based on resolution and dynamic range requirements and can range from one to thirty-two bits per pixel (bpp), 1 bpp being the minimum required for a binary (black-and-white) image; 8 bpp allows for a 256 color image but tend to produce grainy pictures; 16 bpp provide 65,536 distinct colors and is often used in high quality computer graphics cards; 24 bpp allows for 331,776 distinct colors; and 32 bpp provide a true-color image. In this case, we will assume the median 16 bpp. Then the required data rate,  $R$ , is the total number of pixels imaged in one second times the number of bits per pixel. Based on the above numbers, imaging such a large detector array once per second will require a downlink capacity of  $5.3 \times 10^{14}$  bits per second or 530 terra-bits per second (Tbps) - an impossibly high number.

In order to make the data rate manageable, we need to trade it against lower resolution and smaller coverage area. First, we will reduce the size of the coverage area to a more practical size. Referring to the coverage area discussion in section 3.3, we will again assume a coverage area equivalent to the area of operations assigned to the 3d ACR in Northwestern Iraq from May 2005 through February 2006: an area of 3,861 square miles (62 x 62 miles). Next, we will reduce the resolution requirement to the minimum achievable with a 0.3 meter aperture diameter, 0.11 meters at nadir (0.39 meters at the edge). Then, applying equations (4.4) through (4.6), we find we still need  $6.85 \times 10^{12}$  pixels and a data rate of 110 Tbps - a data rate still not supportable with conventional data links.

Clearly, trying to image the entire field of regard (FOR) with a single array requires a data rate that is unsupportable by current communications links and an array size that is not commercially available. Table 4.3[46] shows some commercially available high-resolution charge coupled device (CCD) arrays.

In the following analysis we will use the Lockheed Martin F-979F model CCD array, the largest square array available - approximately 85 Mpixels. Figure 4.8 shows the angular relationships used in the analysis; note that we assume the HALE platform will be operating over the center of the coverage area rather than over the edge. Using this array and again assuming a 3,861 square mile field of regard, we must determine the total number of images required to scan the entire coverage area. First, we take the required resolution at nadir, 0.11 meters, and

Manufacturer	CCD Model	Array Size (pixel)	Pixel Size ( $\mu\text{m}$ )	Data Rate (MHz)
Kodak	DCS-460	3,072 x 2,048	9	10
Lockheed Martin/ Fairchild	Bigshot <sup>TM</sup>	4,096 x 4,096	15	5
Kodak	Mega Plus 16.8i	4,096 x 4,096	9	10
Philips	Icam28	7,168 x 4,096	12	18
Reco/Optical/Dalsa	CA-260/50	10,080 x 5,040	10	64
Lockheed Martin	F-979F	9,216 x 9,216	8.75	160
Philips	FTF3020-C	3,072 x 2,048	12	–

Table 4.3: High-Resolution CCD Arrays in the 1999 Time Frame; Source: "Earth Observation History on Technology Introduction," Herbert J. Kramer, <http://www.eoportal.org/documents/kramer/History.pdf>

divide it by the platform altitude,  $H_p$ , to determine the angular resolution,  $\theta_i$ , of a single image.

$$\theta_i = \frac{\text{resolution}}{H_p} = \frac{0.11 \text{ m}}{25908 \text{ m}} = 4.25 \times 10^{-6} \text{ radians} = 2.43 \times 10^{-4} \text{ degrees} \quad (4.7)$$

Then, we divide the incidence angle, IA, by  $\theta_i$  to determine the total number of pixels from nadir to the edge of the coverage area.

$$Z_c = \frac{IA}{\theta_i} = \frac{62.7}{2.43 \times 10^{-4}} = 2.58 \times 10^5 \text{ pixels} \quad (4.8)$$

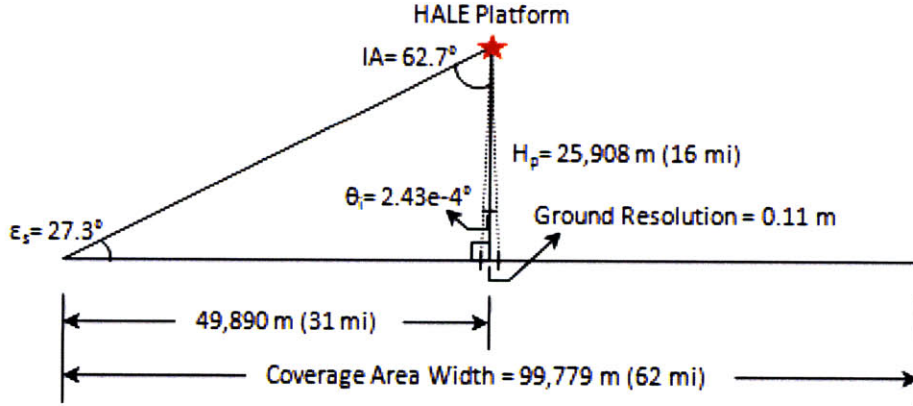


Figure 4.8: Angular Relationships for HALE Performance with an ISR Payload (not to scale)

Dividing the number of pixels from nadir to the edge of the coverage area by the number of pixels on one side of the array, 9,216, we find that the array must take 28 images to cover the FOR from nadir to the edge (56 images to cover one side of the coverage area) and 3,136 ( $56^2$ )



images over the entire coverage area, assuming a square field of regard.

From table 4.3, we see that the Lockheed Martin F-979F model CCD array has a data rate of 160 MHz (here, we will assume 160 Mbps). Then multiplying the number of pixels in the array by the number of bits per pixel and dividing by the data rate, we are able to determine amount of time required to read-out the image data from the array as shown in equation (4.9).

$$\text{Read-Out Time} = \frac{N_{\text{pixels}} * \text{bpp}}{R} = \frac{9,216^2 * 16}{160 \text{ times } 10^6} = 8.5 \text{ seconds} \quad (4.9)$$

Therefore, we assume that the array can take one image every nine seconds: allowing time to position the camera, capture the image, store the data and reposition the camera, then a single array can cover the entire field of regard once every 28,224 seconds (470.4 minutes, 7.8 hours).

Having identified a workable payload configuration, the next step is to determine the data rate and transmitter power required to transmit the images to a ground station. Again assuming 16 bits per pixel, the Lockheed Martin F-979F model CCD array will require a data rate of  $1.36 \times 10^9$  bits per second or 1.36 Gbps - still a very high data rate for conventional communications links; however, this number does not account for any data rate savings due to data compression algorithms.

There are two methods of image compression: lossy and lossless. Lossy compression allows some predetermined acceptable level of information loss in favor of significantly reduced image sizes. Lossy compression works because the lost data is imperceptible to the human eye making the decompressed images nearly identical to the original. Lossless compression yields an image identical to the original while still representing an image signal with the smallest possible number of bits, thus reducing transmission time and storage requirements. Generally lossless compression ratios are smaller than those achievable with lossy compression.[47] In all lossless compression schemes, there is a theoretical upper limit (known as the entropy rate, established by Claude Shannon) beyond which it is impossible to achieve better compression.[36] Since this analysis focuses on military applications in which even a small amount of information loss may be unacceptable, we will conservatively assume a lossless compression algorithm. Table 4.4 shows the compression ratios for two different types of images.[48]

Image Details	Compression Ratios		
	Lossless JPEG	JPEG-LS	JPEG2000
512x512, 24bpp	1.627:1	1.770:1	1.773:1
512x768, 8bpp	3.226:1	6.452:1	3.774:1

Table 4.4: Compression Ratios for Lossless Compression of Two Image Types; Source: The JPEG2000 Still Image Coding System: An Overview, Christopoulos et al, Table VI (excerpt)

Since the compression ratio is heavily determined by factors such as the amount of detail

in an image and the probability with which certain bit values occur, it is impossible to define a set compression ratio without a priori knowledge of the image details. However, as a first order estimate based on table 4.4, we will assume a compression ratio of 2:1 as a likely achievable ratio. Thus, the data rate required by the CCD array used in the analysis above can be reduced to 680 Mbps. Given that we have allocated nine seconds between images, then the required downlink data rate is 75.5 Mbps. For reference, the Global Hawk "direct line of sight capability, could support up to 274 megabits per second,"[7] so our data rate is well within the range of currently available downlink capabilities.

Note that if we are willing to accept a lower image quality, we could assume 8 bits per pixel and the required downlink data rate becomes 679 Mbps. Again assuming a 2:1 compression ratio, the data rate is reduced to 339.5 Mbps. Based on table 4.3 and equation (4.9), the system will require about five seconds to read-out the image data from the CCD array. Therefore the downlink must be able to support a data rate of 67.9 Mbps; again, a very achievable number. Assuming the platform can capture one image every five seconds, then the system could image the entire FOR in 15,680 seconds (261.3 minutes, 4.4 hours).

The next step in the analysis is to determine the transmitter power required to achieve the necessary data rate. Table 4.5 summarizes the parameters used in the calculations. These parameters are fully developed in section 3.1 and reproduced here for the reader's convenience. In this case, we have assumed transmission in the X-band, as that band is reserved for military use (see table 3.1). Additionally, we have assumed the higher data rate determined above (75.5 Mbps) and the omnidirectional ground receive DSCA antenna discussed in section 3.3. Then, referring to the link equation, (3.2), and solving for the required transmitter power,  $P_t$ , we find that the image downlink requires a transmitter power of -0.07 dBW (0.98 watts) to close the link. Since this power requirement is insignificant compared to the required payload power (as will be shown next), we will use the payload power as the average platform power requirement.

Parameter	Value
Energy-to-Noise Ratio ( $E_b/N_o$ )	10.5 dB
Line Loss ( $L_l$ )	0.5 dB
Tx Antenna Gain ( $G_t$ )	22 dBi
Rx Antenna Pointing Loss ( $L_{pr}$ )	-3 dB
Space Loss ( $L_s$ )	-150.45 dB
Path Loss ( $L_a$ )	2 dB
Rx Antenna Gain ( $G_r$ )	8 dBi
System Noise Temp ( $T_s$ )	135 K
Data Rate ( $R$ )	$75.5 \times 10^6$ bps

Table 4.5: Link Equation Parameters Developed in Section 3.1

Finally, we must determine payload size, mass and power requirements. This analysis will

scale the payload from an existing earth observation satellite and as such will not be the definitive solution. Nevertheless, it will provide an order of magnitude estimation for HALE payload requirements. The Space Mission Analysis and Design textbook provides a table of characteristics of typical satellite payloads. Rather than include the entire SMAD table here, we will take an excerpt of two of the most likely candidates, shown in table 4.6

Purpose	Instrument Name	Size (LxWxD) (m)	Mass (kg)	Avg. Power (W)	Data Rate (Mbps)	Aperture (m)	Pointing Accuracy (deg)
Resources	Multi-Spectral Mid-IR	1.5x1 dia.	800	900	30	1	0.1
	Thematic Mapper	2x0.7x0.9	239	280	85	0.406	0.08

Table 4.6: Characteristics of Typical Satellite Payloads; Source: SMAD Chapter 9.4, Table 9-13

In this case, we will select the Thematic Mapper payload as the instrument most similar to the HALE ISR payload. Equation (4.10) shows the scaling ratio based on payload aperture, which is a critical instrument parameter that can be identified early in the design process.[42]

$$R_{scale} = \frac{A_i}{A_o} = \frac{0.3}{0.406} = 0.74 \quad (4.10)$$

Where  $A_i$  is the required aperture of the HALE payload (0.3 m) and  $A_o$  is the aperture of the reference payload (0.406 m). Then we apply the scaling ratio to equations (4.11) through (4.13), we can determine tentative linear dimensions, mass and power requirements of the HALE payload.

$L$  = payload linear dimensions:

$$\begin{aligned}
 L_i &\approx RL_o \\
 L_l &\approx (0.74)(2) = 1.48 \text{ meters} \\
 L_w &\approx (0.74)(0.7) = 0.52 \text{ meters} \\
 L_d &\approx (0.74)(0.9) = 0.67 \text{ meters}
 \end{aligned} \quad (4.11)$$

$M$  = payload mass:

$$\begin{aligned}
 M_i &\approx KR^3M_o \\
 M_i &\approx (1)(0.74)^3(239) = 96.85 \text{ kg} = 213.52 \text{ lbs}
 \end{aligned} \quad (4.12)$$

$P$  = payload power:

$$P_i \approx KR^3P_o \tag{4.13}$$
$$P_i \approx (1)(0.74)^3(280) = 113.46 \text{ W} = 20.55 \text{ dBW}$$

Where  $K$  is an additional weighting factor that is set to 2 when  $R$  is less than 0.5 and 1 otherwise.

Therefore, for a HALE ISR platform, an order of magnitude estimation for the payload size is 1.48 m x 0.52 m x 0.67 m (LxWxD) with a mass of about 97 kilograms (213.85 pounds) and a required power of about 114 watts. Based on the analysis in chapter 2, these numbers are feasible for a HALE platform operating at 85,000 feet.

This section shows that HALE platforms offer a clear improvement in resolution over their orbiting counterparts. In the next section, we will offer some CONOPS considerations that can offer an even faster performance time in order to make these platforms more attractive to combatant commanders.

#### 4.4 ISR Mission Specific CONOPS

There are three primary CONOPS to consider for the use of ISR payloads in HALE platforms.

