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Applications for NAVY UNMANNED AIRCRAFT SYSTEMS

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Prepared for the United States Navy
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Preface

This monograph presents the results of a limited study performed by the RAND Corporation to evaluate the Navy's ongoing and proposed unmanned aircraft system (UAS) programs and to describe the most promising applications of UASs to operational tasks. Completed in September 2008, the study does not provide an exhaustive look at all DoD missions for UAS. However, it does discuss the strengths and weaknesses of manned and unmanned aircraft for certain missions of importance to the Navy. We emphasized traditional Navy missions rather than Navy contributions to irregular warfare, though we included an examination of a few nontraditional missions such as counter-piracy. The study was sponsored by the Office of the Chief of Naval Operations, Assessment (OPNAV N81). It should be of interest to the Navy, the Office of the Secretary of Defense, and Congress.

This study was conducted within the Acquisition and Technology Policy Center of the RAND National Defense Research Institute, a federally funded research and development center sponsored by the Office of the Secretary of Defense, the Joint Staff, the Unified Combatant Commands, the Navy, the Marine Corps, the defense agencies, and the defense Intelligence Community.

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Background

There has been tremendous growth in demand for unmanned aircraft systems (UASs) by the United States military since 2001. The United States Navy is making large investments in a number of major UAS programs, including Broad Area Maritime Surveillance (BAMS) UAS, the Unmanned Combat Aircraft System Demonstrator (UCAS-D), the Fire Scout vertical takeoff/landing tactical UAS (VTUAS), and the Small Tactical/Tier II UAS (STUAS/Tier II UAS). Navy OPNAV N81 asked RAND to provide an evaluation of the Navy's ongoing and proposed UAS programs and to describe the most promising applications of UAS to operational tasks. These assessments were to include arguments for and against using manned vehicles to perform the same tasks as unmanned vehicles, where appropriate. Completed in September 2008, the study does not provide an exhaustive look at all DoD missions for UAS. It does, however, discuss the strengths and weaknesses of manned and unmanned aircraft for certain missions of importance to the Navy. We emphasized traditional Navy missions rather than Navy contributions to irregular warfare, though we examined a few nontraditional missions, such as counter-piracy.

Methodology

We evaluated current UAS applications and applications for future UASs that have been advocated in recent studies and U.S. government published roadmaps (Ehrhard, 2008; OSD, 2005, 2007; O'Rourke, 2006). We characterized UASs currently in use or development by the Navy, Air Force, and Army. We relied on information gathered during visits to the contractors that design, develop, and manufacture these systems to aid us in our characterization. Our primary focus was on applications for Navy UASs in the 2015–2025 time frame, when several of them will have reached initial operating capability and the Navy will potentially have an operational unmanned combat aircraft system. We contrasted the characteristics of these UASs with those of similar manned aircraft and identified potential advantages and disadvantages of the UAS in military applications.

For each Navy UAS program, we then identified the applications that best leveraged the advantages offered by UAS compared with similar manned aircraft, and when possible, we identified ways of mitigating potential disadvantages. We used operational performance as our criterion rather than financial cost.

This research drew on results from several recent studies of UASs conducted within RAND Project AIR FORCE. These included a study of future roles and missions of Air Force UASs led by James Chow, and multiple studies of maritime surveillance with Global Hawk led by Sherrill Lingel.

Advantages and Disadvantages of Unmanned Aircraft Systems

UASs tend to have advantages for applications that are too "dangerous," "dirty," "dull," "demanding," or "different" to be performed by manned aircraft:

- *Dangerous* applications are those involving a high potential for death or injury to the crew. The advantage of UASs in these applications is that the crew is displaced from the threat.
- *Dirty* applications are a subset of dangerous applications that include operating in an environment with dangerous chemical, biological, radiological, or nuclear materials.

- *Dull* applications are repetitive tasks that lend themselves to automation and would otherwise lead to crew fatigue. An advantage of UASs in these applications is that crew may be rotated without landing the aircraft.[1]
- *Demanding* applications include those that place high demand on the crew. For example, crew may be the limiting factor in high-endurance applications or those subjecting the aircraft to high g-forces. Demanding applications may also include those that place high demands on aircraft performance. Eliminating the weight and volume associated with a crew provides additional degrees of freedom in aircraft design, potentially enhancing aerodynamic performance.
- *Different* applications are those that are not feasible for manned aircraft. For example, small hand-launched UASs can provide quick input to organic intelligence, surveillance, and reconnaissance (ISR) and aid in providing situational awareness for Marines in the field; it may be difficult or infeasible to provide rapid access to these capabilities using manned aircraft.

There are also potential disadvantages in using UASs. We found that the most important disadvantage stems from their reliance on communication resources to connect the UAS to offboard operators and analysts.[2] High data rates, especially, are associated with sensors that provide imagery for ISR applications and may be on the order of tens to hundreds of megabits per second. For UASs, this information must be transmitted to offboard crew, and the data links may be vulnerable to attack. This is especially true for satellite communication

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1 It may be possible to cut back crew requirements for applications that are well suited to automation. For instance, a UAS operating as a communication relay may not require a dedicated pilot at all times. It might be possible, for example, to have one pilot controlling many communication relays except during takeoff and landing.

2 We also evaluated their dependence on GPS for position, navigation, and timing. We found that UAS and manned aircraft reliance on GPS is similar: Both rely on it for navigation, precision targeting, sensor and antenna pointing, and synchronization. Manned aircraft crew can aid in these tasks using their senses and decisionmaking capabilities. To some extent this can be done on a UAS by adding sensors and onboard processing capability, but it places additional burden on communication resources.

uplinks, which are vulnerable to noise jamming and kinetic threats. Also, applications in high-threat environments may require stealth for aircraft survival, and the active emissions necessary to connect the UAS to offboard crew make the UAS more susceptible to detection and, ultimately, attack. It is often desirable to send information from manned aircraft, too, but there is the option of exploiting the data onboard the aircraft—or at least filtering what information must be sent. Data-compression techniques can reduce the data-rate requirements, but at the expense of increased distortion in the data products. Technologies such as automatic target classification can also help reduce the data-rate requirements, but many of these technologies are still only in the laboratory and not yet ready for the battlefield.

Recommended Applications for Navy Unmanned Aircraft Systems

We made a detailed evaluation of options for an operational Navy Unmanned Combat Aircraft System (N-UCAS) and a broader evaluation of applications for other Navy UAS.

Airborne communication relays mitigate kinetic and noise jamming threats to satellite communication uplinks by providing an alternative set of links either directly to surface-based terminals or to satellites beyond the range of threats. They are less susceptible to noise jamming threats than satellites because an adversary has to detect, geolocate, and track the airborne asset and operate within line of sight of the receive antenna main beam. High-altitude, long-endurance UASs are particularly well suited to communication relay applications because high altitude extends the line of sight (LOS) and long endurance allows the communication link to be sustained for long durations. For these reasons, and since UASs are often highly dependent on satellite communication resources, we feel that communication relay is an important application for Navy UASs. We developed an operational concept for a theater relay system to provide communication resources to fleet assets, including other UASs. This system consists of two air-to-air links and an air-to-satellite link to provide connectivity to a satellite beyond LOS of jamming and kinetic threats. We also evaluated the design characteristics of communication relay equipment that would be needed.

We made a detailed evaluation of several potential applications for an operational N-UCAS that would follow successful demonstration of carrier capabilities for a low-observable (LO) design using UCAS-D (expected to be complete by fiscal year 2013).[3] The LO characteristics of UCAS-D make it well suited to applications in high-threat environments. Long-range and endurance attributes may give it advantages over manned aircraft, such as F-35C, for similar applications. However, as noted, reliance on communication resources is a disadvantage compared with manned aircraft. For this reason, we evaluated the communication requirements and examined the vulnerabilities that may result. We feel that development of low probability of intercept (LPI) tactical data links can mitigate many potential vulnerabilities and enable N-UCASs to support applications in high-threat environments. While there are ongoing efforts to develop LPI tactical data links—for instance, tactical targeting and networking technology and multifunction airborne data link—those efforts are focused on the needs of manned aircraft, not UASs. These observations led to our recommended applications for N-UCASs, but they are not the only observations that are described in detail in the monograph. Our evaluation of applications for the N-UCAS is summarized in the stoplight chart of Table S.1.

The Fire Scout VTUAS has an operational footprint that is a fraction of that of the multipurpose MH-60-class helicopters; it can operate from, and provide the UAS advantages to, surface ship platforms. Until recently, the Navy's testing and development of Fire Scout was closely tied to the evolution of the Littoral Combat Ship (LCS) program. Because of serious delays in the LCS program, the Navy decided to conduct operational testing on another vessel. With an electro-optical turret equipped with a laser designator and a small

3 By low-observable, we mean that passive signature reduction techniques, such as fuselage shaping and the use of radar-absorbent materials, may be applied. However, we do not mean to exclude the possibility that active signature reductions would also be applied.

Table S.1
Evaluation of Applications for the N-UCAS

Application	Advantages for N-UCAS	Disadvantages for N-UCAS	Comments
Penetrating strike	Range, stealth, no danger to crew	Vulnerability of C2 data links	LPI data links could reduce vulnerability
Penetrating ISR	Range, stealth, no danger to crew	Vulnerability of data links for ISR products	LPI data links could reduce vulnerability
COMINT collection	Stealth	Large number of antennas required is detrimental to stealth	Useful secondary mission for high-threat environment
ELINT collection	Stealth	Antennas required are detrimental to stealth	Low data rate required for transmittal of data
Air-to-air combat	Range, stealth, no danger to crew, g-forces	Latency; vulnerability of C2 and sensor data links	Not useful in dogfight; manned/unmanned less ambitious
Airborne electronic attack	Stealth, range	Self-jamming; POD weight/power; LO compromised	Potentially useful in niche applications
SEAD	Close approach reduces kill-chain	Limited airborne electronic attack capabilities	Weaponized platform for niche applications
Close air support	Range, stealth		UASs already do it
CBRN detection	Range, stealth, no danger to crew	Accommodating sensors in stealth design and decontamination of aircraft are challenging	Sample collection may be good application for STUAS

NOTE: See the Abbreviations section for all acronyms.

surface search radar, the MQ-8B could provide a wide spectrum of surface vessels with an over-the-horizon maritime surveillance capability. Further, the Fire Scout has sufficient payload capacity to provide for a modest armament. Armed variants of Fire Scout could be used to interdict in a variety of small-boat threats. The Army plans to procure a variant of Fire Scout as its Class IV UAS for a Future Combat System (FCS) program during the middle of the next decade. Also, the U.S. Coast Guard is interested in Fire Scout as a sea-based surveillance platform. This provides the opportunity for a rather robust production run of a UAS vehicle family and may provide the Navy, the Coast Guard, and the Army with lower overall production costs.[4]

The A160T Hummingbird is a VTUAS under development by the Defense Advanced Research Projects Agency (DARPA) and Boeing. Flight tests are scheduled through the end of the decade. Although the aircraft is much larger than the Fire Scout with a footprint closer to that of the MH-60, it is expected to have higher altitude and payload performance.

The goal of the Navy and Marine Corps Small Tactical UAS/Tier II UAS (STUAS/Tier II UAS) program is to provide persistent ISR support for tactical-level maneuver decisions and unit-level force defense and protection for Navy ships and Marine Corps land forces. For the Navy, it may provide UAS operational capabilities to surface ships that are unable to support a larger platform such as Fire Scout. ScanEagle is one potential candidate for STUAS; it offers limited ISR capabilities in a high-endurance platform that can be launched and recovered from a wide spectrum of ships. STUASs may also be useful in chemical, biological, radiological, and nuclear (CBRN) applications—in particular, for detection, plume tracking, and collection of samples for offboard analysis after CBRN materials have been released due to an attack on a suspected CBRN weapon site.[5]

Study Recommendations

We recommend communication relay as an application for Navy UASs. Communication relay mitigates kinetic and noise-jamming threats to

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[4] The FCS program was cancelled prior to publication of this monograph.