First, we must determine the desired image quality (16 bpp or 8 bpp). This consideration then drives the amount of time required to image the entire FOR and thus has a direct impact on the number of systems employed by the Army.

Next, we can chose to increase the number of platforms available for earth observation. If it takes one platform about eight hours to image a 3,861 square mile field of regard, then five similar platforms can image the entire area in about an hour and a half. Referring to section 3.3, recall that Iraq is divided into approximately twenty brigade-level units. If we assume that each unit has the same size coverage area, then this course of action would require 100 platforms taking images every nine seconds in order to cover all of Iraq in 1.6 hours. This large number of HALE platforms may make this course of action impractical from the point of view of manufacture and system maintenance. However, should the Army decide that the logistics problems are outweighed by the need to provide valuable imagery information to ground soldiers, the ability to provide current imagery data updated hourly would be a significant combat multiplier and is well worth considering. This relatively rapid refresh rate would allow Soldiers to detect the emplacement of IEDs in enough time to react to the threat before the IED is fully emplaced thus providing a significant improvement to Soldier safety.

The third course of action to consider is to use the platforms to focus on a single area of interest at at time. Again assuming the use of the Lockheed Martin F-979F model CCD array, one platform can stare at an area approximately 3.6 square kilometers at a resolution of 0.11

meters at nadir (0.39 meters at the edge). This area is large enough to cover small villages or significant portions of the larger cities. In the current U.S. Army force structure, most combat brigade-level units have three to four subordinate battalions. Providing each brigade with a similar number of HALE platforms, equipped with earth observation systems, would allow the brigade commander to prioritize the assignment of these platforms based on the historic threat level of a given area or the level of importance of a subordinate unit mission. This option is most likely to be the one preferred by combatant commanders.

Many aerial observation missions involve the use of airborne assets to track people or vehicles of interest. Often, a situation arises in which assets (manned or unmanned) are either unavailable due to competing tasks or are available but cannot reach the required area before the target of interest leaves. Additionally, conventional air assets are only capable of tracking a target forward in time, i.e., they identify a moving target and follow it until ground forces are in position to interdict. Having a HALE platform permanently overhead and constantly monitoring the area of interest may also provide commanders with the ability to track targets backward in time to their point of origin, such as a safe house or a weapons cache. This ability would give commanders another piece of critical information in determining when and where to position ground forces.

## 4.5 Chapter Summary

This chapter has demonstrated that HALE platforms offer significantly improved image resolution when compared to surveillance satellite capabilities. While the analysis has shown that it is not possible for a single platform – or multiple platforms – to provide continuous surveillance over a brigade’s entire area of operations, these platforms are nonetheless capable of allowing sustained observation of critical areas of interest.

Though current conventional UAV assets, such as the Global Hawk, are capable of providing similar image resolutions and coverage areas, the fundamental endurance limitation and limited number of systems make truly continuous coverage impractical. HALE platforms offer the potential to fulfill a much needed role in the search improved surveillance of hostile forces. The ability to provide dedicated surveillance assets to combatant commanders makes HALE platforms an attractive alternative to conventional UAV and satellite capabilities.

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## Chapter 5

# Military Applications — Navigation Payload

In considering global navigation satellite system (GNSS) signals, the primary limiting factor is the signal strength. "At a receiver's antenna, in the open air, [the signal] strength is about -160 dBW or  $10^{-16}$  watts" approximately 10 billion times weaker than the average cell phone signal.[49] This limited signal strength is the primary cause for poor GPS performance in urban and mountainous terrain. Additionally, GPS signals are easy to jam with radio frequency interference (RFI) either intentionally or unintentionally and incorrect or false position signals can be sent to the receivers via a process known as spoofing.[50]

This chapter will provide an overview of the U.S. Global Positioning System (GPS) and a general description of current military GPS systems including the Precision Lightweight GPS Receiver (PLGR), Defense Advanced GPS Receiver (DAGR), BFT and FBCB2 including how these systems work currently. Equations will form the basis for comparing satellite-based GPS capability with the potential benefit of relaying/augmenting that signal through HALE platforms; the primary metric used in this analysis is the power received by the user. This chapter will demonstrate that a stronger GPS signal will offer marked performance improvement in urban and mountainous terrain and reduced susceptibility to jamming and spoofing. Additionally, this section will explore the possibility of reducing the latency (minutes to hours) associated with relaying BFT and FBCB2 signals through satellites. For non-satellite Enhanced Position Location Reporting System (EPLRS) based FBCB2 systems, the section will include a discussion of increasing the range to BLOS transmissions.

There are currently two primary space-based navigation systems in use: the U.S. operated global positioning system (GPS) and the Russian global navigation satellite system (GLONASS). Additionally, the European system, GALILEO, is under development and is expected to be operational in 2013 and the Chinese Compass system is currently expected to be operational after 2020.[51] This chapter will focus on the U.S. operated GPS constellation.

## 5.1 Global Positioning System Overview

The idea for a three dimensional position determination system arose in the early 1960s as a joint effort between the DOD, the National Aeronautics and Space Administration (NASA) and the Department of Transportation (DOT) with the goals of global coverage, continuous/all weather operation, high accuracy and the ability to serve high-dynamic platforms.[50] The U.S. Navy's Transit system was the first space-based radio navigation system and became operational in 1964 but it did not provide truly global coverage and the frequency of obtaining a position fix varied based on the user's latitude and ranged from 30 to 110 minutes - insufficient for highly dynamic platforms. Subsequent efforts to enhance the system performance led to the development of the NAVSTAR GPS system, now known simply as GPS.[50]

Currently, the GPS constellation consists of twenty-four satellites arranged in six orbital planes with four satellites per plane and there are three active spare satellites in orbit, as shown in figure 5.1. GPS satellites are in mid-earth orbit (MEO) at an altitude of 12,543 miles (20,186 km) and have a period of approximately twelve hours.[52] The on-orbit spares are capable of replacing failed satellites within several hours.

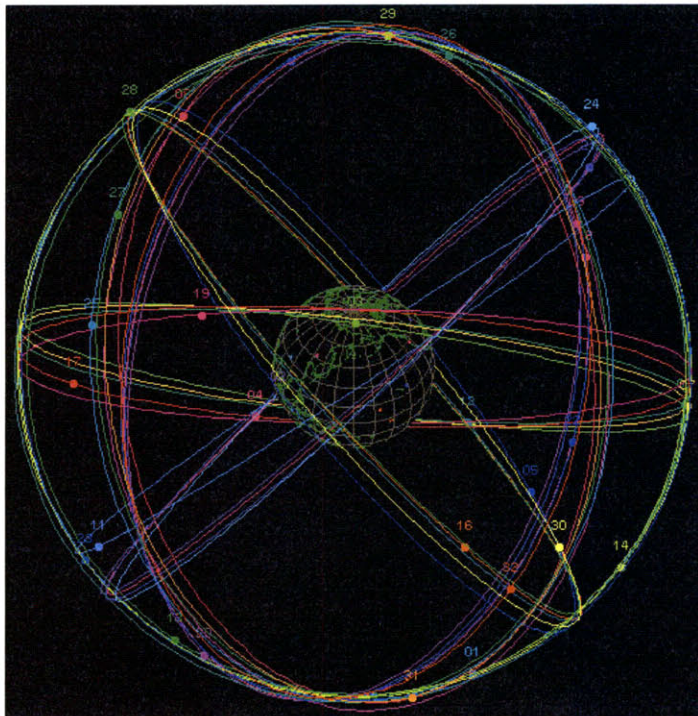


Figure 5.1: GPS Orbit Schematic; Source: GPS World Magazine online, [www.gpsworld.com](http://www.gpsworld.com)

Each GPS satellite has a highly accurate atomic clock on board that is synchronized with a GPS time base. The satellites broadcast ranging codes and navigation data using CDMA



(discussed in section 3.4) on two frequencies, L1 (1,572.42 MHz) and L2 (1,227.6 MHz) and each satellite has a unique code orthogonal to all other satellite codes. Each satellite generates two codes, a short coarse/acquisition (C/A) code and a long precision (P) code.[50] In order for receivers to generate an accurate position solution, a minimum of four satellites must be in view at any given time. The GPS receiver uses these signals to solve four equations with four unknowns: position in the X, Y and Z planes and the timing solution. Positions are computed using the navigation data, which provides the satellite ephemeris at the time of transmission and the ranging data, which determines the propagation time of the signal from the satellite to the receiver. GPS provides dual service to civil and military users, the Standard Positioning Service (SPS) and the Precise Positioning Service (PPS) respectively, where PPS service has higher precision capability and is encrypted to provide anti-jam and anti-spoof protection and selective availability (SA) degradation.[52] Selective availability adds intentional, time varying errors of up to 100 meters intended to deny an enemy the use of civilian GPS receivers for precision weapon guidance; SA was turned off by Presidential order in 2000.

In the late 1990s, the U.S. government announced GPS modernization initiatives which included two additional signals, L2C and L5 (1,176.45 MHz), both to be available to SPS users. These new signals are designed to correct for ionospheric delay through dual frequency measurements and to provide increased resistance to interference. Additionally, the late 1990s saw the introduction of a new military signal (M) code available to PPS users. This new code is transmitted on the L1 and L2 bands but is spectrally separated from the C/A and P codes thus permitting higher power transmissions without interfering with SPS users.[50] The M-code is discussed further in section 5.3.

There are two primary metrics for determining the position accuracy: dilution of precision (DOP) and user equivalent range error (UERE) which contribute to position error based on the following simple formula in equation (5.1) and figures 5.2 and 5.3 provide a further illustration of the sources of these errors. There are five types of dilution of precision: geometric, position, horizontal, vertical and time. Generally speaking, DOP can be reduced by increasing the separation between the satellites, thus allowing the ellipsoid of potential user locations be as small as possible. UERE is typically reduced by taking measurements from as many different satellites as possible. In both cases, a key method of reducing error is to design receivers to detect as many satellites a possible, up to twelve, the maximum

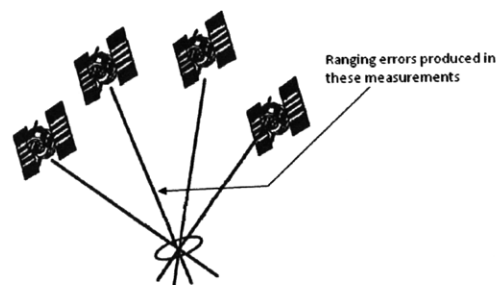


Figure 5.2: Illustration of UERE; Source: Navtech Seminars, Inc, Course 300: GPS Overview

that can be in view of the receiver at any given time.

$$\text{Position Error} = \text{DOP} \times \text{UERE} \quad (5.1)$$

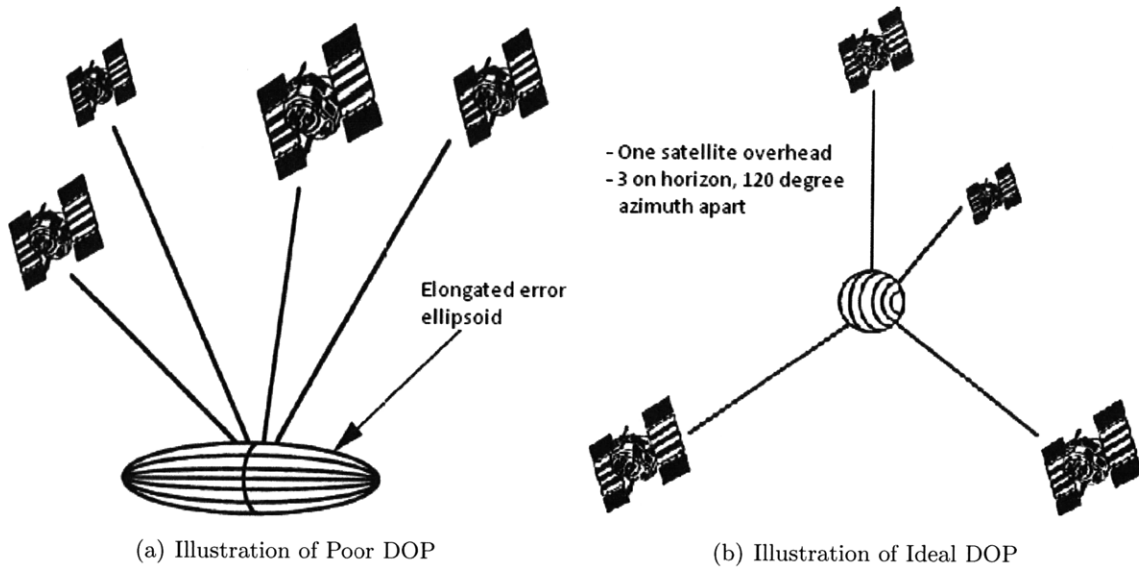


Figure 5.3: Illustration of Dilution of Precision; Source: Navtech Seminars, Inc, Course 300: GPS Overview

In addition to stand-alone GPS operations, systems exist to augment GPS performance such as space-based geosynchronous satellites and inertial navigation systems (INS) that add robustness in the presence of interference.[50] Wheel sensors and internal compasses provide temporary navigation capability in GPS-denied areas such as narrow urban streets surrounded by tall buildings. Additional applications, such as aircraft approach systems, require more precise accuracy which is achieved through the use of differential GPS (DGPS) correction signals as shown in figure 5.4, adapted from Dosis et al.[53]

DGPS involves using one or more ground-based reference stations with exactly known locations. These reference stations monitor the integrity of GPS signals and transmit correctional data to the users allowing accuracies from meters to millimeters.[50] DGPS reference stations range in capability from local area (10km - 100km) coverage to continental coverage; the US. Wide Area Augmentation System (WAAS) is an example of the later.[54, 55]

GPS systems provide a range of military applications including the provision of a reference time source for synchronizing frequency-hop enabled SINCGARS radios, the guidance of UAV flights and individual and vehicle tracking and monitoring on the battlefield. Current military equipment designed to operate with GPS support include the PLGR, DAGR, BFT and FBCB2 as mentioned previously.

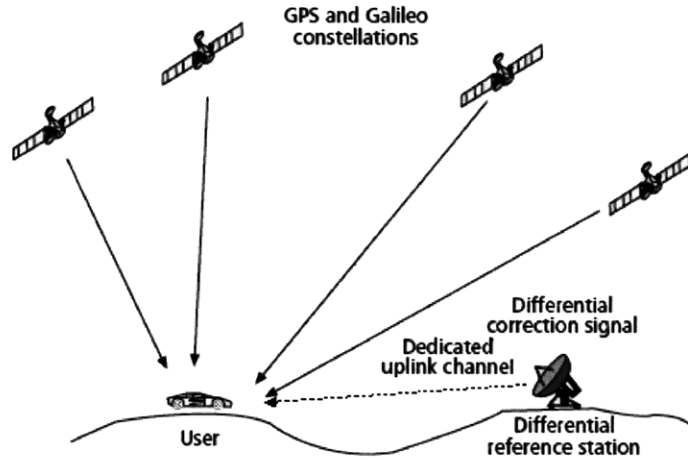


Figure 5.4: Diagram of Differential GPS Correction Signals; Adapted from: Dosis et al, Support Infrastructures Based on High Altitude Platforms for Navigation Satellite Systems, October 2005

PLGRs and DAGRs are simply GPS receivers with decryption software to enable access to the PPS service. The PLGR is a hand-held, single frequency (L1 only) receiver that was fielded in 1994 and used extensively until it was replaced by the DAGR in 2004. The DAGR is a dual frequency (L1 and L2) receiver with communications security components controlled by the National Security Agency (NSA). Table 5.1 outlines the performance enhancements of the DAGR over the PLGR.

Parameter	PLGR	DAGR
Frequency bands	Single (L1 only)	Dual (L1 & L2)
Security	PPS-SM	SAASM
Display	Text only	GUI with maps
Number of channels (satellites)	5	12 (all in view)
Anti-Jam resistance	24 dB	41 dB
Time to first fix (TTFF)	6 minutes	100 seconds
Time to subsequent fix (TTSF)	60 seconds	< 22 seconds
Weight	2.75 lb (1.25 kg)	0.94 lb (0.43 kg)
Dimensions (LxWxD)	9.5" x 4.1" x 2.6"	6.4" x 3.5" x 1.6"
Battery life	13 hours (8 batteries)	14 hours (4 batteries)
Reliability	2000 hours	5000 hours

Table 5.1: Military GPS Receiver Comparison; Source: [http://en.wikipedia.org/wiki/Defense\\_Advanced\\_GPS\\_Receiver](http://en.wikipedia.org/wiki/Defense_Advanced_GPS_Receiver)

Blue Force Tracking (BFT) and Force XXI Battle Command Brigade and Below (FBCB2) are GPS-enabled computer systems used to provide military commanders and forces with lo-

cation information about friendly, enemy and neutral forces. The BFT system displays the location of the user vehicle on a digital terrain-map display along with the locations of other platforms (friendly in blue and enemy in red) and also provides a means for marking and reporting battlefield conditions such as minefields, damaged bridges, etc. Additionally, BFT provides a means to send and receive text and imagery messages.

The FBCB2 system is a variant of BFT and in addition to standard BFT functions, FBCB2 also provide a means for collecting, sending and receiving reports digitally rather than verbally. These reports are provided in standard templates available to the user and include enemy contact reports, logistics reports and requests for support (i.e., artillery and medical evacuation (MEDEVAC)). One additional difference between BFT and FBCB2 is that while BFT relies solely on satellites to transmit data, FBCB2 is also compatible with the Enhanced Position Location Reporting System (EPLRS) which is a secure, jam resistant, computer controlled communications network that distributes near real-time tactical information. EPLRS has the advantage of reducing the latency associated with satellite transmissions but is limited to line-of-site communications and, therefore, of limited availability in a combat theater.

Subsequent sections of this chapter will investigate methods of using HALE platforms to enhance or augment the performance of existing military GPS receivers and GPS-enabled systems.

## 5.2 GPS Satellite Performance Analysis

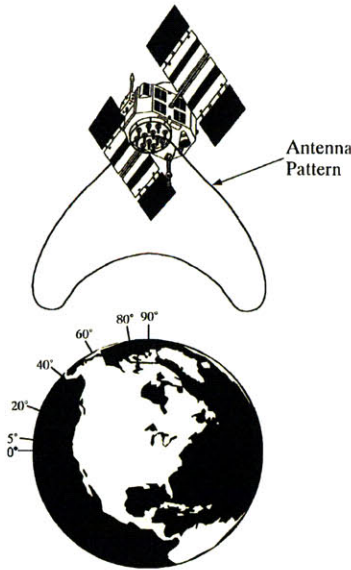


Figure 5.5: Earth Coverage GPS Antenna Pattern; Source: Navtech Seminars, Inc, Course 300: GPS Overview

Figure 5.5 shows the Earth coverage signal pattern of a single GPS satellite. Notice that the antenna pattern has wide sidelobes which mean that the greatest received power is achieved with a spacecraft elevation angle of 40 degrees. This elevation angle is analogous to the elevation angle discussed in sections 2.2 and 3.1. Figure 5.6 shows the corresponding received GPS power level for the C/A code on the L1 band as a function of the spacecraft elevation angle; clearly the highest received power occurs at an elevation of 40 degrees. Additionally, table 5.2, taken from the Navtech Seminars course on GPS signals,[52] shows an estimated link budget analysis for civil and DoD GPS navigation signals.

Though the position of the satellite is helpful in receiving a stronger signal, at best the received signal strength from the satellite is still only -157.5 dBW (from table 5.2) which is still an extremely weak signal. Current GPS receivers are able to

pick the correct signal out of the background noise through a code matching process. Since each C/A code is unique to a specific satellite, the receiver generates a replica code and uses the time delay information in the P code to correlate the signals. The receiver repeats this process for all satellites in view (up to a maximum of twelve) and then resolves the three-dimensional position and time of the user.

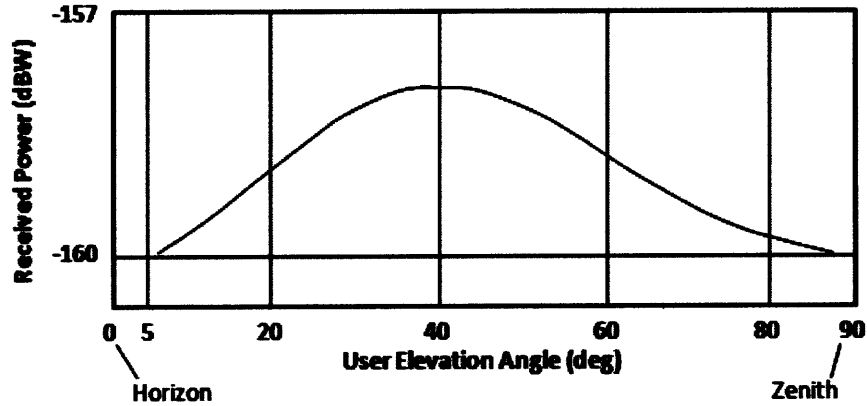


Figure 5.6: GPS Received Power as a Function of Spacecraft Elevation Angle; Source: Navtech Seminars, Inc, Course 300: GPS Overview

Link Parameter	40° Elevation Angle			5° Elevation Angle		
	L1		L2	L1		L2
	SPS†	PPS‡	PPS	SPS	PPS	PPS
Tx Pwr (dB)	14.25	11.25	6.35	14.25	11.25	6.40
Line Loss (dB)	1.0	1.0	1.0	1.0	1.0	1.0
Ant Loss (dB)	0.25	0.25	0.25	0.25	0.25	0.25
Ant Gain (dB)	13	13	13	12	12	12
ERP (dBW)	26	23	18.1	25	22	17.15
Space Loss (dB)	183.5	183.5	181.5	184.2	184.2	182.3
Path Loss (dB)	0	0	0	0.85	0.85	0.85
Rx Pwr (dBW)	-157.5	-160.5	-163.4	-160	-163	-166
Rx Pwr (fW)	0.18	0.089	0.046	0.1	0.05	0.025

Note: Received power assumes 0 dB receive antenna gain

† SPS refers to C/A code

‡ PPS refers to P code

Table 5.2: Link Budget Analysis for Civil and DoD GPS Navigation Signals (Estimated); Source: Navtech Seminars, Inc, Course 300: GPS Overview

The ERP term introduced in table 5.2 is the effective radiated power (also known as effective isotropic radiated power (EIRP)) and is determined by equation (5.2) which is derived from the

the link equation (3.1) introduced in section 3.1.

$$ERP = P_t + L_l + G_t \quad (5.2)$$

Code autocorrelation enables GPS receivers to pick the C/A and P code signals out of the noise floor but these signals are still easily blocked by man-made and natural obstacles such as urban and mountainous terrain and, absent selective availability, anti-spoof or DGPS capability, are relatively easy to jam or spoof. INS systems are helpful in assisting navigation in GPS-denied environments, however, these systems require periodic GPS updates to remain current. Without these periodic updates, INS systems begin to drift and lose accuracy over time, an unacceptable condition in extended urban combat. Finally, DGPS signals are extremely useful in identifying and correcting interference (either intentional or unintentional) and spoofing but are typically not available in combat theaters. Clearly, a system to enhance or augment existing GPS capabilities in combat environments would be a considerable combat multiplier.

### 5.3 HALE Platform Performance Analysis - GPS Payload

While GPS is clearly an enabling and ubiquitous technology, there are some clear inherent limitations to combat applications. This section will examine possible ways in which to use HALE platforms to increase GPS effectiveness to the military. This section will investigate two general methods of using HALE platforms, first as GPS augmentation and second as an alternative to GPS.

#### 5.3.1 HALE as GPS Augmentation

In their 2005 paper, DAVIS et al[53] proposed a method for augmenting DGPS correction by relaying the signal through a HALE platform which they termed a Stratolite as shown in figure 5.7.

This method has the advantage of providing the increased accuracy of a DGPS correction station to areas where DGPS is not currently available effectively extending the range of a single DGPS station to BLOS.

The paper also addresses some of the challenges to overcome including the determination of the HALE platform "pseudo-ephemeris" and investigates methods such as "standalone GPS, differential GPS, carrier smoothing, and RTK Surveying"[53] The authors found that a real-time kinematic (RTK) algorithm, modified to include tropospheric delay, provided an acceptable platform position solution, however the data refresh rate had to be greater than the standard GPS data rate of 50 bps due to the amount of data to be relayed (1000 bits) and the rapidity with which the platform position changes relative to the user. According to the paper, "the

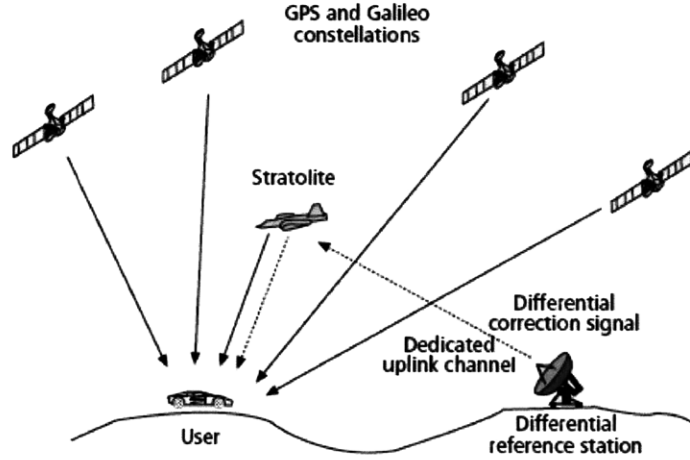


Figure 5.7: HALE Platform Augmentation of Differential GPS Correction Signals; Source: DAVIS et al, "Support Infrastructures Based on High Altitude Platforms for Navigation Satellite Systems," October 2005

transmission rate of the Stratolite can be easily increased, achieving 10 kbit per second (approximately 1000 bits including the differential corrections in 100 ms) which is the requirement of the system." [53] Using HALE platforms in this method can provide significant error correction through the rebroadcast of DGPS correction signals.

A second possibility arises when we consider using HALE platforms to relay standard GPS signals as shown in figure 5.8. This method uses standard GPS receivers onboard the HALE platform, augmented by DGPS correction signals to accurately determine the platform position. In this case, however, rather than simply rebroadcasting the DGPS correction signal, the platform generates its own GPS signal for transmission to the user which can be received at a much higher power than current GPS signals.