[5] Boeing and a team of U.S. biodefense companies were awarded an $8.2 million contract by the Defense Threat Reduction Agency (DTRA) in 2006 to develop a biological combat assessment system for ScanEagle ("ScanEagle to Detect Biological Agents," 2006).

satellite communication uplinks. This will benefit fleet assets that are highly dependent on satellite communication resources, including other UASs. The BAMS UAS is particularly well suited to the communication relay application because of its high-altitude and long-endurance attributes, and the Navy has considered this application for the BAMS UAS.[6] However, a communication relay payload would compete for size, weight, and power needed for BAMS UAS sensors to support its primary role in providing ISR. This could be addressed by developing a modular payload capability for the BAMS UAS so that it could either be configured with multiple sensors to support its primary ISR roles or configured with a communication relay and fewer sensors for a more limited ISR role. Another alternative is to use the BAMS UAS for the air-to-air links only, and another platform, possibly a manned platform, for the air-to-satellite link. The air-to-air links require much less payload power than the air-to-satellite link, making more power available for sensors.

We recommend that the Navy support efforts to develop robust, LPI tactical data links, and to orient those efforts to meet the specific needs of the UAS. Development of this technology could be an enabler for LO UASs, such as the N-UCAS.

We recommend penetrating strike, suppression of enemy air defenses, close air support, and electronic intelligence (ELINT) collection as primary applications for the N-UCAS. We recommend that the Navy not invest in developing air-to-air combat capability for the N-UCAS because it will likely be less effective than manned aircraft in this application (in the 2015–2025 time frame). We also recommend that the Navy not invest in CBRN detection applications for N-UCASs because of the challenge of incorporating a suitable sensor into a stealthy design, and challenges associated with decontamination of the UAS upon recovery on an aircraft carrier. CBRN detection and tracking may be a promising application for other UASs, such as STUAS, but not for N-UCAS specifically. We see limited utility for the

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[6] Low-rate initial production vehicles are likely to include a basic communication relay package that leaves space for spiral development of a more capable communication relay package. See Richfield, 2007.

N-UCAS in penetrating ISR, comunication intelligence (COMINT) collection, and airborne electronic attack applications.

If the UCAS-D program is successful in addressing many of the challenges of operating UASs from carriers, we recommend the Navy consider development of nonstealthy, carrier-capable, medium-altitude, and medium-endurance UASs. The Army and the Air Force have realized tremendous operational advantages with this class of UAS (though they are not carrier-capable) for strike missions against time-sensitive targets. Operating similar UASs from carriers would be particularly advantageous in conflicts where carriers can be among the first assets on scene to project power and where access to air bases is limited. While the N-UCAS could be used for the same applications, it may not be the most cost-effective platform when operating in a benign environment where LO characteristics are not needed. If the UCAS-D program is successful in addressing the challenges of operating UASs from carriers, we recommend the Navy consider a mix of stealthy N-UCASs and potentially lower-cost nonstealthy UASs to meet its mission needs.

The Navy and the Marine Corps are currently leasing STUAS-class aircraft. For the Navy, the STUAS could support maritime interdiction operations by providing information about numbers of personnel aboard a vessel. It could be used to extend LOS communication range or to track vessels in support of counter–small boat attack or counter-piracy missions. STUASs may also be useful in CBRN applications, in particular for detection, plume tracking, and collection of samples for offboard analysis after CBRN materials have been released due to an attack on a suspected CBRN weapon site. Larger and more-capable platforms designed for a broader range of applications, such as Fire Scout, could be used for many of the applications envisioned for the STUAS. However, they would not operate from the same broad range of Navy ships and may not be cost-effective in these specific applications. If these applications are important to the Navy, then the STUAS/Tier II UAS program to acquire, own, and operate these platforms should move forward.

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Abbreviations

ACTD	Advanced Concept Technology Demonstration
AEA	airborne electronic attack
AOR	area of responsibility
ASW	anti-submarine warfare
ATC	automatic target cueing
BACN	Battlefield Airborne Communication Node
BAMS	Broad Area Maritime Surveillance
BCT	brigade combat team
BM	battle management
C2	command and control
CAS	close air support
CBRN	chemical, biological, radiological, nuclear
COMINT	communication intelligence
CONOP	concept of operations
CSG	carrier strike group
CVN	nuclear aircraft carrier
DARPA	Defense Advanced Research Projects Agency

DoD	U.S. Department of Defense
DTRA	Defense Threat Reduction Agency
EIRP	equivalent isotropically radiated power
ELINT	electronic intelligence
EO/IR	electro-optical infrared
EW	electronic warfare
FCS	Future Combat System
FMV	full motion video
FY	fiscal year
GEO	geosynchronous earth orbit
GCS	ground control station
GHMD	Global Hawk Maritime Demonstration
GPS	Global Positioning System
HALE	high-altitude, long-endurance
HSI	hyperspectral imaging
IMINT	image intelligence
INS	inertial navigation systems
ISAR	inverse SAR
ISR	intelligence, surveillance, and reconnaissance
JCTD	Joint Capability Technology Demonstration
LCS	Littoral Combat Ship
LO	low-observable (stealthy) through passive or active signature reduction techniques
LOS	line of sight

LPI	low probability of intercept
LRE	launch and recovery element
LWIR	long-wave infrared
MAE	medium-altitude, medium-endurance
MCE	mission control element
MICE	Multiple Image Coordinate Extraction
MMA	Multimission Aircraft
MMTI	maritime moving target indicator
MWIR	mid-wave infrared
N-UCAS	Navy Unmanned Combat Aircraft System
PNT	position navigation and timing
RF	radio frequency
RSTA	reconnaissance, surveillance, and target acquisition
SAB	Scientific Advisory Board
SAR	synthetic aperture radar
SATCOM	satellite communication
SDD	system development and demonstration
SEAD	suppression of enemy air defenses
SIGINT	signals intelligence
SOCOM	U.S. Special Operations Command
SOF	special operations forces
STUAS	Small Tactical Unmanned Aircraft System
SWIR	short-wave infrared

TCS	Tactical Control Systems
TRL	technical readiness level
TTP	tactics, techniques, and procedures
UAS	unmanned aircraft system
UAV	unmanned aircraft vehicle
UCAS-D	Unmanned Combat Aircraft System Demonstrator
VNIR	very-near infrared
VTUAS	vertical takeoff/landing tactical UAS
VTUAV	vertical takeoff/landing tactical UAV
WAS	wide area search

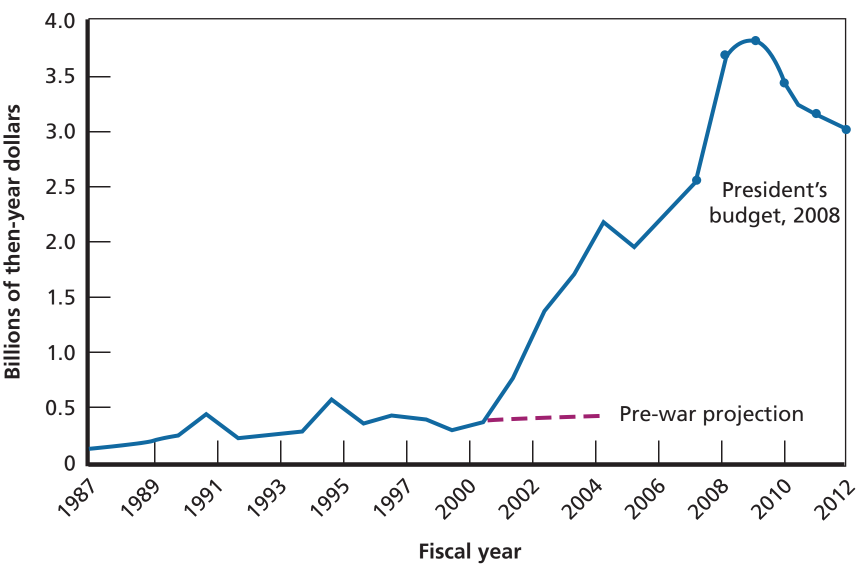
CHAPTER ONE

Introduction and Objectives

Introduction

There has been an explosion of interest in unmanned aircraft vehicles and systems since September 11, 2001. For instance, Figure 1.1 shows the Department of Defense (DoD) investment in unmanned aircraft

Figure 1.1
DoD Investment in Unmanned Aircraft Systems



SOURCE: Unpublished RAND research by Brien Alkire, Jessie Riposo, Randall Steeb, and Louis Moore.
RAND *MG957-1.1*

systems from 1987 to 2012. DoD funding in 2001 was $363 million; two years later, in 2003, funding had nearly quadrupled to $1.4 billion, with estimates for a $300 million increase in funding each year after that. During testimony before the Senate Committee on Armed Services on March 1, 2005, General John P. Abizaid, Commander of U.S. Central Command, described the appetite for the unmanned aircraft system (UAS) as "insatiable."

Due to this explosion in interest in recent years, the military community has become more specific about what constitutes unmanned aircraft vehicles and systems.[1] Joint Publication (JP) 1-02, *DoD Dictionary of Military and Associated Terms,* April 12, 2001, as amended through March 4, 2008, broadly defines an unmanned aircraft vehicle (UAV) as a "powered, aerial vehicle that does not carry a human operator, uses aerodynamic forces to provide vehicle lift, can fly autonomously or be piloted remotely, can be expendable or recoverable, and can carry a lethal or non-lethal payload." To signify that operation of a UAV involves more than just the vehicle, the term *unmanned aircraft system* has been adopted.[2] The DoD definition goes on to state that "ballistic or semi-ballistic vehicles, cruise missiles, and artillery projectiles are not considered unmanned aerial vehicles." Other, more-restrictive definitions for the UAS emphasize this last clause by requiring that a UAS be nominally recoverable and capable of carrying alternative separable payloads. Weapons and munitions, on the other hand, tend to be expendable along with their payloads, usually warheads, which are integrated into the vehicle.

The Department of the Navy is on the verge of making large investments in a number of major UAS programs. These systems will need to accomplish missions that range over the full spectrum from the very-high-threat major combat operations to global and protracted operations associated with irregular warfare.

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1 In this study, we use "unmanned aircraft" as opposed to "unmanned air," or "unmanned aerial" vehicles and systems. This is the convention used by the Navy Persistent Maritime Unmanned Aircraft Systems program office (PMA-262).

2 In 2009 the United States Air Force adopted the term Remotely Piloted Aircraft (RPA) to replace the term UAS.

The Navy is investing in two types of unmanned aircraft as part of the Broad Area Maritime Surveillance (BAMS) program: a high-altitude UAS and a vertical takeoff/landing tactical UAV (VTUAV). The Navy initiated a competitive procurement process for a high-altitude UAS in 2006 and awarded Northrop Grumman a $1.16 billion cost-plus-award-fee contract for system development and demonstration (SDD) in April 2008. The high-altitude UAS, designated RQ-4N, would enter the fleet beginning in 2016 and the Navy would acquire 68 by 2019 (DoD, 2008). The Navy has already fielded a small number of VTUAVs, designated as the MQ-8B Fire Scout. In February 2009, it awarded a contract to Northrop Grumman, not to exceed $40 million, for procurement of three additional MQ-8B's (Northrop Grumman, 2009), and expects to acquire a total inventory of 131 vehicles (U.S. Navy, 2008).