Since relaying GPS signals through a HALE platform is essentially a communications link, we can apply the same link equations used in chapter 3. In this case, we will use the values provided in table 5.2 and solve for the new received power. The equation for calculating the received power,  $C$ , is derived from equation (3.1) and is shown in equation (5.3). [33]

$$C = P_t L_l G_t L_s L_a G_r = (EIRP) L_s L_a G_r \quad (5.3)$$

As noted in table 5.2, the receive antenna gain,  $G_r$ , is assumed to be zero decibels. In order to more easily manipulate the parameters, we can convert the equation into decibel form as shown in equation (5.4).

$$C_{dB} = P_t + L_l + G_t + L_s + L_a + G_r \quad (5.4)$$

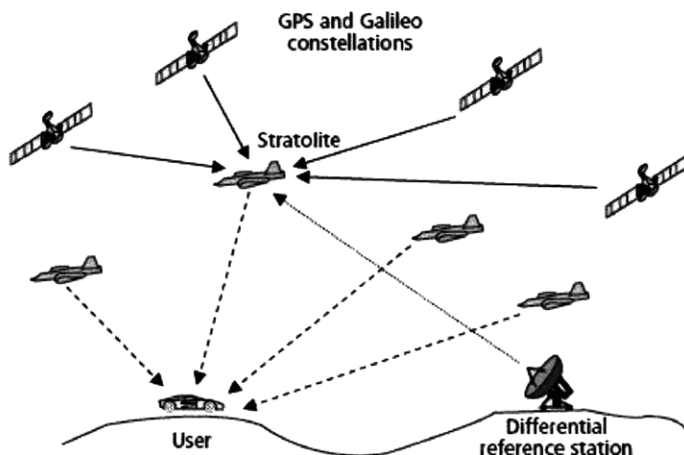


Figure 5.8: HALE Platform Relay of Standard GPS Signals

The values from table 5.2 are valid for  $P_t$  and  $L_l$ , additionally, since our model for rain attenuation (figure 3.3) does not include values for the L1 and L2 frequency (approximately 1 GHz), we will assume the same path loss values as table 5.2. However, it is necessary to calculate new values for the space loss and transmit antenna gain. We will use equation (3.5) for the nominal operating altitude of 85,000 feet this time determining the path length,  $S$ , for elevation angles of  $5^\circ$  and  $40^\circ$  and for each of the two frequencies, L1 and L2. Table 5.3 shows the four values of space loss.

	40° Elevation Angle	5° Elevation Angle
<b>L1 (1,572.42 MHz)</b>	-128.46 dB	-144.14 dB
<b>L2 (1,227.6 MHz)</b>	-126.31 dB	-141.99 dB

Table 5.3: Space Loss Values for HALE GPS Signals (From the Platform to the Ground)

Regarding the new antenna gain, the 13dBi gain available on a GPS satellite does not provide a beamwidth wide enough to cover a brigade’s area of operations. Equations (5.5) and (3.20) provide the formulas necessary to calculate the required beamwidth and thus the required transmit antenna gain.

$$G_t \approx \frac{27,000}{\theta^2} \quad (5.5)$$

Converting 13dBi yields a gain of 19.95 and equation (5.5) tells us that the resulting beamwidth is 36.79 degrees (0.642 radians) and equation (3.20) then gives a footprint radius of  $1.66 \times 10^4$  meters (10.34 miles, 336 square miles). Again referring to section 3.3, our nominal brigade area of operations is 3,861 square miles (35 mile, 56,327 meter radius) and applying



equations (5.5) and (3.20) yields a required transmit antenna gain of 2.45 dB as shown below. This smaller transmit antenna gain will result in a lower received power value, however, the significantly reduced altitude will help to offset this loss.

Beamwidth for HALE GPS antenna:

$$\theta = \frac{F_r}{H_p} = \frac{56,327}{25,908} \quad (5.6)$$

$$= 2.17 \text{ rad} = 124^\circ$$

Required gain for HALE GPS antenna:

$$G_t \approx \frac{27,000}{\theta^2} = \frac{27,000}{124^2} \quad (5.7)$$

$$= 1.76 = 2.45 \text{ dBi}$$

Applying these values for the space loss and transmit antenna gain to equation (5.4), table 5.4 shows the resulting received power again for each of the two look angles at each of the operating frequencies.

Link Parameter	40° Elevation Angle			5° Elevation Angle		
	L1		L2	L1		L2
	SPS†	PPS‡	PPS	SPS	PPS	PPS
Tx Pwr (dB)	14.25	11.25	6.35	14.25	11.25	6.40
Line Loss (dB)	1.0	1.0	1.0	1.0	1.0	1.0
Ant Gain (dB)	2.45	2.45	2.45	2.45	2.45	2.45
Space Loss (dB)	-128.46	-128.46	-126.31	-144.14	-144.14	-141.99
Path Loss (dB)	0	0	0	0.85	0.85	0.85
Rx Pwr (dBW)	-110.76	-113.76	-116.51	-125.59	-128.59	-131.29
Rx Pwr (pW)	8.39	4.20	2.23	0.28	0.14	0.07

Table 5.4: Received Power Values for HALE GPS Signals

Converting the received power from dBW to watts shows the ranges of received power to be between  $8.4 \times 10^{-11}$  and  $7.4 \times 10^{-14}$  watts. These are still very small received power values, however they are between 1,000 and 100,000 times stronger than current GPS signals – a significant improvement in terms of signal availability and reliability.

Table 5.4 assumes that the transmitter power on the HALE platform is the same as that of the GPS satellites. However, if we are interested in increasing the received power even further, we can simply place a higher power transmitter onboard the HALE platform. While it may not be possible for a HALE platform to carry a transmitter with enough power to overcome all ground-based jamming attempts, it is still possible to raise the received signal power thus increasing the likelihood of receiving GPS signals in areas that are currently GPS-degraded or GPS-denied. In this case, we will assume a transmitter power of 100 watts (20 dBW). Table 5.5 shows the resulting received power values:

One can see, from table 5.5, that increasing the transmitter power to 100 watts causes a

Link Parameter	40° Elevation Angle			5° Elevation Angle		
	L1		L2	L1		L2
	SPS†	PPS‡	PPS	SPS	PPS	PPS
Tx Pwr (dB)	20	20	20	20	20	20
Line Loss (dB)	1.0	1.0	1.0	1.0	1.0	1.0
Ant Gain (dB)	2.45	2.45	2.45	2.45	2.45	2.45
Space Loss (dB)	-128.46	-128.46	-126.31	-144.14	-144.14	-141.99
Path Loss (dB)	0	0	0	0.85	0.85	0.85
Rx Pwr (dBW)	-105.01	-105.01	-102.86	-119.84	-119.84	-117.69
Rx Pwr (pW)	31.52	31.52	51.72	1.04	1.04	1.70

Table 5.5: Received Power Values for HALE GPS Signals with Increased Transmitter Power

corresponding received signal power is five orders of magnitude (or 100,000 times) stronger than the signals currently received from GPS satellites.

In addition to the standard P/A and C code signals discussed in section 5.1, there is also the M-code signal specifically designed for military applications. This new signal is designed to improve the anti-jamming and secure access of the military GPS signals. While the M-code is transmitted in the same L1 and L2 frequencies already in use, the new signal is shaped to place most of its energy at the edges (away from the existing P(Y) and C/A carriers).[56] The M-code became operational with the launch of the first of eight Block IIR-M satellites, in September 2005.[57] The M-code is designed to have two modes, full-earth and spot beam. The full-earth signal is currently available with the Block IIR-M satellites and the spot beam mode is scheduled to be launched aboard the Block III satellites in 2013.

In a technical paper published by the Mitre corporation in 2000, the authors state that, "The earth coverage signal will be received at a nominal power level of -158 dBW over the entire surface of the earth viewed by the satellite, and extending into space. The spot beam signal will be received at a nominal power level of -138 dBW." [58] One can see, from table 5.5, that a HALE platform with a transmitter power of 20 dBW has the capability to provide a received signal that is between 100 and 10,000 times stronger than the M-code spot beam.

From the above tables, using HALE platforms to relay GPS signals clearly allows for increased performance in GPS-denied and GPS-degraded areas that the military often faces on the modern battlefield. The most significant drawback to relaying GPS signals through HALE platforms is that each platform must be allocated its own unique C/A and P codes orthogonal to all satellite codes and to other HALE platform codes. The generation of the codes is less of a problem than updating all existing GPS receivers with the new codes, an undertaking that may well prove to be too expensive or time intensive for implementation. Finally, the need to have at least four platforms in view at any give time may also make the system infeasible.

Nevertheless, if the military is willing to invest in solving these logistics problems, augmenting GPS signals with HALE platforms offers the potential for significant performance improvement and is well worth considering.

### 5.3.2 HALE as GPS Alternative

There are two possible uses for HALE platforms as alternatives to GPS signals. The first is to create synchronized beacons on three or more platforms to be used in multilateration, or hyperbolic positioning, to locate the receiver by measuring the time difference of arrival (TDOA) of the signals. This method has the advantage of not requiring unique, orthogonal codes. However, it requires the development and fielding of an entirely new series of receivers and transmitters, does not allow for the messaging and reporting functions of BFT and FBCB2 and still poses the problem of accurate platform position information (though this last problem could be solved with GPS receivers onboard the HALE platforms).

In 2001, Myoung et al[59] proposed a constellation of stratospheric GPS airships designed exclusively for civilian use and independent of any existing GPS architectures as shown in figure 5.9.

In their article, the authors demonstrate that it is possible to triangulate the position of the airships from ground stations, transmit that position data to the airship which then retransmits to the user. User position is then determined using conventional autocorrelation techniques described in the literature.[50, 52] Their research shows that a constellation of stratospheric airships is capable of achieving improved distance root mean square (DRMS) error and thus improved GDOP over existing GPS satellites.

While a stand-alone stratospheric GPS constellation has attractive features for exclusive civilian availability and improved performance, it is unlikely that an entirely new GPS constellation is either feasible or desirable for U.S. military applications. First, because the proposed system requires ground stations to determine the position of each HALE platform which must be designed, built and then placed within a combat theater thus adding an increased element of vulnerability. Second because a military system already exists with a proven performance record and finally, achieving the required global coverage with a constellation of HALE platforms leads to an impossibly large number of airships, both in terms of manufacture and maintenance of the systems. Simply put, there are more feasible alternatives for improving GPS performance that should be explored before deciding to invest in an entirely new system.

## 5.4 Navigation Mission Specific CONOPS

This chapter has proposed four potential uses for HALE platforms either in the augmentation or replacement of the existing GPS system. Each option has unique merits but each also has



Figure 5.9: Configuration of the Navigation System Covering the South Korean Peninsula; Source: Adapted from Myoung et al, "A System Design of Stratospheric Airships for the Navigation in Korea," August 2001

significant drawbacks to feasibility.

As discussed previously, any use of HALE platforms to replace the current GPS system is unlikely in the near future due to the time required for development, increased vulnerability to ground assets in combat areas, and the fact that the current system has a proven record of good performance for military applications.

Additionally, as with GPS satellites, there must be at least four HALE platforms in view at all times in order to provide the navigation solution. Referring to figure 2.10 and the Iraq example used in section 3.3, we again assume an altitude of 85,000 feet and a fifteen degree elevation angle. Given that each HALE platform can cover a circular area of 3,861 square miles (70 mile diameter) and a total Iraqi land area of 168,754 square miles, continuous coverage of Iraq with at least four platforms in view at any given time will require a minimum of 176 HALE platforms.

The most likely short term application of HALE platforms for GPS augmentation is the rebroadcast of DGPS correction signals. This technique requires nothing more than a bent-pipe communications relay to provide significantly improved position and timing accuracy. This

application echoes the analysis conducted in section 3.3 and would require the same number of platforms as required to support communications relay in a given area of operations. Continuing with Iraq as the reference combat theater, twenty HALE platforms are capable of providing regional DGPS support over the country of Iraq.

It has been shown in previous research that it is possible to accurately determine the position of a HALE platform. Extending this research to include the broadcast of GPS signals from a HALE platform, the analysis shows that it is possible to attain significantly improved received signal strength which would translate to improved performance in areas that are currently GPS-denied or degraded such as urban and mountainous terrain and possibly including signal acquisition within buildings. Another alternative to improving GPS performance is to design the HALE platform to transmit the signals at higher frequencies to allow better indoor penetration. Again, due to the requirements to update all existing GPS receivers with the new C/A and P codes and add higher frequency receivers, this application is not likely to be used in the short term. Nevertheless, it is an attractive method for improving GPS signal acquisition and should be considered further.

## 5.5 Chapter Summary

This chapter has demonstrated that HALE platforms designed to augment the existing GPS system are capable of providing improved performance either through relaying DGPS correction signals or by relaying the actual GPS signal. Both applications are feasible but require significant modifications/upgrades to existing GPS receivers.

The advantages and drawbacks to each of the proposed applications are outlined in the various sections but, in general, any use of HALE platforms for navigation payloads will require changes to the existing system. The degree of change required, the timeline for implementation and the cost of the proposed changes will all play an important role in the decision to use HALE platforms to enhance navigation capabilities.

The bottom line is that while HALE platforms do have the potential to improve GPS system performance and there are elements that make HALE platforms attractive for navigation applications, GPS service is not likely to provide the most effective use of HALE platforms for military applications.

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## Chapter 6

# HALE Integration with Current Operations

### 6.1 Existing Military Space Doctrine

According to Field Manual (FM) 3-14: Space Support to Army Operations:

"Space is the newest of the warfighting media, alongside air, land, and sea. The harsh space environment, vast distances, and high speeds of orbiting satellites are all very different from what the Armed Forces deal with in the air, on land, and on or under the sea. Still, many of the principles that successfully guide operations in those environments are applicable to the space medium. The Army is committed to using space to its best advantage. Indeed the advantages are so great that it is clearly worthwhile to overcome the characteristic difficulties of the space environment. Use of space-based capabilities is not only common; it is critical, in Army operations."<sup>[60]</sup>

Clearly, the Army leadership recognizes the importance of space in supporting ground operations and the applications discussed in the preceding chapters are areas of emphasis for the Army leadership as well.<sup>[61]</sup> FM 3-14 also outlines several key elements of Army Space Operations including the control and exploitation of space to enhance land warfighting power. This control and exploitation covers a spectrum of activities from deploying, operating and maintaining U.S. satellites to denying space capabilities to an adversary.<sup>[60]</sup> Due to the vast expanse of space, even orbital space, and the number of satellites in orbit – friendly, neutral and hostile – it is not possible to control all of space all the time. Rather, the military focuses on "maximum control of particular space assets at particular times; this requires the ability to exercise control of any space asset at any time."<sup>[60]</sup> Just as situational understanding is critical to ground operations, space situational understanding is a critical, continuous process that allows the Army to exercise its will at decisive points in support of the joint and Army land campaign. Army

field manual FM 3-0: Operations defines a decisive point as:

"a geographic place, specific key event, or enabling system that allows commanders to gain a marked advantage over an enemy and greatly influence the outcome of an attack. ... Normally, a situation presents more decisive points than the force can control, destroy, or neutralize with available resources. Part of operational art consists of selecting the decisive points that will most quickly and efficiently overcome the enemy center of gravity." [62]

The accepted paradigm of Army operations is that "units develop situations out of enemy contact, maneuver to positions of advantage, engage enemy forces beyond the range of enemy weapons, destroy the enemy with precision fires, and conduct tactical assault at times and places of their choosing. Commanders accomplish this by maneuvering dispersed tactical formations linked by battle command and enabled, in part, by integrated space systems." [60] Another way to describe this operational concept is the OODA loop developed by Air Force Colonel John Boyd (shown in figure 6.1). OODA is the acronym for Observe, Orient, Decide and Act which describes a set of actions that military commanders endeavor to complete faster and better than the enemy thus maintaining initiative and keeping enemy forces off balance.

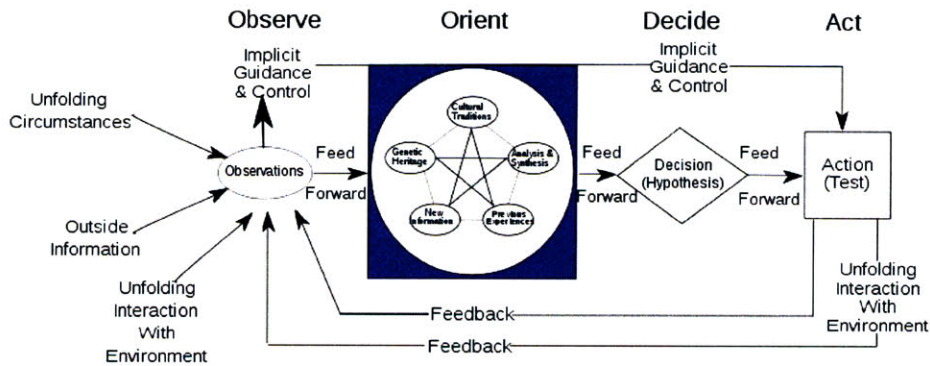


Figure 6.1: Observe, Orient, Decide and Act (OODA) Loop Diagram; Source: [http://en.wikipedia.org/wiki/OODA\\_Loop](http://en.wikipedia.org/wiki/OODA_Loop)

Army space operations capabilities enable the implementation of these concepts by assisting with information superiority, situational understanding and high-tempo operations thus allowing ground forces to see first, understand first, act first and finish decisively – all aspects of the general operational concept and the OODA loop. The list below summarizes some of the key space applications which provide critical support to these ground force capabilities.[60]

- See first: missile warning, space-based ISR, space control (in-theater negation and surveillance), SATCOM



- Understand first: SATCOM, BFT, in-transit visibility, information operations (IO), space control and PVT
- Act first: space control, in-transit visibility, PVT and SATCOM
- Finish decisively: space control, PVT, precision engagement, ISR, continuous battle damage assessment (BDA) and SATCOM

The Army has developed a list of core competencies and FM 1-0: Human Resources Support details the enduring capabilities necessary to achieving these competencies.[63] These enduring capabilities include *a)* Shaping the Security Environment through the constant, conspicuous presence of Soldiers in the field thus building confidence among allies and deterring adversaries; *b)* Prompt Response by quickly limiting enemy achievement of objectives and reversing successes; *c)* Mobilizing the Army through the mitigation of training, logistical, and operational challenges; *d)* Forcible Entry Operations through the use of the en-route mission planning and rehearsal system (EMPRS) allowing Soldiers to exploit optimum access points for enemy engagement and *e)* Sustained Land Dominance by influencing the Army's ability to win and hold territory which hinges not only on Soldiers and firepower, but also on comprehensive situational understanding enabled by space assets.[60] The routine use of space-based capabilities such as GPS, SATCOM and ISR enable ground forces to monitor force buildups, precisely fix the locations of force elements, provide targeting information, find optimum staging areas and lines of communication, and track personnel and material movements throughout theater. Clearly, space-based capabilities play a critical role in sustaining the Army's enduring capabilities.

While current Army doctrine focuses on the application of space-based assets, the Army is also sponsoring studies on HALE platform development through the Army Space Master Plan as mentioned in chapter 1. Army leadership recognizes the inherent importance of space-based assets to ground operations and there is no attempt to replace the unique satellite capabilities with HALE platforms. Rather, the studies focus on adding another layer of coverage and support in the high altitude regime as shown in figure 6.2.[61] To that end, the Army SMDC has been designated as the Army proponent for high-altitude studies as an enabling capability for future operations support.

## 6.2 HALE Operational Considerations

The SMCD is currently involved in conducting a High-Altitude Enabled Capabilities Assessment (HA-ECA). While the ECA has not yet been approved for public release, there are some concepts in the study that we can discuss here based on previously released literature and military doctrine. The ECA looks at ways in which the high-altitude domain can supplement

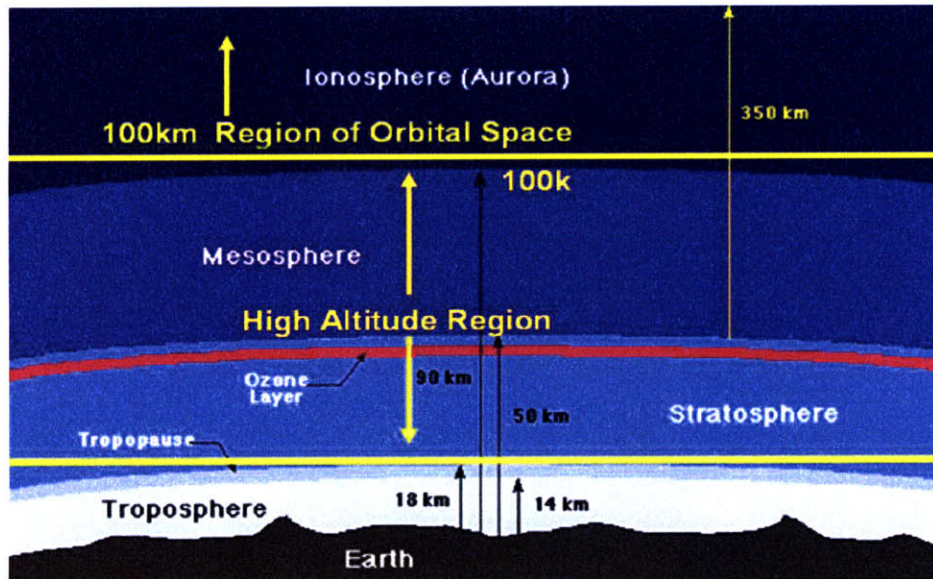


Figure 6.2: Regions of the Earth’s Atmosphere and Orbital Space; Source: U.S. Army Space and Missile Defense Command Battle Lab, Colorado Springs, CO 80916

and integrate satellite-like capabilities into the environment that deliver persistence, long endurance, and increased coverage areas to support Army and Joint Force Commanders in a theater with emphasis at the operational and tactical level. Specifically as these capabilities relate to force enhancement; information operations; command and control (C2); interoperability; and implications for Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel and Facilities (DOTMLPF).[61] Figure 6.3 shows one possible operational view for HALE platform employment.

HALE platforms will use current and advanced technologies to support and expand upon terrestrial, airborne and space-based capabilities. By leveraging the communications, ISR and navigation payloads discussed previously, HALE platform applications will include support to offensive and defensive operations; stability and support operations; civil and host-nation support and Homeland Security. In short, HALE platforms have the potential to support the full spectrum of operations from low- to high-intensity conflicts and across all phases of a campaign from force build-up to redeployment.

Additionally, with the expanded capabilities of HALE platforms providing service in theater, currently available low-altitude and space-based assets could be reassigned to support other tasks or to perform missions to which they are better suited. For example, communications satellites that are operating at or near capacity in support of ground operations in Iraq could be retasked to support world-wide, long-haul communications back to the continental U.S. (CONUS) with HALE platforms handling the BLOS communications load in theater. Additional communications capabilities and the associated network expansion provided by HALE

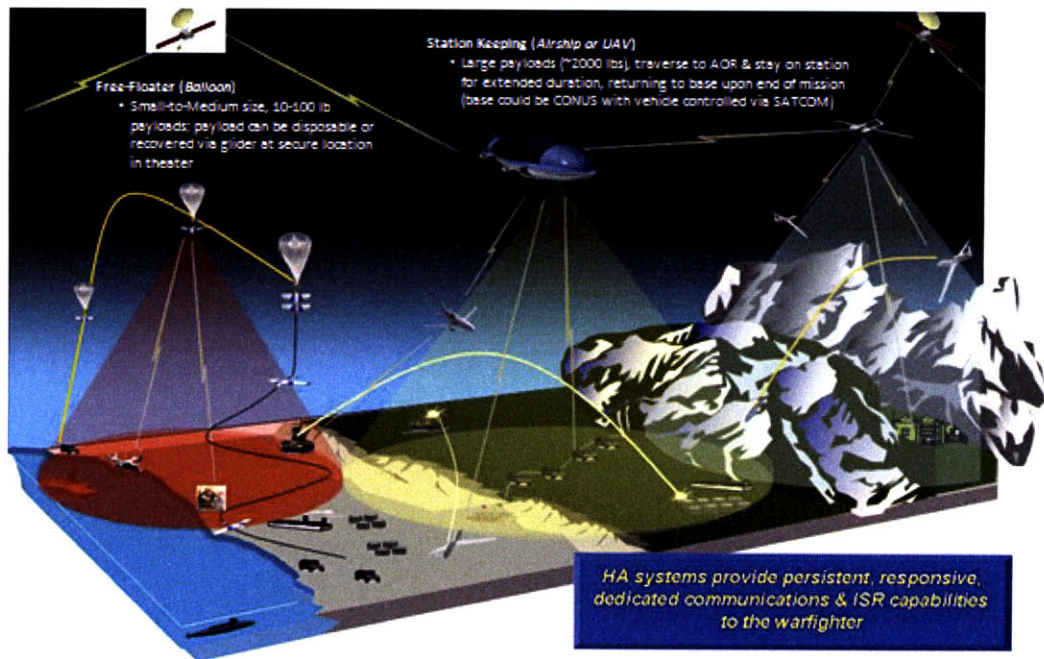


Figure 6.3: HALE Platform Operational View; Source: U.S. Army Space and Missile Defense Command Battle Lab, Colorado Springs, CO 80916

platforms could also allow the military to reduce its dependence on commercial and civil communications satellites; in turn allowing those assets to perform the missions for which they were designed.

In addition to the three application areas discussed in this thesis, the ECA addresses other potential applications of HALE platforms including *a*) Targeting, Detection and Assessment of time-sensitive targets (TST) and high-priority targets (HPT) through extended sensor to shooter linkages, direction of precision munitions, real time effects assessment and immediate focus on follow-on targets; *b*) Weather, Terrain and Environmental Monitoring (WTEM) by detecting surface, near surface and mid-to-upper level weather parameters and phenomena thus assisting comprehensive situational understanding; *c*) Missile Warning and Missile Defense through the use of previously discussed ISR payloads to detect missile launches, predict the impact point and provide advanced warning to threatened units; and *d*) Information Operations (IO) to affect enemy or defend friendly information and information systems by identifying and locating sources of jamming and broadcasting coalition messages to a local or hostile population.[61]

There are several key decisions that Army planners will need to make regarding the command and control and interoperability of HALE platforms and platform implications for DOTMLPF.