In 2007, the Navy awarded a $635.8 million contract to Northrop Grumman to build two demonstration vehicles for the Unmanned Combat Aircraft System Demonstrator (UCAS-D) program (Northrop Grumman, 2007a). The goal of the UCAS-D program is to demonstrate a carrier-capable unmanned combat aircraft system. Demonstration is expected to be complete by fiscal year (FY) 2013. If UCAS-D is successful, the Navy may decide to acquire an operational platform with an initial operating capability in FY 2025 (Northrop Grumman, 2007b).

The Navy signed a $14.5 million contract with Boeing in 2005 to provide intelligence, surveillance, and reconnaissance (ISR) coverage with the ScanEagle small tactical UAS (STUAS) during Naval Expeditionary Strike Group missions and security for oil platforms in the Persian Gulf. Subsequently, the Navy and the Marine Corps began a competition program to acquire their own STUAS capability to provide persistent ISR support for tactical-level maneuver decisions and unit-level force defense and protection for Navy ships (U.S. Navy, 2008).

Study Objectives

The Office of the Chief of Naval Operations, Assessment (OPNAV N81) asked the RAND Corporation to provide an evaluation of the Navy's ongoing and proposed UAS programs and to describe the most promising applications of UASs to operational tasks. Emphasis was to be placed on UASs that could operate from naval platforms. These assessments were to include arguments for and against using manned vehicles to perform the same tasks as unmanned vehicles, where appropriate. The present study, completed in September 2008, does not provide an exhaustive look at all DoD missions for UASs. However, it does discuss the strengths and weaknesses of manned and unmanned aircraft for certain missions of importance to the Navy. The objective of the study, then, is to describe missions and tasks for Navy UASs and to assess the feasibility of the UAS to perform these tasks.

The focus of the study was to consider the UAS from the perspective of technological and operational risk and benefit, as opposed to cost, in the context of the evolving requirements derived from the current articulated maritime strategy (Chief of Naval Operations and the Commandants of the U.S. Marine Corps and U.S. Coast Guard, 2007). This included an evaluation of both the UAS and its current and future manned competitors in the context of the full spectrum of requirements identified by the maritime strategy and its maritime mission requirements, using features of a "strategy to tasks" methodology. Our primary focus was on applications of Navy UASs in the 2015–2025 timeframe, when several Navy UASs will have reached initial operating capability and the Navy will potentially have an operational unmanned combat aircraft system.

This research drew on results from several recent studies of UASs conducted within RAND Project AIR FORCE. These included a study of future roles and missions of Air Force UASs led by James Chow, and multiple studies of maritime surveillance with Global Hawk led by Sherrill Lingel.

Organization of the Monograph

Chapter Two describes many UASs currently in use or under development, and highlights many of their important characteristics. Chapter Three provides an analysis of the potential advantages and disadvantages of UASs compared with manned aircraft, from a performance perspective. In Chapter Four, we apply this analysis to several Navy UAS programs and identify useful applications for them. Chapter Five summarizes our conclusions. We provide an appendix with a summary of the equations used in our analysis of communication systems.

CHAPTER TWO

Unmanned Aircraft Systems in Use or Development Today

Many different types of UASs are used today or are being developed for U.S. military applications. We provide an abbreviated but representative description of several and describe some of these systems in more detail in subsequent chapters. Additional information, including a comprehensive list of UASs, may be found in the recent Unmanned Systems Roadmap (DoD, 2007, Appendix A).

Global Observer

Global Observer is a high-altitude, long-endurance (HALE) platform being developed as part of a Joint Capability Technology Demonstration (JCTD) (see Figure 2.1). The JCTD is funded by the U.S. Special Operations Command (SOCOM), the Army, Air Force, Department of Homeland Security, and Coast Guard. The prime contractor is AeroVironment. This platform would use liquid hydrogen–powered hybrid engines to provide 400 pounds of payload capability at an altitude of 65,000 feet with an endurance of approximately one week. Potential applications include ISR and communication relay.

Figure 2.1
Global Observer

SOURCE: AeroVironment. Used with permission.
RAND *MG957-2.1*

RQ-4B Global Hawk and RQ-4N Broad Area Maritime Surveillance UAS

RQ-4B Global Hawk is a HALE UAS derived from the smaller RQ-4A that completed its first flight in 1998 (see Figure 2.2). It flies at 55,000–60,000 feet and has a 28-hour endurance with a payload capacity of 3,000 pounds and a loiter speed of 310 knots. It is currently in use by the Air Force as a multisensor ISR platform. Current payloads include electro-optical infrared (EO/IR) and synthetic aperture radar (SAR). Newer Block-30 versions will include a signals intelligence (SIGINT) payload ("Global Hawk RQ-4A-B High Altitude Long Endurance UAV: SIGINT Mission Payload," 2005). There are efforts at Air Force Research Labs to develop a hyperspectral imaging (HSI) sensor called SPIRITT (Rockwell,

Figure 2.2
RQ-4B Global Hawk

SOURCE: U.S. Air Force photo by Bobbi Zapka.
RAND *MG957-2.2*

2005). There are also efforts to develop communication relay systems for Global Hawk, for instance, the Battlefield Airborne Communication Node (BACN) that is part of the Objective Gateway program. Global Hawk is produced by Northrop Grumman. The launch and recovery element (LRE) operates within LOS of Global Hawk. It is connected to the remote mission control element (MCE) at Beale Air Force Base, California, via satellite communication (SATCOM) for flight control. Air Force officers who are rated pilots for manned aircraft are employed for piloting Air Force UASs, although the Air Force is considering the creation of a distinct career path for pilots of unmanned aircraft.

In FY 2003, the Navy purchased two RQ-4A variants with EO/IR and SAR sensors, as well as the requisite ground control and support equipment. These are known as the Global Hawk

Maritime Demonstration (GHMD) platforms. GHMD provides the Navy with demonstration capability primarily for doctrine; concept of operations (CONOP); and tactics, techniques, and procedures (TTP) development. The Navy worked with contractors and labs to develop software modes for the sensors to enhance their operation in a maritime environment. For instance, maritime moving target indicator (MMTI) and inverse SAR (ISAR) software modes were developed for the radar.

Northrop Grumman was awarded U.S. Navy's BAMS UAS program on April 22, 2008.[1] The BAMS UAS, designated RQ-4N, is a maritime derivative of Global Hawk equipped with Navy-specific control stations called Tactical Control Systems (TCS). Whereas the fields of regard for radar systems on Air Force RQ-4A and RQ-4B are side-looking only, the BAMS UAS will have a full 360-degree field of regard. Unlike the Air Force variants, the BAMS UAS will have the capability to collect full motion video (FMV). The BAMS UAS is part of a broader program that includes a manned P-8 Multimission Aircraft (MMA), and the MQ-8 Fire Scout VTUAV, to recapitalize the capability of the aging fleet of P-3 Orion aircraft and provide maritime domain awareness for the Navy. The BAMS UAS will be a fleet asset, and crew will be collocated and interoperable with MMA crew. Note that all Global Hawk variants, including the RQ-4N BAMS UAS, require a runway for takeoff and landing and are not carrier-capable. The TCS will be collocated with the base for the MMA and the BAMS UAS. The MMA will be able to receive information directly from the BAMS UAS (level 2 communication).

We discuss communication relay applications for BAMS UASs in Chapter Four.

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1 Competitor Boeing proposed an unmanned version of the 550 Gulfstream manned aircraft; General Atomics and Lockheed partnered for the competition and offered a Predator variant.

MQ-1 Predator, MQ-1C Sky Warrior, MQ-9 Reaper, and Avenger

MQ-1 Predator was an Air Force Advanced Concept Technology Demonstration (ACTD) in 1994; it transitioned to an Air Force program in 1997. It has flown surveillance missions since 1995 and was armed with Hellfire missiles in 2001. It is operated principally by the Air Force and the Army; however, the Navy has purchased three early variants for research and development.

The Army's MQ-1C Sky Warrior is a variant of the MQ-1 that employs a diesel engine and is operated by the Army's One System ground control station (GCS) (see Figure 2.3). MQ-1C includes EO/IR sensors with FMV and SAR sensors. A laser rangefinder/designator and hard-points under the wings provide attack capability. The operat-

Figure 2.3
MQ-1C Sky Warrior

SOURCE: General Atomics. Used with permission.
RAND *MG957-2.3*

ing ceiling is 28,000 feet. It has an 800-lb external payload capability, an endurance of around 28 hours, and a loiter speed of 60 knots. MQ-1C will be fielded to each of the Army's divisions. Army philosophy is to use operators, not rated pilots, although warrant officer pilots are often used to pilot Army UASs (Hunn, 2006). The Army plans to provide direct control of the UAS to Army division commanders in the field (GAO, 2006). The Army's One System GCS can provide flight control to a variety of UASs in addition to MQ-1C, including Shadow.

The Air Force MQ-9 Reaper (formerly Predator B) is a larger variant of MQ-1 with a 50,000-ft ceiling, 24-hour endurance, 120-knot loiter speed, a 3,000-lb external payload on wing hard-points, and a 75-lb internal payload (see Figure 2.4). It carries EO/IR sensors with FMV capability and a SAR sensor. Its primary role is as a persistent

Figure 2.4
MQ-9 Reaper

SOURCE: U.S. Air Force photo by Staff Sergeant Brian Ferguson.
RAND *MG957-2.4*

hunter-killer for time-sensitive targets. The LRE is within LOS of the UAS, and flight control is currently performed remotely from Creech Air Force Base, Nevada.

Currently, all fielded Predator variants are shore-based and not carrier-capable.

In the 1990s, the Navy considered a Predator variant to meet its medium-altitude, medium-endurance (MAE) requirements. A marinization study was completed on October 1, 1996 (U.S. Navy, 1996). The Chief of Naval Operations decided not to go forward with a fully marinized Predator system as the solution for the Navy's MAE requirement but instead to use the data receipt and positional control of the Air Force's Predator systems. On January 29, 1997, a letter to Congress on Predator Marinization was signed by the Office of the Assistant Secretary of the Navy (Research, Development and Acquisition) and Defense Airborne Reconnaissance Office (ASN RDA & DARO). It stated that, based on the results of the marinization study, "The Navy has decided not to develop a launch and recovery capability for the Predator UAV from CV/CVN [aircraft carrier and nuclear aircraft carrier] and LHA/LHD [amphibious assault] class ships." Mariner was the version of Predator offered by partners Lockheed Martin and General Atomics during competition with Northrop Grumman and Boeing for the BAMS UAS. General Atomics indicated that it could develop a carrier-capable version of Mariner.[2] Ultimately, Northrop Grumman won the contract. The Navy is acquiring one Air Force MQ-9 for demonstrating sensor capabilities and TTP. Unarmed variants of MQ-9 entered service for the Office of Customs and Border Protection (CBP) in 2005 and are used for border monitoring (Customs and Border Protection, 2007).

A smaller and less-capable version of the SPIRITT HSI sensor, called ACES-Hy, is being developed for Predator variants. Predator is also a candidate platform for communication relay payloads, including BACN.

[2] Note that General Atomics has contracted for system development and demonstration of the Electromagnetic Aircraft Launch System (EMALS) for aircraft carriers. See Electromagnetic Aircraft Launch System (EMALS), undated, on the General Atomics website.

The newest in the Predator line is the Predator-C, known as the Avenger (Figure 2.5). First flown on April 4, 2009, this version is jet powered and has an exterior design intended to reduce its signature (Fulghum and Sweetman, 2009).

While Avenger is still in the early developmental phases, it is reported to have similar endurance as the MQ-9 Reaper and capable of carrying similar payloads. This version contains an internal weapon bay in addition to the external weapon connection hard-points. The jet allows the Avenger to reach a higher altitude than its predecessors, planned for 60,000 feet, and faster speeds (Fulghum and Sweetman, 2009).

Figure 2.5
Predator-C Avenger

SOURCE: General Atomics. Used with permission.
RAND *MG957-2.5*

Unmanned Combat Aircraft System Demonstrator

Northrop Grumman was awarded a contract in August 2007 for a critical technology demonstration of a carrier-capable unmanned combat air system (UCAS-D). The goal is to develop an operationally relevant, tailless, low-observable (LO) platform prototype and to demonstrate technical readiness level (TRL) 6 maturity of carrier related technologies by FY 2013 that include

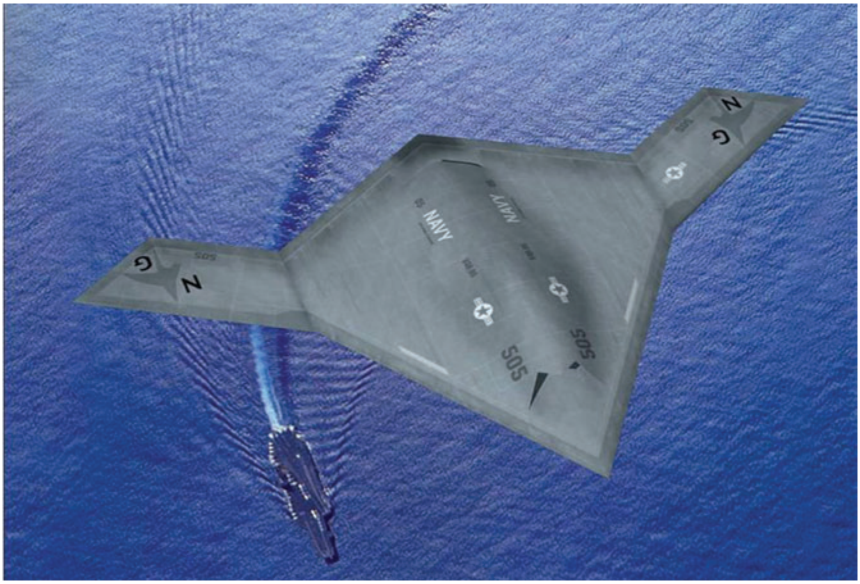
- launch and recover operations, including catapult launch, wave-off, and arrested landing
- deck handling and support, including remote powered and unpowered flight deck handling, fueling/defueling, and maintenance
- flight operations, including in-air refueling and manned and unmanned flight formations.

The LO characteristics for the demonstration platform will be achieved by passive signature reduction using fuselage shaping. (Additional passive and active signature reduction techniques, including the use of radar absorbent materials, may be applied to an operational platform.) The UAS will be unarmed and will not incorporate any sensors other than those required for the demonstration.

UCAS-D will provide the Navy with insight about the operational readiness rate of a fighter-sized UAS with stealth features that can operate over a wider spectrum of conditions. If these operational tests are deemed successful, the Navy will decide on the characteristics and applications of an operational UCAS for acquisition, designated the Navy Unmanned Combat Aircraft System (N-UCAS).

Northrop Grumman's design is based on the X-47B Pegasus (see Figure 2.6). It is designed to carry a 4,500-lb payload with a combat radius of 2,100 nm and an unrefueled endurance of six hours in the strike variant. Alternatively, it can be optimized as an ISR platform and could carry internal fuel instead of ordnance. If the vehicle carries only fuel, it will have a combat radius of 5,000 nm and an endurance

Figure 2.6
UCAS-D



SOURCE: Defense Advanced Research Projects Agency.
RAND *MG957-2.6*

of 14 hours and could operate as a pure ISR platform using organic sensors. The ISR variant could also carry fuel in one of the ordnance bays and additional sensors in the other ordnance bay. The latter could be a radar package optimized for maritime surveillance missions. So equipped, this variant would have less endurance than the pure ISR variant.

We identify options for an operational N-UCAS in Chapter Four.

RQ-7 Shadow

The Army selected Shadow in 1999 for support of ground maneuver commanders, and the Marine Corps selected Shadow to replace its Pioneer UASs in 2006 (see Figure 2.7). The prime contractor is AAI. Shadow has an automated takeoff and landing system. It is catapult-

Figure 2.7
RQ-7 Shadow

SOURCE: AAI Corporation. Used with permission.
RAND *MG957-2.7*

launched and lands on an airstrip.[3] It has six-hour endurance, a 15,000-ft ceiling, a loiter speed of 60 knots, and a 60-lb payload capacity. It operates within LOS (no SATCOM) and is controlled with the Army One System GCS. It features an EO/IR payload, and future versions will include laser designation. A communication relay package has been developed that can extend LOS communication capability for users on the ground and connect dissimilar radios. There are no munitions on Shadow. The design of Shadow is based on the MQ-5B Hunter, which does have the capability to carry munitions. Hunter is a dedicated reconnaissance, surveillance, and target acquisition (RSTA) platform used by the Army.

Shadow is often employed in Iraq to support convoy protection and counter–improvised exposive device (IED) missions. Each Army

3 It includes a tail-hook to allow it to land on a short runway.

Brigade Combat Team (BCT) has one Shadow system that includes four vehicles and two ground stations.[4]

MQ-8B Fire Scout

MQ-8B is a vertical takeoff/landing tactical UAV (VTUAV). The prime contractor is Northrop Grumman (see Figure 2.8). Fire Scout was selected by the Army as its Category IV unmanned aircraft for the Future Combat System (FCS) program to support RSTA applications. It was selected by the Navy to support the Littoral Combat Ship (LCS). Specifically, it will support mine countermeasure, surface

Figure 2.8
MQ-8B Fire Scout

SOURCE: U.S. Navy photo by Kurt M. Lengfield.
RAND *MG957-2.8*

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[4] This information was provided to RAND in a briefing by BG Rick Rife, U.S. Army G-8, on June 6, 2008.

warfare, and antisubmarine warfare mission modules of LCS. It may employ different configurations of sensors and weapons in support of those mission modules. Its operational footprint is a fraction of that of the multipurpose MH-60 class helicopter, and it can be flown from a wide range of surface ship platforms. Development and deployment of Fire Scout was closely tied to LCS. However, the Navy wisely decided to conduct operational testing on another vessel because of delays in LCS. Fire Scout has an operating ceiling of 20,000 ft, a payload capacity of 600 lb, a loiter speed of 117 knots, and an endurance of at least six hours. Sensors include EO/IR, laser designator, and rangefinder. Future sensors may include surface search radar with MMTI, multispectral sensor, or SIGINT sensors. The capability of deploying and/or monitoring sonobuoys may be developed, and communication relay to extend LOS communications is also a potential future payload. Fire Scout has wing stubs that can support armament—for example, Hellfire missiles or Viper Strike laser-guided glide weapons. Future weapons may include a compact and very lightweight torpedo. It utilizes LOS communication capability and will be controlled from shipboard TCS. The Coast Guard has also expressed interest in Fire Scout to meet its UAV needs.

Boeing Hummingbird

The Boeing A160T Hummingbird is a next-generation VTUAS (see Figure 2.9). Currently, DARPA is funding the development program, with flight tests scheduled through the end of the decade. The aircraft is larger than Fire Scout, with a footprint closer to an MH-60. However, it holds the promise of higher altitude and payload performance, which could support broad-area maritime domain awareness applications from a sea platform. It will have a 15,000-ft ceiling in hover and a 30,000-ft ceiling in cruise, a payload capacity of 300–1,000 lbs, an endurance of ten hours with a 300-lb payload, and a loiter speed of 60 knots. This UAS could also serve in a hunter-killer role or provide close air support (CAS) to Special Operations Forces (SOF) and Marine Corps units during ground operations.

Figure 2.9
Hummingbird

SOURCE: Boeing Company. Used with permission.
RAND *MG957-2.9*

ScanEagle

ScanEagle is a small tactical UAS (STUAS) optimized for endurance rather than payload and employing a ship launch and recovery mechanism (see Figure 2.10). It is deployed by the Marine Corps in Iraq to provide force protection and is also deployed on Navy ships. ScanEagle was designed and produced by Insitu Group in partnership with Boeing. (Boeing has since acquired Insitu.) Boeing currently leases and operates ScanEagle for the Navy and Marine Corps. The platform has a payload capacity of around 13 lb, an endurance of at least 15 hours (it has demonstrated an endurance of up to 29 hours), and a loiter speed of 49 knots. It is launched via pneumatic catapult and recovered using a SkyHook. It may be operated from a variety of ships, including those that do not have any type of flight deck, as well as from remote,

Figure 2.10
ScanEagle

SOURCE: U.S. Navy photo by John F. Williams.
RAND *MG957-2.10*

unimproved areas. It is operated via LOS data links and employs EO/IR sensors. Boeing has worked with ImSAR to develop a small SAR payload. Boeing is also working to create a variant of ScanEagle with chemical and biological sensing capabilities as part of an Advanced Technology Demonstration with the U.S. Defense Threat Reduction Agency (DTRA) (Fein, 2007). The UAV would be equipped with an Iridium data link for beyond-LOS communications in this application.

Integrator

Boeing/Insitu is developing the Integrator as a UAS with a larger payload than ScanEagle. Integrator is intended to be the next step in the Insitu UAS series. It has an extended range, payload, ceiling, speed, and size compared with ScanEagle (see Table 2.1). Integrator would be able to perform the same missions currently planned for ScanEagle, at a potentially increased capacity. It is worth noting that the 57-percent

Table 2.1
Comparison of ScanEagle and Integrator

	ScanEagle	Integrator
Performance		
Maximum horizontal speed	75 knots	90 knots
Cruise speed	48 knots	55 knots
Ceiling	19,500 ft	20,000 ft
Endurance	20+ hours	40 hours
Dimensions		
Wing span	10.2 ft	16 ft
Fuselage diameter/cross section	7.0 in	10 in x 10 in
Length	3.9 ft	7.2 ft
Weight		
Maximum takeoff weight	44 lb	135 lb
Fuel and payload	12.4 lb	70 lb
Maximum fuel	12.1 lb	25 lb
Empty structure weight	26.5 lb	60.1 lb

SOURCE: InSitu website and resource documents.

increase in wingspan and 85-percent increase in platform length raise concern about whether Integrator can operate from the same broad range of ships as ScanEagle. Also, the increased payload weight and doubling of empty structure weight raise concern about safety to the crew, the UAS, and the ship during the SkyHook recovery process. If these concerns can be addressed, the Integrator UAS could provide the Navy with a candidate for the maritime control and tactical ISR missions and could supplement other assets in long-duration missions.

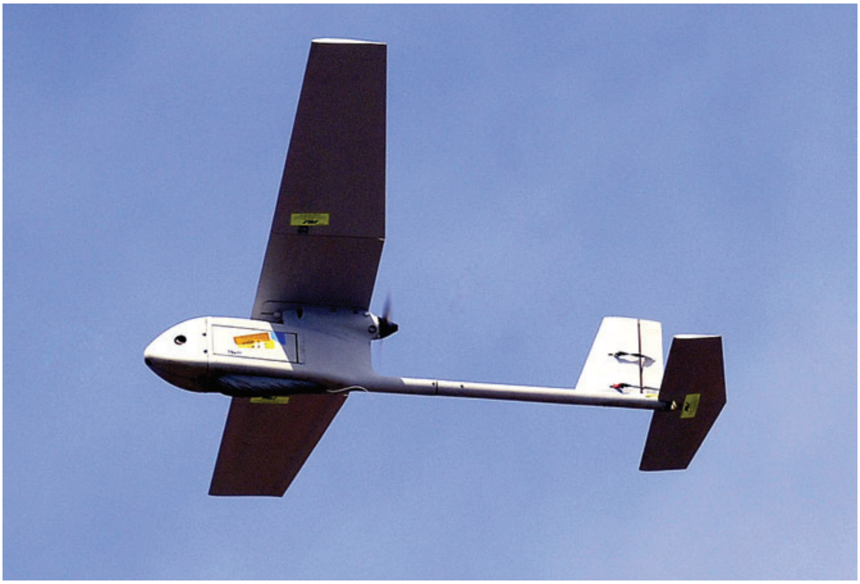
According to Insitu, the issue of launch and recovery of ScanEagle and Integrator has resulted in an upgraded pneumatic launch system that actually requires a smaller footprint than the original, as well as a more robust SkyHook to retrieve the UAS, while maintaining the size of the original SkyHook. To deal with the force associated with the UAS snagging the SkyHook, Insitu has modified the wing flap bolts to break away before damage to the flaps is done. These bolts are easily reattached after recovery.