Command and control relates both to the platform itself and to the payloads, especially in the cases of multi-modal or multi-functional payloads. C2 also relates to the Army echelon to

which specific platforms should be assigned. In the CONOPS sections of previous chapters, we assume that these platforms will be available to brigade-level commanders; however, there are some significant employment considerations that must be overcome in order for that concept to be possible. Not least among those concerns is the fact that brigades, as they are currently organized, do not have the organic capability to control the platforms or payloads. If a commander has a dedicated asset to position and task based on his priorities but no direct ability to control that asset, then it is of limited utility to him. It is the opinion of the ECA authors that these platforms would be best assigned to Division, Corps or even Army level units in a theater.[61] However, these higher echelon units already have access to a large number of space-based capabilities. If we accept that one of the primary capability gaps exists at echelons below Division, then the Army must make some clear organizational changes to enable brigade commanders to directly control these emerging HALE platforms. Organic control at the brigade level has clear implications for the platforms to have a low burden on ground operators. Note that even without these organizational changes to enable organic control, brigade-level units should still have the ability to request support from HALE platforms operating over their areas of operation.

Interoperability refers to a HALE platform's ability to operate seamlessly with many agencies, forces and levels of command.[61] The level of interoperability among unmanned aircraft systems (UAS) varies widely, from systems that can pass full control of the aircraft and/or payload from one operator to another (such as commonly employed during Predator remote split operations), to systems that can only transmit sensor data to specific recipients. Examples of mission needs for interoperability are operating one UAS through another to extend the range of control, or passing control from one ground control station (GCS) to another. Since mission needs are not always predictable, technologies and employment options that facilitate interoperation provide enhanced flexibility.[61] HA systems will meet all levels of interoperability:

**Level 1** Indirect receipt/transmission of UAS related payload data

**Level 2** Direct receipt of ISR/other data where "direct" covers reception of the UAS payload data by a remote video terminal when it has direct communication with the UAS

**Level 3** Control and monitoring of the UAS payload in addition to direct receipt of ISR/other data

**Level 4** Control and monitoring of the UAS, less launch and recovery

**Level 5** Level 4, plus launch and recovery functions

In general, HALE platform implications for Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel and Facilities (DOTMLPF) should be similar to the requirements for existing and planned conventional UAVs.

**Doctrine:** The overall doctrine will not change in terms of the requirement for commanders to see first, understand first, act first and finish decisively. HALE platforms will provide additional capabilities to accomplish the same goals, therefore existing doctrine should only require minor changes to support effective platform employment.

**Organization:** The preceding paragraphs discuss the potential organization changes required for brigade-level units to effectively employ HALE platforms. In addition to the unit-level organization, HALE platforms will also require platform and payload operators, mechanics and engineers for anomaly resolution.

**Training:** Current, high-altitude, short-duration platforms such as the Global Hawk (section 1.3) require the operators to be licensed pilots to allow Global Hawk to transit conventional airspace. Future HALE platforms will likely have similar requirements and the training programs should closely mirror existing programs.

**Materiel:** In addition to the platform material concerns address in section 2.1.4, future HALE platforms will have specific equipment requirements, such as operator terminals and interfaces, required to successfully operate the platforms. Wherever possible, these platforms should be designed for seamless integration into existing ground control station equipment.

**Leadership and Education:** The unique capabilities afforded by HALE platforms will provide ground commanders with direct access to assets with which they have no prior experience. Leaders who will be using these future HALE systems must clearly understand their capabilities and limitations in order to most effectively employ them. Professional development programs and service school curricula must be updated to train leaders at every echelon. The CONOPS for these HALE platforms are far from set and leaders will discover additional capabilities and uses after the platforms have been used operationally. Training programs should be designed to incorporate these lessons learned from the field.

**Personnel:** Future HALE platforms will likely vary in size and scope with the larger, more complex systems requiring operational and maintenance support from a combination of Soldiers, civilians and contractors. HALE platforms should be designed along the lines of current military systems with maintenance requirements ranging from simple user-level fixes to complex depot-level repair and refurbishment at the end of the platform's programmed life cycle.

**Facilities:** In this case, consideration must be given to storage, transport, deployment and recovery facilities. Due to the physical size requirements of the platforms (section 2.3.1) necessary to operate at very high altitudes, conventional hangars will likely be insufficient for HALE platform storage. Additionally, HTA platforms will require prepared surface runways that may not be available in a combat theater. Section 2.4 discusses some of the CONOPS considerations that may mitigate availability and security considerations for launch/recovery facilities.

The current Army doctrine is designed around flexibility both in terms of leader capabilities

and force development. To that end, the Army should be able to integrate future HALE platform capabilities with minimal changes to the existing doctrine and support infrastructure.

### 6.3 Assessment of HALE Operational Benefits

In order to provide robust performance in all three application areas, the ideal platform constellation will make use of all three aerial sub-layers (low, medium, and high-altitude) as well as space-based platforms. The low and medium-altitude layers (sea-level to 60,000 feet) and orbital space are technologically mature regions and conventional systems are currently supporting military operations. As shown in the literature and by this thesis, the high-altitude layer has room for significant technological advancement.

In all three of the application areas discussed in this thesis, there is a great deal of interdependence among the payload types. For example the increased bandwidth made available through communications network expansion will also facilitate the transmission of ISR imagery data. Navigation payloads operate via radio frequency signals transmitted through conventional communications links and thus are very similar to communications payloads. Section 7.1 will discuss the potential for multi-modal payloads in greater detail.

#### 6.3.1 Communications Payload Operational Benefits

HALE platform enabled communications have the potential to augment multiple military communications networks such as EPLRS radios, BFT, SINCGARS radios and the Tactical Common Data Link (TCDL), discussed previously. All of these systems have compatible military ground terminals greatly simplifying the integration requirements. Army units at every echelon have significant bandwidth requirements for the exchange of voice, imagery and full-motion video data.

There is currently limited information available regarding the specific bandwidth requirements of units deployed to a combat theater. The limited data is due, in part, to the fact that individual unit requirements vary greatly in the course of the mission with routine operations requiring a fairly small amount of data transfer and emergency or high-tempo operations requiring more. Therefore, as a first order estimate of the bandwidth requirements for a typical brigade, we will refer to the Military Information Technology Online article referenced in the introduction to chapter 3, "a Joint Chiefs of Staff document estimates that satcom bandwidth requirements for theater-of-war capability will be 14 Gbps by 2010." [32]. If we assume, conservatively, that a typical "theater-of-war" will consist of one Corps with three Divisions each comprised of three brigades, then the nine brigades and four higher headquarters elements will each require approximately 1.1 Gbps by 2010.

Military SATCOM capabilities will be unable to satisfy the projected demand thus causing

the military to rely on commercial and civil systems to fill the gap. While these commercial and civil systems are able to satisfy the required bandwidth capacity, they are not designed with military security and survivability considerations in mind. HALE assets have the potential to provide the required network expansion while still providing the necessary communications security and survivability for military operations. HALE platforms will be persistent; less vulnerable to low-altitude threats; simplify airspace C2 requirements by operating above controlled airspace; and be mobile, responsive and consistently available to ground commanders.[61]

Operations at and below the brigade level currently require low-capacity, short-duration communications consisting mostly of voice and data and can usually be satisfied by line-of-sight communications links. However, as the Army continues to field new battlefield sensors, units will have an increasing requirement to send large volumes of raw image and video data to their higher headquarters. These sensors will require high-capacity links that are not currently supported by brigade and below communications systems. Additionally, line-of-sight links are limited by operations in complex terrain such as mountainous and urban areas. HALE platforms will provide high-capacity links while extending the range of communications beyond line-of-sight, thus freeing organic communications assets for the critical function of command and control.

A further change in the Army warfighting paradigm in Iraq is the increasing dispersion of small units throughout the local population in order to provide increased security and to develop better relations with the populace. These small patrol bases are often isolated from their higher headquarters for extended periods of time and out of range of LOS communications. Dedicated, persistent HALE platforms will allow these dispersed and isolated units to remain in constant contact without the need for vulnerable ground relay sites.

Chapter 3 demonstrated that HALE platforms are capable of providing communications performance comparable to that of the WGS satellites with power requirements reduced by an order of magnitude due to the shortened transmission path length. This order of magnitude power reduction comes with the added benefit of closing the link with an omnidirectional ground receive antenna. Thus, a HALE communications platform can provide beyond line-of-site communications on-the-move capability at a tenth of the power required by WGS – one of the most advanced communications satellites.

The most significant limitation to HALE communications payloads is their reduced fields of view compared to satellites in geosynchronous orbit. Applications at the tactical level of combat (division and below) mitigate this limitation and help to reduce the bandwidth load currently imposed on orbital communications links. HALE platforms have the potential to provide increased high-capacity links, limit the Army's reliance on unsecure commercial communications and allow units to use their organic communications systems for mission critical command and control.

### 6.3.2 ISR Payload Operational Benefits

Ground commanders at all levels require timely, current intelligence of their areas of operations throughout all phases of an operations. Commanders use this imagery to assist in planning deployments, troop movements, combat operations and redeployments including finding the best locations for patrol bases, planning secure routes for convoy operations and monitoring enemy activities. The persistent ISR and reconnaissance, surveillance and target acquisition (RSTA) performance afforded by HALE platforms will greatly increase situational understanding in highly fluid combat environment and will support the rapid identification and engagement of high-priority targets such as weapons caches, insurgent leaders, IED emplacements.

Chapter 4 focuses primarily on visual and infrared surveillance capabilities; however, as sensor technologies become more advanced, it will be possible for HALE platforms to carry a wide array of payloads such as *a*) laser designators for precision munition guidance; *b*) light detection and ranging (LIDAR); *c*) Synthetic Aperture Radar (SAR); *d*) ground and air moving target indicators (GMTI/AMTI); *e*) mine detection; and *f*) Chemical, Biological, Radiological and Nuclear (CBRN) detection.[61]

There are many Battlefield Operating Systems (BOS) that can directly benefit from dedicated, persistent ISR capabilities including maneuver; indirect fires (artillery); air support; engineering support for mobility, countermobility and survivability; and intelligence collection. HALE enabled ISR will also help the commander observe the battlespace over extended distances in real-time thus greatly increasing the ability to command and control subordinate units.

As demonstrated by chapter 4, HALE platforms offer significantly improved image resolution when compared to their surveillance satellite counterparts. Additionally, the reference earth observation satellite, GeoEye-1, does not have the capability to provide imagery in the infrared spectrum while the proposed HALE platform does provide IR imagery with nadir resolution improved by an order of magnitude over a satellite in LEO (compare figure 4.7 and table 4.1). While the analysis has shown that it is not possible for a single platform – or multiple platforms – to provide continuous surveillance over a brigade’s entire area of operations, these platforms are nonetheless capable of allowing sustained observation of critical areas of interest without the endurance limitation imposed by current high-altitude UAV assets like the Global Hawk. As with communications payloads, HALE ISR payloads will provide additional capability to supply detailed imagery over a wide area thus allowing units to use their organic surveillance assets on targets affecting the immediate, or close, fight.

### 6.3.3 Navigation Payload Operational Benefits

The HA-ECA conducted by the SMDC focuses on the benefits of using HALE platforms for differential GPS correction signals as DGPS is the most practical and realizable application of



HALE platforms for GPS augmentation.[61] The benefits discussed in the ECA largely mirror the conclusions reached in chapter 5 and are summarized below.

- Resistance to GPS jamming
- Accurate blue/red force tracking and reporting
- Precise air navigation, including precision approaches to airports
- Enhanced GPS correction message broadcast

In addition to these similarities, the ECA also proposes three additional benefits of HALE enabled PN&T. Frequency hopping radios and communications networks require a precisely controlled time standard in order to function. The highly accurate atomic clocks onboard GPS satellites combined with their ubiquitous presence make GPS the military time standard. HALE platforms can aid in precision time transfer for improved network synchronization throughout the area of responsibility thus ensuring remote units are able to maintain communications.

GPS payloads combined with the laser designator discussed above can provide additional support to target designation and precision weapon employment. This capability allows for remote target designation without requiring ground personnel to be in direct visual contact with the target thus reducing exposure both to hostile engagement and friendly weapons affects.

Combined GPS and ISR payloads are capable of providing precise and current maps of a given area. Frequently, units plan operations based on outdated maps and imprecise or low resolution imagery. While this limitation does not significantly impact operations in open desert areas, it often results in plan changes for operations in urban areas. The ability to receive current (minutes to hours old) maps and imagery will significantly improve the level of fidelity with which commanders are able to plan their operations and provide a common reference for subordinate units to coordinate their actions.

Of the three applications, navigation payloads offered the lowest potential utility based on the scope of required changes to the existing ground infrastructure. While chapter 5 has demonstrated that HALE platforms designed to augment the existing GPS system are capable of providing received power values that are five orders of magnitude stronger than current GPS satellite signals. Although, these platforms can improve performance either through relaying DGPS correction signals or by relaying the actual GPS signal, both applications required significant modifications or upgrades to existing GPS receivers; thus limiting their utility.

## 6.4 Future Role of Army Space Operations

Current and emerging military satellite capabilities, with respect to the applications discussed previously, are largely derived from Army requirements.[64] However, aside from dictating re-

quirements, Army Space Operations has very little involvement with the actual design, development and acquisition of space-based military assets. Rather, the Army leverages existing technology and capabilities to support the warfighter. While this arrangement works and space operators are able to provide critical space capabilities to enable and enhance land warfare, there is little argument among Army space professionals that increased involvement in the initial stages of capability development will provide a marked improvement in the ability to support ground operations.