ScanEagle or Integrator may be candidate platforms, along with offerings from other contractors, for the Navy and Marine Corps SDD phase of the STUAS/Tier II UAS ACAT program. This program will fill ISR capability shortfalls identified by the Navy and Marine Corps and delineated in an initial capabilities document in 2007.

RQ-11 Raven

RQ-11 Raven is a hand-launched small UAS developed in 2002 to provide force protection at the maneuver battalion level and below. It is produced by AeroVironment (see Figure 2.11). Several thousand aircraft are in the combined inventories of the Army, SOCOM, the Air

Figure 2.11
RQ-11 Raven



SOURCE: U.S. Air Force photo by Dennis Rogers.
RAND *MG957-2.11*

Force, and the Marine Corps. It has a ceiling of 14,000 ft, a 1-pound payload capacity and an endurance of 1.5 hours. Standard payloads are EO/IR. Raven can be remotely controlled from a ground station within LOS or can fly autonomously using Global Positioning System (GPS) navigation.

Puma

Puma is a hand-launched small UAS being designed in two variants: one for use in a marine environment and one for land use. It is being developed by AeroVironment. Potential users would be SOCOM and Army (see Figure 2.12). Puma will have a ceiling of 10,000 ft, a 2–4-lb payload capacity, and an endurance of two hours.

Figure 2.12
Puma

SOURCE: AeroVironment. Used with permission.
RAND *MG957-2.12*

CHAPTER THREE

Performance Advantages and Disadvantages of Unmanned Aircraft Systems

Potential Advantages of Unmanned Aircraft Systems

UASs have performance characteristics that make them attractive for applications that are inherently too "dangerous," "dirty," "dull," "demanding," or "different" to be supported by manned aircraft.

Dangerous missions are usually associated with the possible death or injury to a human. Examples of dangerous missions are the use of decoy vehicles to provoke a local air defense system to reveal its operational locations. UASs can be used in such missions at the risk of suffering aircraft attrition without losing a human pilot. Armed platforms used to find and destroy targets in a high-threat environment also fall into this category. Persistent armed reconnaissance has proven the worth of Predator variants for antiterrorism missions in Iraq and Afghanistan.

Dirty missions are a subset of the dangerous missions. A prime example would be detection of chemical, biological, radiological, or nuclear (CBRN) materials.

Dull missions are those associated with tasks that are repetitive and boring, and thus well-suited to automation—for example, repetitive monitoring of oil lines or borders. Piloting a UAS for this task can be automated to a great degree, and both pilots and analysts on the ground can be rotated frequently to keep fresh crew performing the mission without having to land the aircraft. UAS can help alleviate the risk of crew fatigue.

Those missions that require better speed, accuracy, precision, accessibility, reliability, or endurance characteristics than possessed by humans fall into the *demanding* category. A clear example of demanding missions is the use of the large high-aspect-ratio UAS, such as Global Hawk, to perform HALE ISR missions. The use of a UAS for this mission allows the human pilot, often the lowest common denominator, to be taken out of the endurance equation. Also, human pilots conducting high-altitude operations are exposed to the risk of decompression sickness. Without the weight and volume associated with a human pilot, it is now possible to design unmanned aircraft with range, payload, and survivability features exceeding those of a manned aircraft, often only limited by the amount of fuel that can be carried.

Missions that otherwise would not be considered for manned aircraft are known as *different*. For instance, many reconnaissance missions performed by a small tactical UAS could not be performed by manned aircraft because they are not man-portable.

Potential Disadvantages of Unmanned Aircraft Systems

We compared the dependence of manned and unmanned aircraft systems on GPS satellites for position navigation and timing (PNT) information, and we compared their dependence on communication resources.

GPS Dependence

GPS satellites and user equipment are vulnerable to a variety of threats, including kinetic and electronic threats. These threats and countermeasures are well documented (see Preston and Baker, 2002). Modern military aircraft, whether manned or unmanned, rely on PNT information provided by GPS for a range of tasks, including the following:

- **Navigation.** Typically, GPS is integrated with inertial navigation systems (INS).

- **Precision Targeting.** GPS is often employed in conjunction with photogrammetry systems, such as the Multiple Image Coordinate Extraction (MICE) for precision-guided munitions that is employed on Predator (Puels, 2006).
- **Sensor and Antenna Pointing.** For example, GPS receivers are employed on SAR antennas to aid motion compensation.
- **Synchronization for Communication and Sensing.** For example, GPS timing information may be used to synchronize communication systems employing frequency-hopped spread-spectrum techniques or code division multiple access schemes.

Manned aircraft have the advantage that crew can provide onboard situational awareness and decisionmaking that can aid in these tasks in the absence of GPS. To some extent, sensors and onboard processing can add these capabilities to a UAS, but this either places burden on communication resources to send the sensed information back to an offboard operator or requires more reliance on autonomy for decisionmaking.

Many past and even existing UASs are highly dependent on GPS—much more so than manned aircraft. For instance, some UASs cannot take off without a GPS-resolved position. Other UASs are programmed to automatically return to base if GPS is lost. However, these issues can be resolved with careful engineering practices, such as providing the technical means to upload position information prior to takeoff or programming alternative behaviors in the event that GPS signal is lost. For this reason, we suggest that future manned and unmanned aircraft have similar dependence on GPS for PNT.

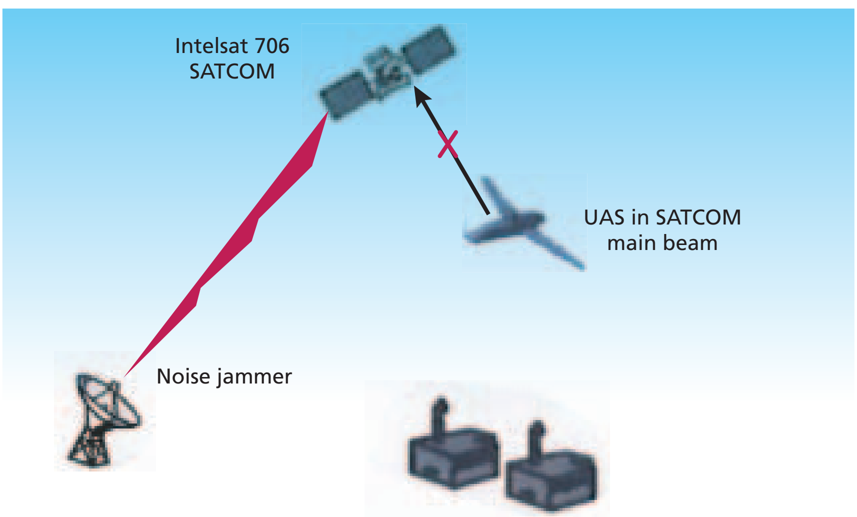
In summary, while GPS is vulnerable to a variety of threats, those threats have similar implications for manned and unmanned aircraft since both types of aircraft have similar dependence on PNT provided by GPS. The UAS has a similar dependence on GPS for PNT; however, in the absence of PNT resources, it may have an increased reliance on communication resources or autonomy compared with manned aircraft.

Communication Dependence

Many UASs, including the Air Force's RQ-4B Global Hawk, the Navy's RQ-4N BAMS UAS, Predator variants, and, potentially, the Navy's UCAS-D, depend on the availability of SATCOM for command and control (C2) and for sending sensor data products to the ground for exploitation. Similar to the case for GPS, communication satellites are vulnerable to a variety of threats, including kinetic threats and noise jamming. To illustrate the threat posed by noise jammers, consider a UAS utilizing a Ku-band uplink to an Intelsat 706 commercial communication satellite (see Figure 3.1).

In the figure, we see that the UAS is in the main beam of the SATCOM receive antenna. Under a reasonable set of assumptions, and in the absence of noise-jamming threats, one SATCOM transponder can support a data rate of about 36 Mbps with a reasonable quality of

Figure 3.1
Illustrative Example of Communication Vulnerability



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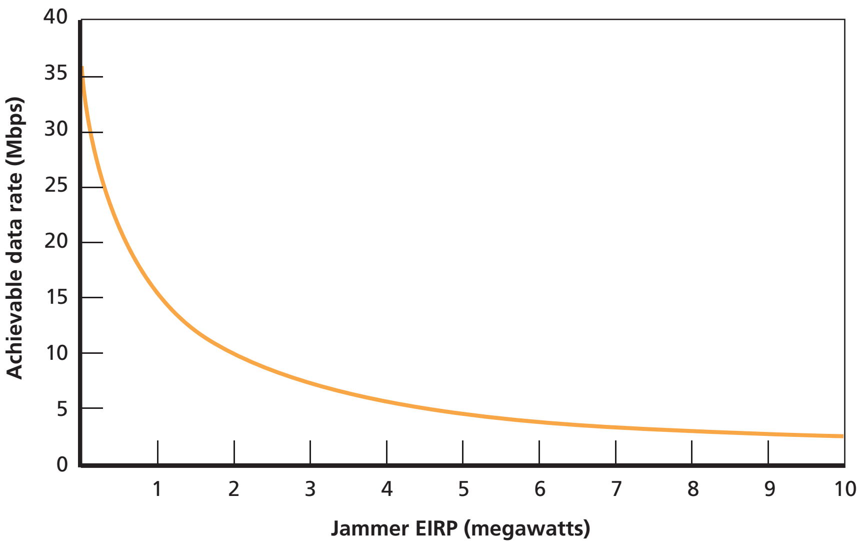
service.[1] However, the receive antenna on the satellite is being attacked by a ground-based noise jammer that is injecting noise into it. We calculated how the achievable data rate varies with the equivalent isotropically radiated power (EIRP) of the noise jammer. The result is shown in Figure 3.2.[2]

Figure 3.2
Achievable Data Rate Versus Jammer Equivalent Isotropically Radiated Power



RAND *MG957-3.2*

[1] Equations and background information for link budget analysis are detailed in the appendix. This analysis assumed the performance of an Intelsat 706 Ku-band spot 1 transponder (see Intelsat website, 2010) and a UAS SATCOM payload similar to what is used aboard RQ-4B (see L-3 Communication Systems West, 2006). We assumed binary phase shift keying (BPSK) modulation, and a fixed quality of service defined as a symbol error rate (before correction) of 10^{-6}. The equivalent isotropically radiated power (radio frequency [RF] power and antenna gain) from the UAS to close the link is 7.6 megawatts.

[2] We assume a fixed quality of service and that the noise jammer is within the main beam of the satellite receiver. Note that a 10-megawatt jammer that has a 10-dB disadvantage due to sidelobe suppression would have the same effect as a 1-megawatt jammer in the mainlobe.

We see from the figure that even a 1-megawatt noise jammer in the main beam of the receive antenna is sufficient to reduce the achievable data rate by more than 50 percent for a fixed quality of service. Note that only "receivers" are vulnerable to noise jamming. Therefore, the downlink between the satellite and the UAS in our illustrative example would not necessarily be affected by the presence of a noise jammer.

Unlike the case for GPS, the UAS tends to be much more dependent on communication resources than manned aircraft. This is especially true for a UAS that collects large volumes of image intelligence (IMINT) with sensors such as high-resolution spot mode SAR or EO/IR, wide area search (WAS) SAR or EO/IR, FMV, or HSI. We evaluated peak data rates for these sensors and sensor modes and use those rates as a measure of dependence on communication resources.[3] The data rates we evaluate are not for specific systems in use but are typical of the data rates associated with sensors and sensor modes based on an analysis using first principles. The results are shown in Figure 3.3.[4]

We can see from the figure that peak data rates for uncompressed imagery ranges from tens to hundreds of Mbps.[5] Compression can reduce data-rate requirements, but (lossy) compression increases image distortion and reduces image interpretability. Typically, a SAR, EO, or image

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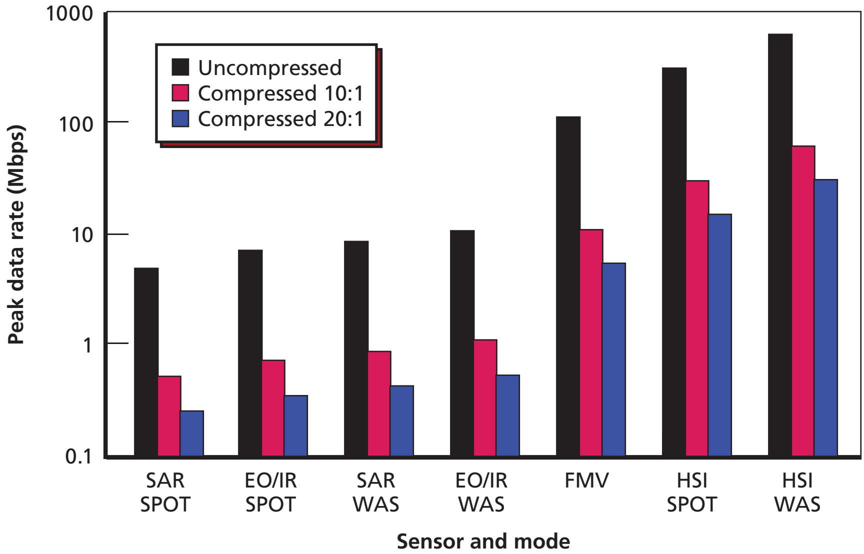
[3] Equations and background information required for this analysis are summarized in Hovanessian, 1988.

[4] We assumed a 15-percent overhead for error coding for all sensor modes. For spot SAR, we assumed a 2 × 2 km spot, 0.5m resolution, 16 bits per pixel, and 60 seconds per image. For spot EO/IR we assumed 640 × 480 pixels per frame, 120 frames per image, 10 bits per pixel, and 60 seconds per image. For WAS SAR, we assumed 4,000 square km per hour, 1.5-m resolution, 16 bits per pixel. For WAS EO/IR we assumed 640 × 480 pixels per frame, 1,000 frames per image, 10 bits per pixel, 300 seconds per image. For FMV we assumed 720 x 1,280 pixels, 30 frames per second, 4:2:0 Y′CbCr, 8 bits per sample. For HSI spot we assumed 3 × 3 km spot, 1-m resolution, 16 bits per pixel, 200 bands, 90 seconds per image. For HSI WAS we assumed 3,000 square km per hour, 2-m resolution, 16 bits per pixel, 200 bands. Y'CbCr refers to a method of coding image color information. Y′ is the luma component, and Cb and Cr are the blue-difference and red-difference chroma components.

[5] Also note that peak data rates associated with SIGINT sensors can also be very high, typically on the order of 10–20 Mbps depending on the instantaneous bandwidth of the sensor.

Figure 3.3
Typical Data Rates Associated with IMINT Sensors



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can be compressed 10:1 with JPEG before there is noticeable degradation as measured by the National Imagery Interpretability Rating Scale (for instance, see Werness et al., 1999).[6] Compression ratios of 10:1 or less are typically employed for SAR, EO, and IR imagery; 20:1 compression ratios are typical for FMV (note that another way to reduce the data rate associated with FMV is to reduce the frame rate, a technique sometimes used on small UASs that utilize analog communication links for which compression is not an option).

Noise jammers can significantly reduce the SATCOM data rates that can be achieved between UASs, ground control, and exploitation sites. With manned aircraft, it may be possible to do all control and exploitation tasks on board the aircraft, although it is often desirable to send data products to the ground for further exploitation and fusion. However, crew on board the aircraft can select the data to be sent and

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[6] The National Imagery Interpretability Rating Scale is described in Leachtenauer and Driggers, 2001, pp. 135–143.

reduce the overall data-rate requirement. To some extent, automation can add this capability to a UAS. For example, automatic target cueing (ATC) performed aboard the UAS can be applied to collected imagery and the image sent to the ground for further exploitation only if it is likely to contain targets. As an alternative, ATC can be used to select the compression ratio applied to an image, greatly compressing images that are unlikely to contain target information. Unfortunately, these approaches rely on the performance of ATC, which is still a developing technology. Of course, it is possible with both manned aircraft and UASs to store the sensor data for post-mission analysis, and/or to send it at a low data rate, but this reduces the timeliness of the intelligence generated from the data and does not allow for real-time retasking based on the collected intelligence products.

In summary, UASs are much more dependent on communication resources than are manned aircraft, especially a UAS that employs multisensor capability for ISR. We see this as a key vulnerability for the UAS, especially for missions in high-threat environments. However, addressing this vulnerability and providing robust communications might allow U.S. forces to leverage some of the advantages that the UAS has, particularly in dirty, dull, and dangerous missions.

CHAPTER FOUR

Applications for Navy Unmanned Aircraft Systems

Current and Advocated Applications for Unmanned Aircraft Systems

Recent studies—namely, the *Unmanned Aircraft Systems Roadmap 2005–2030* and *Unmanned Systems Roadmap 2007–2032,* and the 2003 Air Force Scientific Advisory Board (SAB) UAS study—advocate many applications for UASs to support the services. Table 4.1 summarizes these applications, along with a list of current UAS applications.

In the sections that follow, we recommend applications that are most promising for the Navy's ongoing and proposed UAS programs. In particular, we provide a detailed evaluation and set of recommendations for an operational N-UCAS, and a broader evaluation and set of recommendations for RQ-4N BAMS, Navy VTUAS, and STUAS.

RQ-4N BAMS Unmanned Aircraft System

The RQ-4N BAMS UAS has a well-defined role as part of recapitalization of P-3 Orion aircraft and in providing ISR for maritime domain awareness. It will employ multiple sensors and provide a persistent ISR capability. In major combat operations, it will provide reconnaissance prior to hostilities and intelligence preparation of the battlefield. In

Table 4.1
Current and Advocated Applications for the Unmanned Aircraft System

Current	DoD Roadmaps	2003 USAF SAB
Close air support	Communication relay	Communication relay
Armed reconnaissance	Strike/SEAD/counterair	SEAD
Nonpenetrating ISR	Penetrating strike	Surveillance/battle management
Facility security	SIGINT collection	Airborne electronic attack
	Maritime patrol	Penetrating ISR
	Strike/SEAD	Penetrating strike
	Aerial refueling	Positive identification and battle damage assessment
	Surveillance /battle management	Persistent strike/combat air patrol
	Counterair	ISR of hazardous environment
	Airlift	

SOURCES: Air Force Scientific Advisory Board, 2003; DoD, 2005 and 2007.

support of operations for irregular warfare, it will aid in detecting movements of irregular enemy forces.

Although the primary role of the BAMS UAS is to provide persistent ISR, communication relay is also a requirement for BAMS, and a low-rate, initial-production UAS is likely to include a basic communication relay package that leaves space for spiral development of a more capable communication relay package (Richfield, 2007). In this section, we develop a CONOP for a communication relay application and characterize the desirable design attributes of a suitable communication relay payload. This application is well-suited to the BAMS UAS, and we assumed the same high-altitude attribute for the relay platforms in our development.

We developed the CONOP for the Pacific area of responsibility (AOR) since this is potentially an important operating area for the Navy that may require significant reachback communication connectivity for fleet assets. The CONOP could be used to provide high-data-rate connectivity in support of a range of operations in this AOR—from humanitarian and disaster relief or maritime interdiction operations in regions where there is limited SATCOM availability to global war on terrorism and major combat operations in regions where SATCOM is denied by noise jamming or kinetic threats.

As a stressing case, we will assume limited or no availability of high-data-rate SATCOM uplinks due to noise jamming. We will sketch a CONOP for a communication relay system employing airborne platforms at a 55,000-ft altitude to provide connectivity to a satellite in geosynchronous earth orbit (GEO) that is beyond LOS to ground-based noise jammers and kinetic threats in the West Pacific and East Asia.[1] We estimated that a satellite located at 151°W longitude would be beyond LOS to ground-based noise jammers and kinetic threats in most countries in this region.[2] Furthermore, a satellite in this location is within LOS of Pearl Harbor, Naval Base Guam, and portions of the continental United States. This satellite is also within LOS of surface ships and carrier strike groups (CSGs) located 650 nm east of the east coast of Taiwan. We calculated that three airborne platforms could provide connectivity to a position at a ground range of 4,700 nautical miles from the satellite. For instance, it could provide connectivity to a relay located 50 nm east of the east coast of Taiwan. This CONOP is summarized in Figure 4.1. Relay 1 in the figure could provide a high-data-rate communication uplink to a surface asset at a slant range of up to 170 nm, or to a 55,000-ft altitude airborne asset at a slant range of up to 256 nm.[3] This could be used for a variety of tasks, such as providing communication resources to ships, to manned

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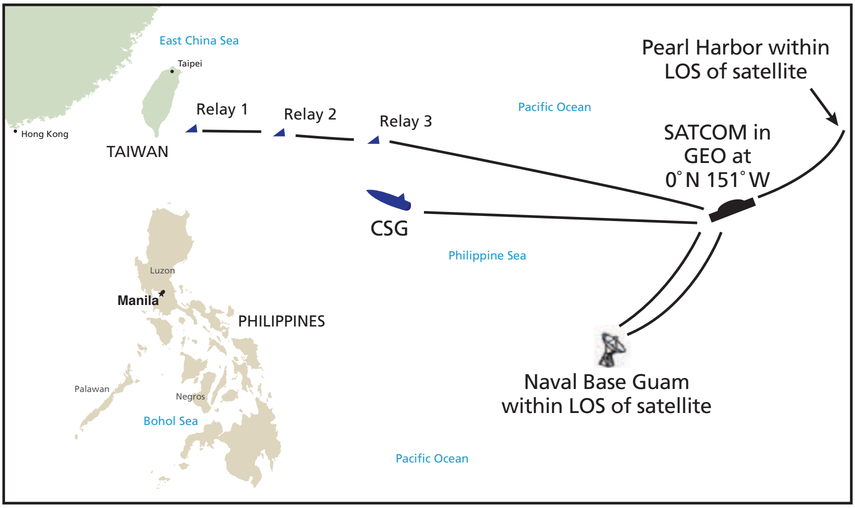
1 The GEO is located over the equator at an altitude of 37,500 kilometers. We will assume design characteristics that are similar to Intelsat 706.

2 Our line-of-sight calculations assume that a minimum 2° elevation angle is needed because of multipath effects and the potential for terrain masking. For air-to-air and air-to-surface links, we assumed a 4/3 scaling of the earth radius to account for RF propagation effects (see Skolnik, 1990; or Larson and Wertz, 1999, for details). RF propagation effects are more complex for air-to-satellite and ground-to-satellite links. We relied on an online satellite antenna look angle calculator for these links (see Satre, 2010).

3 This assumes that a 2° minimum elevation angle is required to mitigate multipath effects and potential terrain masking and takes RF propagation effects into account.