The Army is currently leading the military development of HALE platform capabilities with little Air Force involvement in the programs.[61] If the Army is able to maintain this level of involvement, it will be able to gain entry at the ground-level of platform design and development. Current Army doctrine describes "an essential component of the Army's efforts to maximize the contributions that space capabilities bring to land warfare." [60] Further, the Army's "dependence on space will increase in the future as space-based capabilities enable the future force concepts of information superiority, enhanced situational awareness, and high-tempo, noncontiguous operations." [60] There is no doubt among Army leaders and space professionals that space-based capabilities will only increase in importance for future generations of Soldiers. To that end, the Army must increase its influence over space capabilities from the earliest design efforts.

All the work to date suggests that the general mindset is that HALE platforms are an extension of airborne assets. If we instead view HALE platforms as an extension of space assets, then the Army is perfectly positioned to take advantage of this emerging capability.

# Chapter 7

## Summary

### 7.1 Military Applications — Multi-modal Capabilities

Based on the preceding findings for smaller, lighter payloads, this section will discuss options for placing multiple payload types (i.e., Communication/ISR or ISR/GPS) on a single HALE platform. Adding multi-modal capabilities will reduce the number of required platforms and allow for increased mission flexibility without requiring the retasking of additional assets.

#### 7.1.1 HALE Platform Limitations & Candidate Payload Combinations

Referring to section 2.3, recall that the operational altitude is inversely proportional to the atmospheric density which in turn directly affects the size of the platform and the mass of the payload. For the purposes of this thesis, we have assumed an operating altitude of 85,000 feet and a maximum payload weight of 2,000 pounds (907 kilograms). Further, referring to section 2.3.2, the extended eclipse duration has a negative impact on the amount of power that the system is able to supply to the payload and other subsystems. In this case, we will assume an upper limit to the average power requirement of 130 watts (21.1 dBW).

Drawing on the payload sizing results from chapters 3 through 5, table 7.1 summarizes the payload weight and power requirements for each of the three application areas. The weight of the communications payload is taken from the Space Mission Analysis and Design textbook, table 11-26 which states that the total mass for a typical X-band communications subsystem is 20.2 kg (45 lbs) and for a typical Ku-band subsystem is 13.3 kg (29 lbs).[65]. In this case, we will assume that the requirements for a Ku-band subsystem are equivalent to a Ka-band subsystem since the frequencies are similar and the services they provide are identical (table 3.1). Therefore, the total mass of a communications payload with X- and Ka-band capabilities is 33.5 kg (74 lbs).

Since, at the time of this writing direct data for the weight of a GPS payload was not

available, we will derive the GPS payload weight from two sources. SMAD, table 10-10 states that the payload weight typically consists of 15% to 50% of the spacecraft dry weight[25]; in this case, we will assume the average value of 33%. Then from an Air Force data sheet[66], the weight of the GPS block IIR/M satellite is 4,480 pounds (2,217 kilograms). Therefore, the assumed weight of the GPS payload is 1,478 pounds (670 kilograms).

<b>Payload Type</b>	<b>Weight</b>	<b>Power</b>
Communications	74 lbs	87.5 watts
ISR	213.52 lbs	113 watts
GPS	1,478 lbs	100 watts

Table 7.1: HALE Platform Payload Requirements for Primary Military Applications

Then, table 7.2 outlines the total required weight and power for all seven possible payload combinations (assuming a maximum of one of each payload type per platform).

<b>Payload Type</b>	<b>Payload Combination Number</b>						
	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>
Communications	1	0	0	1	1	0	1
ISR	0	1	0	1	0	1	1
GPS	0	0	1	0	1	1	1
Required Weight (lbs)	74	213.52	1,478	287.52	1,552	1,691.52	1,765.52
Required Power (W)	87.5	113	100	200.5	187.5	213	300.5

Table 7.2: HALE Platform Payload Requirements for Primary Military Applications

Note that table 7.2 presents the worst-case scenario as these payload combinations will not add mass and power linearly. Designers will be able to save mass and power by sharing processor and communications subsystem capabilities.

Clearly, the power subsystem is the limiting factor on the ability to place more than one payload on a platform. In order to allow a combination of any two payload types, the platform must be able to provide an average of 240 watts (23.8 dBW). Referring to section 2.3.2, providing 240 watts over a twelve-hour eclipse period requires a battery capacity of  $1.1 \times 10^5$  watt-hours and a total battery mass of 336 kilograms (741 pounds), assuming a specific energy density of 300 watt-hours per kilogram. This additional weight now satisfies the power requirements but puts all multi-modal payload combinations over budget on weight and makes a single GPS payload impractical as well.

As technology progresses and batteries and solar cells become more efficient, HALE platforms will be able to support multi-modal payload combinations. Perhaps by the time HALE technology becomes feasible and reliable, the power generation and storage technology will be

able to provide sufficient average and peak power to operate the combined payloads and other platform subsystems.

### 7.1.2 Potential Mission Enhancements

As mentioned in section 6.3, there is a great deal of interdependence among the three payload types discussed in this thesis. All remotely operated platforms, regardless of their operational altitude, must have at least a rudimentary communications system in order to receive commands and transmit telemetry. Therefore, it is natural to consider payload combinations for multi-modal platform capabilities.

ISR payloads require a robust communications system in order to downlink the imagery and video data it collects. Based on the analysis in section 4.3, our estimated bandwidth requirement is 75.5 Mbps per image. Then from section 6.3.1, we anticipate that a typical brigade will require a bandwidth of 1.1 Gbps by 2010. If HALE communications payloads are designed to satisfy this bandwidth requirement (with room for future expansion – assuming a continued upward trend in bandwidth requirements), then the platform would easily be able to support the downlink of ISR payload data. Combining an ISR payload with a robust communications payload will provide service in two of the three areas in which there are significant capability gaps (figure 7.2).

GPS payloads operate via RF navigation signals and are therefore, by definition, broadcast communications payloads. Adding an additional payload to support voice and data relayed communications seems a natural extension to platform capability. The most significant drawback to this combination is that it more than doubles the payload power requirement (table 7.2) thus significantly increasing the total mass of the system. Again accounting for emerging technology, combining communications and GPS payloads on the same platform will allow for significantly reduced latency currently associated with BFT and FBCB2 transmissions while also supporting BLOS communications and C2 on-the-move.

Chapter 5 discusses ways in which HALE platforms can be used to augment the GPS satellite constellation. One additional application that was not discussed in the chapter but was referenced in section 6.3.3 is the combination of GPS and ISR payloads which would be capable of precisely mapping an area of operations. Increasing the timeliness and precision of overhead maps and imagery would provide a critical advantage to combatant commanders at all echelons. Timely imagery is especially important for operations in urban areas in which trafficable routes and street configurations may change based on hostile roadblocks or destroyed buildings.

The ideal multi-modal payload combination would satisfy all three capability gaps with a single HALE platform. This application requires the resolution of significant mass and power challenges but the resulting advantages to combatant commanders make this concept well worth

pursuing. This concept has one other significant drawback in terms of the level of risk that senior Army leaders are willing to accept. Should the platform be lost – either due to malfunction, accident or hostile act – ground commanders will lose all of their network expansion, persistent surveillance and augmented GPS capabilities. Application of the risk mitigation techniques discussed in section 2.1.5 will help reduce platform vulnerability, nevertheless leaders must give strong consideration to the inherent benefits of HALE platforms versus their survivability limitations.

## 7.2 Known Limitations

This section outlines the known limitations of the preceding research.

### Chapter 2: HALE Platform Overview

1. Section 2.1.1, figure 2.1 clearly shows that the most favorable operational altitude for HALE platforms is between 65,000 feet and 80,000 feet. In this analysis, we chose to focus on an operational altitude of 85,000 feet for survivability reasons, however, even this relatively small altitude increase has significant ramifications in terms of the platform's ability for station keeping, the power and propulsion subsystems and the platform physical size. It is almost universally accepted among HALE designers that future systems will operate between 65,000 feet and 75,000 feet.[61]
2. In section 2.1.2, we assume that nuclear reactors are too heavy and too dangerous for applications within the Earth's atmosphere. However, a paper by Gary Bennett discusses the uses of nuclear power to enable space exploration missions.[67] This research suggests that nuclear power sources may soon be a viable alternative to solar arrays or fuel cells for operations near the Earth's surface.
3. Section 2.1.2 assumes an average 12-hour eclipse period corresponding to the local night but a true requirements analysis will include a more accurate model to account for seasonal and latitude variations. The 12-hour assumption generally accounts for the average case scenario.
4. The threat analysis conducted in section 2.1.5 is limited to an unclassified, open source review of threat capabilities and is therefore incomplete.
5. The AFRL study of system survivability referenced in 2.1.5 focuses primarily on the platform properties, not those of the payload. Further detailed study of payload affects is required to ensure platform survivability.

6. In section 2.4, we assume that future HALE platforms will be available to brigade level commanders. The SMDC proponent for high-altitude studies anticipates that HALE platforms will only be available at echelons above brigade.[61]
7. The assumed five-year operational life (section 2.4) of future HALE platforms is probably too long to be realistic with respect to system cost and reliability; additionally, the assumption of satellite-like operations not requiring the platform to land for periodic maintenance is likely not feasible. It is more likely that operational HALE platforms will be designed for two to three year life cycles with periodic scheduled maintenance between missions lasting on the order of weeks to months. The maintenance conducted at the end of the life cycle can replace worn-out components and refurbish the platform for further use while re-using components that are capable of longer lifetimes – such as solar arrays, which can be designed for a fifteen year operational life.

### **Chapter 3: Military Applications — Communications Payload**

1. Chapter 3 focuses primarily on the relay of mission critical command and control and imagery data, however, there are also military applications for broadcast communications. Information operations (IO) encompasses efforts to attack enemy C2 systems and protect friendly systems that are equally important in the conduct of ground operations. The core capabilities within IO are electronic warfare (EW), computer network operations (CNO), psychological operations (PSYOP), military deception (MILDEC), and operations security (OPSEC). FM 3-13 Information Operations: Doctrine, Tactics, Techniques, and Procedures[68] discusses these broadcast applications in detail.
2. Section 3.1 makes assumptions of several link margin equations in order to provide a generic link budget analysis. In order to develop a truly accurate link margin, designers will need to know exact values for the line loss, transmission path loss and system noise temperature which are system-dependent parameters.
3. At the time of this writing, exact specifications for WGS antenna size and antenna gain were not available. Therefore, section 3.2 antenna values are derived from coverage area assumptions which may not result in accurate transmit power requirements. The values presented in this section provide an order of magnitude estimate only.
4. The parametric relationships of antenna size to payload weight and weight to system cost are only sufficient to provide order of magnitude estimates. As with the link margin, designers will need to know specific system parameters in order to develop an accurate weight budget and system cost.

5. Since HALE platform technology is still in its infancy, there are no established cost estimating relationships for these platforms. The cost estimate in section 3.3 is based on satellite CERs and is therefore less accurate than a cost comparison based on current high-altitude platforms such as Global Hawk.

#### **Chapter 4: Military Applications — ISR Payload**

1. Sections 4.1 and 4.3 do not discuss any platform or camera stabilization requirements. The theoretical ground resolution achievable from a HALE platform depends on the stability of the payload and station keeping capabilities of the platform. Without stabilization, the images will have significantly reduced resolution and thus reduced utility.
2. While figure 4.3 describes the atmospheric transmission characteristics of the Earth's atmosphere, there is no specific discussion of the affects of atmospheric distortion, such as scintillation, on image resolution. Truly accurate resolution modeling must go beyond the theoretical capabilities and account for these distortions.

#### **Chapter 5: Military Applications — Navigation Payload**

1. Section 5.3.1 assumes that using HALE platforms to relay GPS signals at a higher power would require assigning independent C/A and P(Y) codes to each HALE platform in order to avoid corruption of the satellite timing and ephemeris data. It may be possible to allow the HALE platform to modify the received satellite codes with new data for the platform and rebroadcast the modified codes. This course of action may allow currently fielded GPS receivers to recognize HALE codes as if they were original satellite codes thus avoiding the need to field new receivers with HALE specific codes.
2. The M-code spot beam, scheduled for launch on the BPS Block III satellites (section 5.3.1) is designed to assist the receiver to establish initial synchronization with the satellite. Once the receiver has identified the signal, it is easier to maintain synchronization even with a lower power, earth coverage signal through the use of code correlation. This chapter does not discuss the feasibility of using HALE platforms to assist in satellite-receiver synchronization; an additional GPS augmentation technique that may be worth exploring.

### **7.3 Future Work**

Potential avenues of future research are based largely on the known limitations outlined in the previous section. These areas include *a)* a more detailed analysis of technical requirements to ensure HALE platform feasibility; *b)* an examination of the affects of payload properties on



platform survivability; c) the development of more accurate CERs for HALE platforms; d) a detailed discussion of ISR payload requirements including camera stabilization and the affects of atmospheric distortion on image resolution; and e) an analysis of the feasibility of relaying GPS signals through HALE platforms without corrupting the satellite timing and ephemeris data.

There can be little doubt of the military utility of HALE platforms to support and expand upon terrestrial, airborne and space-based capabilities by adding another layer of coverage and support in the high altitude regime. However, any discussion of HALE platform utility necessarily depends upon the technical feasibility of such a platform. Section 2.1 outlines a number of engineering challenges that must be solved in order to establish HALE feasibility. This thesis assumes the future availability of HALE technology in order to focus on potential applications; however, the future of HALE platforms is far from certain and significant work remains before the potential of high-altitude platforms can be realized.