Figure 4.1
CONOP for Theater Relay Application



NOTE: The relays are assumed to operate at an altitude of 55,000 ft.
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or unmanned strike assets (including N-UCASs), to high-altitude ISR platforms, or to Marines on the ground. Note that it would be difficult for an adversary to attack the relay receivers using ground or sea-based noise jammers since they must be able to geolocate and track the UAS, and either have LOS to the receive antenna main beam or use very large and high-power noise jammers to attack the sidelobes. Large, high-power noise jammers would be easy to detect and vulnerable to attack by U.S. forces.

Next, we derived transceiver and antenna characteristics for a Ku-band theater relay payload. We derived these characteristics using the communication link budget equations that are described in the appendix. As we did in Chapter Three, we assumed that communication satellite performance is similar to that of Intelsat 706. We assumed that 9-inch parabolic antennas are used for air-to-air links between the airborne relays, and a 48-inch dish antenna, such as that currently used on RQ-4B Global Hawk, for the link between the airborne relays and the satellite receiver. Transceiver requirements are determined by the air-to-satellite link. We found that a transceiver with 720 watts RF power could provide a 100-Mbps uplink with a reasonable quality of service.[4] We estimated the size, weight, and input power of the transceiver using parametric data that relate these parameters to RF input power for similar SATCOM payloads.[5] We found that the transceiver would require approximately 3.7 kilowatts of input power, weigh 370 pounds, and take up 14,800 cubic inches.[6]

An input power of 3.7 kilowatts dedicated to the communication relay payload may be a significant portion of the total input power available for payloads on a platform such as the BAMS UAS. Current RQ-4B Global Hawk can provide about 25 kilovolt amperes (kVA) for payload power. However, we note that the air-to-air links require only about 10 watts of RF power, and probably less than 200 watts of input power, so that only the relay with the satellite uplink will require significant amounts of input power for the communication relay package. We also observe from Figure 4.1 that most of the relays are far from the area of operations where other sensor payloads are unlikely to provide much utility. Thus, the platform does not need to use its sensors, and input power can instead be dedicated to communication relay.[7]

Detailed Evaluation of Applications for N-UCAS

The LO attributes of the N-UCAS make it suitable for applications in high-threat environments, and it would have an advantage over similar manned aircraft in dangerous applications because the crew is dis-

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[4] We assumed a symbol error probability (before correction) of 10^{-6} and BPSK modulation. In addition to freespace losses, the link budget includes factors for pointing loss, weather and atmospheric losses, and a 7-dB margin. Channelization and three transponders would be required since spectral efficiency would be 1 bps/Hz and each transponder can provide a bandwidth of 36 MHz.

[5] We used the model described in Chaput, 2003, and added additional data for more-recent SATCOM payloads to the model.

[6] These are the requirements for the communication relay transceiver only; they do not include the antennas or communication needs that are organic to the platform.

[7] The 100-Mbps data rate would also have to support the organic uplink needs of the airborne relays.

placed from the threat. As we have noted, however, UASs have a higher dependence on data links, which makes them vulnerable to noise jamming and kinetic threats to their communication resources. Also, the increased communication dependence requires active transmissions with more power than may be needed for manned aircraft, which makes the UAS more vulnerable to detection, tracking, and attack by enemy air defenses. For these reasons, we evaluated potential communication needs for the N-UCAS.

Estimated Characteristics for a Low Probability of Intercept (LPI) Tactical Data Link

Peak data-rate needs are driven by sensor data rates. Referring to Figure 3.3, we see that 6 Mbps is sufficient to support any one of a number of sensor types and modes (individually, not simultaneously), including FMV at 20:1 compression; EO/IR in WAS mode at 10:1 compression; EO/IR spot mode; SAR spot mode; and SAR in WAS mode at 10:1 compression. Also, it is sufficient for ISAR (useful for classifying maritime targets), MMTI, or electronic intelligence (ELINT). Note that sensor resources would be used to provide situational awareness to control the aircraft, as well as collect intelligence products. The total data-rate needs, including 6 Mbps for a sensor and in addition to other data-rate needs, are summarized in Table 4.2. Clearly, the data-rate requirements are dominated by the 8 Mbps return link from the LO UAS shown in the table.

Next, we considered design characteristics for an LPI return link to support this data rate. Note that these may not be the characteristics of an optimal design, but they should provide an illustration that allows us to assess the vulnerability of an LPI link for an N-UCAS.

High frequencies are often selected for LPI applications because they produce narrow beam widths, making it difficult for adversaries to gain LOS to the main beam, and because one can achieve higher data rates for a given RF power (Belcher, 1990; Allen et al., 2000). On the other hand, high frequencies are more attenuated by atmosphere and rain than are lower frequencies. We chose 20 GHz for our

Table 4.2
Estimated Data Rate Needs for Tactical, LO UAS

	Message Size	Urgency	Peak Rate
Position, heading, and velocity	104 bits	1 sec	104 bps
Radar warning receiver	13 bits	1 sec	13 bps
System status report	6000 bits	30 sec	200 bps
Sensor data			< 6 Mbps
Overhead for error coding			15%
Total return link			8 Mbps
Instructions	6000 bits	5 sec	1200 bps
Target location	47 bits	1 sec	47 bps
Overhead for error coding			15%
Total forward link			1.5 kbps

notional design, which offers a compromise between the advantages and disadvantages.[8] In terms of antennas for the LO UAS, a phased-array antenna offers potential advantages, such as the ability to use spatial filtering to attenuate interference and a profile that is easier to incorporate into a stealthy design. We estimate that a 15 × 15 element rectangular array with an overall efficiency of 40 percent can provide 24 dB of antenna gain.[9] Another important design choice for LPI applications is waveform. There is a trade-off between RF power required and spectral efficiency. In LPI applications, it is desirable to choose a waveform that requires little power and accept poor spectral efficiency as a result. We chose a 64-ary waveform.[10] We determined

[8] BAMS UAS antennas are expected to have dual Ku- and Ka-band capability, which should support the 20 GHz frequency selected for our notional LPI tactical data link.

[9] This allows four elements to be dedicated for spatial nulling of interference sources. Space-time-adaptive-processing (STAP) capability may allow nulling of additional sources without significant loss of gain, and would allow time filtering of multipath from the airframe.

[10] The waveform spectral efficiency is 0.1 bps/Hz, and an error energy-per-bit-to-spectral-noise-density ratio of 4 dB results in a symbol error probability of 10^{-5}.

how much RF power would be required to close a link to a communication relay aboard a platform such as the BAMS UAS at a range of 227 nautical miles from the N-UCAS. A large-aperture antenna on the communication relay is desirable for the LPI application. We assumed that the 48-inch SATCOM antenna would be used for this purpose, but we note that there are technical challenges to providing the means of pointing this antenna for use in an air-to-air application. As an alternative, a large-aperture phased-array antenna producing the same gain could be used. Using these assumptions, we determined that the RF power from the active emission of the N-UCAS would be 248 milliwatts (not including antenna gain).[11]

A detailed analysis of the vulnerability of this data link to an adversary's passive ELINT detection systems would have to be conducted at a high level of classification. However, Figure 4.2 shows the received signal power on the ground from the N-UCAS as a function of slant range. The result is based on the assumption that the received signal is 10 dB below isotropic.[12] For reference, we show the received signal power on the ground from a GPS satellite, which is well below the noise floor. We see that the received signal power from the N-UCAS emissions is well below the signal strength of GPS. A detailed discussion of the potential vulnerability of this signal to intercept by adversary passive detection systems would be classified. We note that the N-UCAS emissions to support the 8 Mbps data rate are spread out over an 80 MHz bandwidth using frequency hopping; an adversary will not necessarily know which frequency ranges to monitor to intercept the signal.

The design characteristics we derived are notional. Much more detailed analysis of LPI tactical data link performance would have to be conducted to assess requirements for an operational system and assess potential threats. We believe, however, that our results suggest

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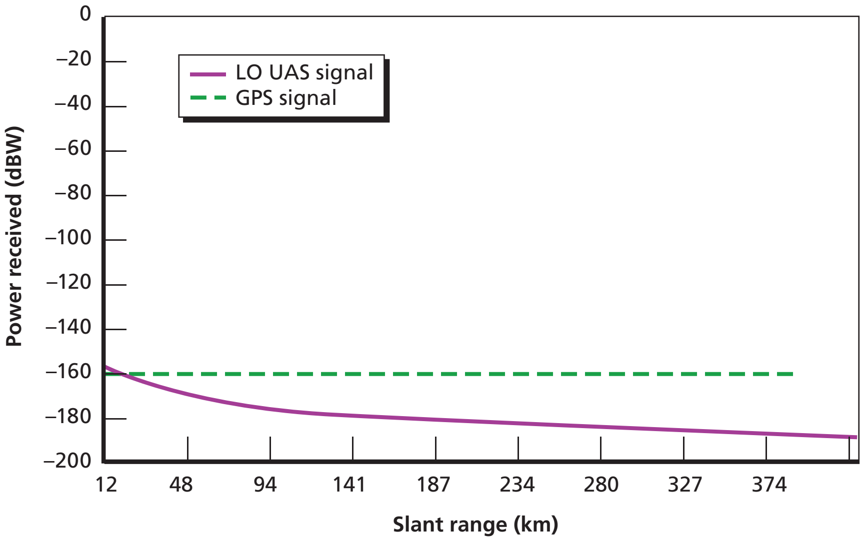
[11] The link budget assumes freespace loss at 227 nautical miles, an atmospheric attenuation of 0.1 dB per kilometer, 10 dB for rain, 2 dB for pointing loss, and a margin of 6 dB.

[12] Obviously, the received signal power would be more if the adversary can detect in the first sidelobes or main beam, but this is made difficult by the fact that it is an air-to-air link with a narrow beamwidth.

Figure 4.2
Received Signal Power Versus Slant Range for RAND Data Link



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there is promise in developing a suitable LPI tactical data link that would enable an N-UCAS to operate in high-threat environments.

Next, we assume that such a data link is available and examine the following potential applications for an operational N-UCAS:

- penetrating strike
- penetrating ISR
- COMINT collection
- ELINT collection
- air-to-air combat
- airborne electronic attack
- suppression of enemy air defenses
- close air support
- CBRN detection.

Note that there are numerous other potential missions for Navy UASs. Due to scope limitations, however, we did not perform an evaluation of all of them. For instance, we did not evaluate the application of UASs to cruise missile defense.

Penetrating Strike

Deep penetrating strike is a challenging application for both manned and unmanned aircraft. We assume that targets in a deep penetrating application are highly defended. An aircraft may have to loiter to be successful against fleeting targets. However, the longer a penetrating aircraft loiters over a given area, the higher the probability that a nearby surface-to-air missile (SAM) will have an opportunity to shoot with a high probability of kill. Penetrating aircraft may attempt to counter this by varying the flight path while they loiter, although this may expose the aircraft to additional SAM sites.

Fuselage shaping will be used to provide UCAS-D with an LO design. Clearly, penetrating strike is an intended mission for an operational N-UCAS. N-UCAS would have two key advantages over manned aircraft for this application: greater range and displacement of crew from threat environment. The unrefueled range of the N-UCAS is expected to be more than double the 1,400-nm unrefueled range of the F-35C. Unlike the F-35C, the N-UCAS is subsonic. But this is not necessarily a disadvantage for this application because subsonic operation reduces the signature of the LO UAS. An additional benefit for N-UCAS over existing platforms is the ability to perform over-the-horizon targeting in support of manned aircraft. The disadvantage of the N-UCAS over manned aircraft in this application is that it requires active emissions for communications to connect the UAS to the displaced crew. Active emissions make the UAS more vulnerable to detection and attack by air defense systems. But careful design of an LPI tactical data link can mitigate this vulnerability.

We recommend penetrating strike as an application for the N-UCAS, and we again emphasize the importance of LPI tactical data links to enable this application for the UAS.