## 7.4 Conclusions

Chapter 3 demonstrated that HALE platforms are capable of providing communications performance comparable to that of the WGS satellites with significantly reduced power requirements due to the shortened transmission path length. These power savings consequently resulted in a lower system cost although the resultant cost savings were not as high as anticipated due to the limitations of the CERs used. The most significant limitation to HALE communications payloads is their reduced fields of view compared to satellites in geosynchronous orbit. Applications at the tactical level of combat (division and below) mitigate this limitation and help to reduce the bandwidth load currently imposed on orbital communications links.

Aside from communications network expansion, the other important contribution of HALE platform capabilities is in ISR/RSTA as demonstrated by chapter 4. HALE platforms offer significantly improved image resolution when compared to their surveillance satellite counterparts. While the analysis has shown that it is not possible for a single platform – or multiple platforms – to provide continuous surveillance over a brigade’s entire area of operations, these platforms are nonetheless capable of allowing sustained observation of critical areas of interest without the endurance limitation imposed by current high-altitude UAV assets like the Global Hawk.

Of the three applications, navigation payloads offered the lowest potential utility based on the scope of required changes to the existing ground infrastructure. While chapter 5 has demonstrated that HALE platforms designed to augment the existing GPS system are capable of providing improved performance either through relaying DGPS correction signals or by relaying the actual GPS signal, both applications required significant modifications or upgrades to existing GPS receivers.

Taking an intuitive, qualitative view of the future direction of communications, ISR and

GPS technology, figure 7.1 shows the desired improvement in each of the application areas and anticipated pareto frontiers. Due to the inherent limitations of UAV and satellite technology, it appears that HALE platforms offer the best opportunity to maximize performance in each of the military application areas.

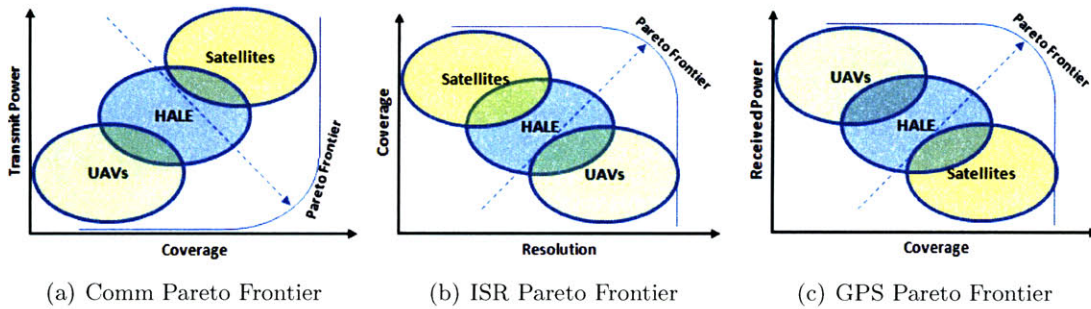


Figure 7.1: Intuitive Interpretation of Communications, ISR and GPS Payload Pareto Frontiers

The advantages and limitations of multi-modal payloads, as discussed in section 7.1, are primarily dependent upon the current capabilities of the power supply system. Additional technological advances in the areas of power generation and storage are required in order to make multi-modal payloads a viable alternative.

We once again return our attention to the question posed by the Army Space Master Plan, "Where should the Army invest in near-space and high-altitude, long-endurance platforms as a lower cost, more responsive alternative to space platforms if they prove technically feasible?"[1] Having identified the existing user needs (figure 7.2) and explored the capabilities and limitations of HALE payloads, the answer is clear. The Army should invest in developing the technical feasibility of HALE platforms for use with communications and ISR payloads.

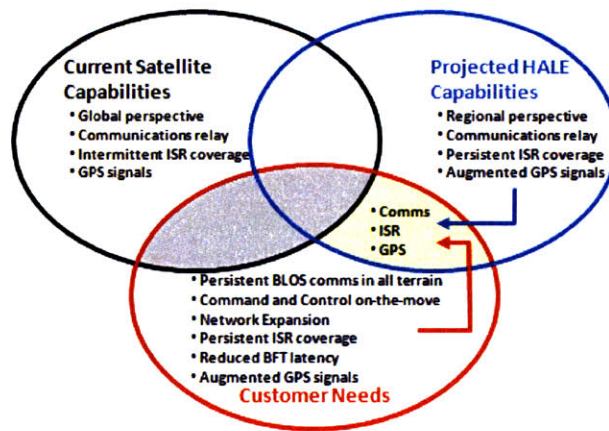


Figure 7.2: Expanded Ven Diagram of Current Capability Gaps between Satellites and Military User Requirements

# Appendix A

## Subsystem Governing Equations

This Appendix details some of the key governing equations required for sizing the various platform subsystems discussed in Section 2.1 (Design Drivers and Engineering Challenges).

### A.1 Power Subsystem Sizing

To begin sizing the power system for the HALE platform, one must first determine the mission life and average power requirements of the platform by considering the end-of-life (EOL) power requirements of the system rather than the beginning-of-life (BOL) requirements. Sizing for EOL power requirements allows designers to account for solar array degradation over the life of the system, however EOL designs will cause excess power generation during BOL operations and the system must be designed to account for and dissipate the excess power to avoid thermal problems.[24] Initial power budgets are achieved by estimating the power requirements for the payload and the platform bus, sizing the batteries and estimating the power system degradation over the mission life.[25]

Next, one must determine the total power generation requirements of the solar arrays, based on the initial design budget, as follows:[24]

$$P_{sa} = \frac{\left( \frac{P_e T_e}{X_e} + \frac{P_d T_d}{X_d} \right)}{T_d} \quad (\text{A.1})$$

Where  $P_{sa}$  is the power generation requirement of the solar arrays during daylight,  $P_e$  and  $P_d$  are the platform's power requirements during eclipse and daylight, respectively,  $T_e$  and  $T_d$  are the lengths of the eclipse and daylight periods,  $X_e$  is the efficiency of the paths from the solar arrays through the batteries to the loads and  $X_d$  is the efficiency of the path directly from the solar arrays to the loads. Efficiency values during eclipse and daylight hours depend on the type of power regulation used.

Once we have determined the power generation requirements, we can select the type of

Appendix A. Subsystem Governing Equations

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solar cells to use based on energy-conversion efficiency and radiation-degradation sensitivities ensuring to account for efficiency losses inherent to panel assembly; referred to as inherent degradation,  $I_d$  (elements of inherent degradation are shown in table A.1). The other source of inefficiency in solar cells is shadow losses caused by platform appendages; proper design of the platform layout can minimize these losses.

$I_d$ Element	Nominal	Range
Design & Assembly	0.85	0.77-0.90
Temperature of Array	0.85	0.80-0.98
Shadowing of Cells	1.00	0.80-1.00
Inherent Degradation	0.77	0.49-0.88

Table A.1: Elements of Inherent Solar Array Degradation; Source: SMAD Chapter 11.4, Table 11-36

The governing equations for sizing the solar arrays are shown below.[24]

$$P_{BOL} = P_o I_d \cos \theta \tag{A.2}$$

Where  $P_{BOL}$  is the beginning-of-life power generated,  $P_{ideal}$  is the ideal solar cell output per unit area and  $\theta$  is the sun incidence angle between the vector normal to the surface of the array and the sun line. The ideal solar cell output,  $P_o$ , is simply the product of the solar cell efficiency and the solar constant (1,367 W/m<sup>2</sup> at 1 AU) as shown in equation (A.3)

$$P_{ideal} = 1,367 * \eta_{sa} \tag{A.3}$$

Where  $\eta_{sa}$  is the solar array efficiency. Table A.2 shows the efficiencies of three of the most common types of solar cells.

Solar Cell Type	Efficiency
Silicon (Si)	14.8%
Gallium-Arsenide (GaAs)	18.5%
Multijunction	22%

Table A.2: Common Solar Cell Efficiencies; Source: SMAD Chapter 11.4, Table 11-34 (excerpt)

The life degradation ( $L_d$ ) of the solar cells occurs due to thermal cycling and radiation exposure and is found by equation (A.4).

$$L_d = \left( 1 - \frac{\text{degradation}}{\text{year}} \right)^{\text{mission life}} \tag{A.4}$$

And the array's performance per unit area at the end-of-life is shown in equation (A.5):

$$P_{EOL} = P_{BOL}L_d \quad (A.5)$$

Finally, the solar array area required to support the platform's power requirement can be found using equation (A.6):

$$A_{sa} = \frac{P_{sa}}{P_{EOL}} \quad (A.6)$$

Once the solar array requirements are determined, we must also size the energy storage system (typically batteries) to provide power during peak power demands and eclipse periods. Elements that factor into the determination of the system energy storage requirements are *a*) mission length; *b*) eclipse frequency and duration; *c*) voltage and current requirements *d*) depth of discharge *e*) duty cycle and *f*) charge/discharge cycle limits. Next we select the type of battery to be used based on specific-energy density and efficiency and determine the size of the batteries (battery capacity).[24] The battery capacity ( $C_r$ ) is determined with equation (A.7).

$$C_r = \frac{P_e T_e}{(DoD)N_b \eta_b} \quad (A.7)$$

Where  $N_b$  is the number of batteries in the system,  $\eta_b$  is the transmission efficiency between the battery and the load,  $DoD$  is the depth of discharge and  $C_r$  is measured in Watt-hours (for battery capacity in Amp-hours, divide by the bus voltage).

The final step in designing the power system is to design the power distribution, control and regulation system by considering the electrical load profile, centralized versus decentralized control and the fault protection subsystem. Critical to this process is managing excess power from the solar arrays during BOL operations through a peak-power tracker (PPT) or a direct-energy-transfer (DET) system. PPT systems extract the exact amount of power required to operate the system and charge the batteries while DET systems dissipate excess power through external shunt resistors.[24]

## A.2 Thermal Control Subsystem Sizing

The Stefan-Boltzmann equation determines the radiating power of a radiator which is given by equation (A.8).

$$Q_r = \epsilon_r \sigma A_r T_r^4 \quad (A.8)$$

Where  $\epsilon_r$  is the radiator emissivity,  $A_r$  is the surface area of the radiator,  $T_r$  is the absolute ra-

## Appendix A. Subsystem Governing Equations

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diator temperature in (K) and  $\sigma$  is the Stefan-Boltzmann constant ( $5.67051 \times 10^{-8} \text{ W/m}^2\text{K}^4$ ).

To simplify equation (2.8), we assume that the net  $Q_{MLI}$  is negligible. This simplification is conservative for spacecraft and particularly valid for HALE platforms operating in the more benign temperature environment of the Earth's stratosphere. Substituting equation (A.8) for  $Q_{radiator}$  and  $q_{external}A$  for  $Q_{external}$ , the simplified radiator heat balance is shown in equation (A.9).

$$Q_{internal} + q_{external}A = \epsilon\sigma AT^4 \quad (\text{A.9})$$

Where  $q_{external}$  is the external environmental heat load on the radiator per unit area and all other quantities are as described above.

The external environmental load,  $q_{external}$ , is composed of the following individual components (equation (A.10)).

$$q_{external} = q_{solar} + q_{albedo} + q_{EarthIR} + q_{backload} \quad (\text{A.10})$$

Subsequently, the incident solar energy on the face of a platform ( $q_{solar}$ ), the heat input from the Earth's albedo ( $q_{albedo}$ ) and the absorbed Earth IR heat load per unit area ( $q_{EarthIR}$ ) can be calculated using equations (A.11) through (A.13).

$$q_{solar} = A_p K_{solar} \cos \beta \quad (\text{A.11})$$

Where  $A_p$  is the surface area of the platform face,  $K_{solar}$  is the solar constant in the vicinity of the Earth ( $1367 \text{ W/m}^2$ ) and  $\beta$  is the angle between the Sun and the vector normal to the platform face.

$$q_{albedo} = \alpha I_{solar} \rho_{albedo} F_{albedo} \quad (\text{A.12})$$

Where  $\alpha$  is the absorptivity of the radiator,  $I_{solar}$  is the intensity of the solar flux,  $\rho_{albedo}$  is the Earth's albedo and  $F_{albedo}$  is a geometrical factor that accounts for the direction of the radiator relative to the Sun.

$$q_{EarthIR} = \epsilon I_{EIR} F_{EIR} \quad (\text{A.13})$$

Where  $\epsilon$  is the emissivity of the radiator,  $I_{EIR}$  is the intensity of the Earth IR flux, and  $F_{EIR}$  is a geometrical factor that accounts for the direction of the radiator relative to the Earth.

The geometrical factors  $F_{albedo}$  and  $F_{EIR}$  for common altitudes and attitudes can be found in look-up tables in various spherical geometry texts (including SMAD Appendix D) and are not calculated here.

Additionally, it is beyond the scope of this thesis to calculate the radiative backload from

other platform surfaces (i.e., the  $q_{backload}$  component of  $q_{external}$ ) as that calculation requires geometric modeling of the individual platform configuration in question. In general, effective heat radiation requires that the surface upon which a radiator is mounted must not be blocked by other platform surfaces. Therefore, radiators are usually located on surfaces that have a clear view to space.

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