Penetrating ISR

The N-UCAS is better suited to penetrating strike than penetrating ISR missions, because the information collected from the ISR sensors either has to be stored and analyzed when the UAS has exited the threat environment or transmitted via communication links, again making the UAS vulnerable to attack in traditional force-on-force military operations. With a manned aircraft, the onboard crew has the option of directly exploiting the ISR data products, or at least filtering which data products are transmitted. Note that ISR collected by passive means is preferred, when possible, for manned and unmanned aircraft.

The N-UCAS is less suitable for penetrating ISR than for penetrating strike because of the vulnerability that results from transmitting ISR data products to offboard crew.

COMINT Collection

SIGINT is often collected by nonstealthy aircraft at standoff range. A variety of manned aircraft are equipped to collect SIGINT, including Navy EP-3E and Air Force Rivet Joint.

SIGINT can be broken into two different categories. The first is communication intelligence (COMINT). Collection of COMINT is passive. Exploitation of COMINT data products requires a human analyst, and, in the case of UASs, the data products must be transmitted to an offboard analyst at potentially high data rates—typically on the order of 20 Mbps—or stored for post-mission analysis, which reduces the timeliness of the information.[13]

N-UCAS is not particularly well suited for COMINT collection because the active emissions required to send the information to offboard crew would make the platform less stealthy; manned aircraft have the advantage of exploiting COMINT information onboard the aircraft.

ELINT Collection

The second SIGINT category is ELINT collection, which is a passive process principally used to collect radar signals. ELINT is an important component of early warning radar used for self-protection aboard

[13] This is based on a 20 MHz instantaneous bandwidth and a spectral efficiency of 1 bps/Hz, which are typical.

penetrating assets. Processing onboard the UAS can be used to detect, characterize, and geolocate ELINT emitters. The characteristics and location of the ELINT emitters, as opposed to the raw signal data, would be transmitted off board the aircraft. This greatly reduces the power level of active emissions required for sending the intelligence products to offboard crew, since the data rate would typically be less than 100 kilobits per second.[14] If raw signal data must be analyzed off board, as is sometimes the case when the signal from an emitter of an unknown type is collected, it may be stored for post-mission analysis and only the characteristics and location of the emitter transmitted in real time.

N-UCAS may have an application as an ELINT collector because the data rate and active emission requirements are much lower than they are for COMINT. As discussed earlier, the data transmission requirements for ELINT are within the bounds that would be possible for an N-UCAS. We note that variants of the Northrop Grumman Airborne Signals Intelligence Payload (ASIP) SIGINT sensor and LR-100 ELINT sensor have been developed for UASs, including RQ-4B Global Hawk and Predator variants ("Global Hawk RQ-4A-B High Altitude Long Endurance UAV: SIGINT Mission Payload," 2005).

Air-to-Air Combat

Air-to-air combat against highly maneuverable enemy aircraft—in other words, "dogfighting"—is not a suitable application for a UAS in this time frame because the situational awareness and reaction time of an offboard pilot is insufficient. For a manned system, the pilot's reaction time is around 200 milliseconds. For an unmanned system, such a reaction time is currently almost impossible. The data rate required to provide the pilot on the ground with situational awareness is very high, and any loss of communication signal could be disastrous for the UAS. If SATCOM provides the data link, propagation delay alone would

[14] This estimate assumes that the data sent off board include the frequency and location of the emitter, the pulse repetition interval, pulse width, signal strength, and modulation characteristics.

triple the reaction time from 200 to 600 milliseconds.[15] A UAS could be designed to automatically react to information gathered on its sensors, but mature automation technology does not exist to provide this capability, and many challenges remain.

The UAS may be suitable for other air-to-air applications, such as attacking enemy high-value airborne targets that are less maneuverable, such as bombers or ISR aircraft. However, these targets are likely to be defended by fighter aircraft.

The best option for using a UAS in an air-to-air capacity is to have the UAS be part of a larger formation that includes manned aircraft. The manned aircraft, perhaps Navy F-35 aircraft, can lead the UAS into combat and provide "guidance" to the UAS weapons. In essence, the UAS is simply providing the manned platform with more weapons. The UAS itself may be programmed to follow the lead of the manned aircraft and fire weapons at selected targets when instructed. Note that this would place additional demands on the pilot of the F-35. Also, significant technical challenges would have to be overcome.

In summary, we do not recommend air-to-air combat as an application for an N-UCAS. Advances in automation technology and development of CONOPS and capabilities for integrated manned and unmanned aircraft systems may enable air-to-air applications in future UASs. But considerable challenges exist today. For this reason, we do not consider air-to-air combat a promising application for an operation using N-UCAS in the 2025 timeframe.

Airborne Electronic Attack

The Navy currently uses a modified version of the F/A-18, known as the EA-18G Growler, for this application. The Air Force currently uses F-16 aircraft with electronic warfare (EW) pods for this application. Like the F/A-18, the EA-18G is carrier-capable. Unlike the F/A-18, the EA-18G carries both weapons and EW pods.

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[15] It is worth noting that the pilot is usually the limit for g-forces in manned fighter aircraft. Moving the pilot off board eliminates this limitation. However, N-UCAS is not optimized for high g-forces.

The LO features of the N-UCAS would enable close approach to threats and provide an element of surprise in electronic attack applications. However, electronic attack uses high-powered emissions; once those emissions are made, the UAS would no longer be LO. Additionally, the size, weight, and power requirements for EW pods are significant. For instance, each EW pod used aboard the EA-18G Growler weighs 2,200 lbs and requires 37 kVA for operation. It would be significantly challenging to incorporate the capability of an EA-18G EW pod into an LO design. Finally, extreme care in design would be required to shield the UAS data links from the electronic attack equipment to avoid self-jamming of the UAS.

For these reasons, we see limited utility in using an N-UCAS for airborne electronic attack applications. It would have some utility in niche attacks in high-threat environments, where the LO characteristics and element of surprise are an advantage. It would not have the broad range of electronic attack capabilities of the EA-18G because of the challenges of incorporating those capabilities into an LO design and the potential of self-jamming the UAS data links. It should be noted, however, that an exhaustive look at electronic warfare was beyond the scope of this monograph. For instance, we did not evaluate electronic protection with the exception of our discussion of ELINT applications.

Suppression of Enemy Air Defenses

Suppression of enemy air defenses (SEAD) involves the use of electronic attack platforms with weapons. The Navy uses the EA-18G Growler equipped with weapons. The current antiradiation missiles, the AGM-88 high-speed antiradiation missile (HARM) and the AGM-88E advanced antiradiation guided missile (AARGM) have speeds of over 2,000 km per hour and a range of over 90 km. Other weapon options include the AIM-120 advanced medium-range air-to-air missile (AMRAAM), the AGM-154 Joint Standoff Weapon, and cluster bombing of enemy air defense sites.

LO characteristics of the N-UCAS would allow the platform a close approach to enemy air defense systems. This would shorten the kill-chain and improve the chances of successful suppression. This application is dangerous for manned aircraft, and displacing the crew is an advantage for the UAS. It should be noted that after N-UCAS deploys a weapon, its stealth characteristics would be compromised because the weapons bay door would be open. Manned and unmanned LO aircraft would have the same problem. Once the stealth is compromised, the probability of detection would be increased, but only after the mission is performed.

For these reasons, we recommend SEAD as an application for the N-UCAS. A weaponized, LO version of the N-UCAS with the limited electronic attack capabilities previously described would have the advantages of close approach and displacing the crew from harm's way.

Close Air Support

CAS is currently performed by both manned and unmanned aircraft. The Air Force uses MQ-9 Reaper for CAS duties in both Iraq and Afghanistan. The attribute of long endurance provides an advantage to the UAS in this application. Although no LO aircraft are currently used for CAS applications, there may be a time and place where a stealthy CAS platform is needed. We recommend CAS as an application for the N-UCAS.

CBRN Detection and Tracking

Detection of CBRN threats is a dirty application. Detection can be made either before or after release of CBRN agents. It is generally easier to detect CBRN agents after release than it is before release—for instance, by flying through a plume created immediately after an attack on a suspected CBRN weapon site to collect samples, or using sensors to analyze the content of the plume from standoff range to detect the presence of weapon agents and perhaps track the movement of the plume.

Radiation and thermal signatures can be used for detection of some radiological and nuclear threats. Spectral analysis can be used to detect some chemical and biological threats. For instance, an HSI system can be used to characterize the spectral content of a plume and compare the measured spectra to a catalog of known spectra to see if there is a high probability it contains a chemical or biological warfare agent, for instance, using a hypothesis test (see Leachtenauer and

Driggers, 2001, p. 342, for more details). Some agents may not have unique spectral signatures, leading to false alarms (Leachtenauer and Driggers, 2001, p. 366).

HSI systems usually incorporate several sensors, each capable of sensing a different portion of the spectrum. For instance, the system might have separate sensors for the very-near infrared (VNIR) spectrum (0.4 to 1 micrometer [μm] wavelength), the short-wave infrared (SWIR) spectrum (1 to 3 μm wavelength), the mid-wave infrared (MWIR) spectrum (3 to 6 μm wavelength), and the long-wave infrared (LWIR) spectrum (6 to 14 μm wavelength) (Leachtenauer and Driggers, 2001, p. 14). Data from these sensors are combined in the HSI system to create an image with hundreds of individual sub-bands per pixel (Leachtenauer and Driggers, 2001, p. 65).[16] As shown in Table 4.3, chemical and biological warfare agents tend to have spectra with centers primarily in the LWIR spectrum range (see Accetta, 2009, p. 48).

Unfortunately, LWIR sensors suitable for aircraft tend to be more challenging to design than sensors for other spectrum ranges. The reason is that the optics of an LWIR sensor tend to be larger and heavier and tend to have poorer performance in dynamic environments because of their sensitivity to vibration (Wright, 2000). Additionally, even though HSI is a passive sensing mode, aircraft survivability may be compromised due to optical augmentation from the LWIR sensor.[17]

Perhaps the greatest challenge of incorporating a suitable HSI sensor into N-UCAS is processing the vast quantities of data collected by the sensors. Recall from Figure 3.3 that the peak data rate associated with an HSI system is hundreds of Mbps. Processing the data off board the aircraft is not practical because it would require large antennas

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[16] Note that multispectral imaging (MSI) systems are similar but typically have only 3–15 sub-bands with wider bandwidth spectral resolution that is suitable for spectral identification of major features, such as trees, grass or roads, but not well suited to identification of materials (Accetta, 2009, pp. 2–3).

[17] *Optical augmentation* is a phenomenon whereby light is reflected from a focused optical system.

Table 4.3
Chemical and Biological Warfare Agents Tend to Have Spectra with Centers in the LWIR Range

Agent Type	Agent	MWIR Spectral Centers (3–6 μm)	LWIR Spectral Centers (6–14 μm)				
Nerve	Tabun (GA)		7.5	9.6	9.9	13.6	
	Sarin (GB)		7.5	9.8	10.8	11.8	
	Soman (GO)		7.7	9.8	10.1	10.8	11.8
	GF		7.7	9.6	9.8	10.1	11.9
Blistering	Mustard		7.7	8.2	13.9		
Poison gas	Hydrogen cyanide	3.0	7.2	14.1			
	Phosgene	5.5	6.0	7.1	9.9	11.8	
V-nerve stabilizer	Diisopropylcarbodiamide	4.7	7.2	7.6	8.6	9.0	
V-nerve hydrolysis product	2-Diethylaminoethanethiol		6.8	7.2	7.7	8.3	9.3

SOURCE: Accetta, 2009, p. 48.

NOTE: None of these agents have significant spectral centers in the VNIR or SWIR range, so these ranges are omitted from the table.

and transmitting a high-power signal from the aircraft, which would adversely affect aircraft survivability. A more promising option would be to equip the N-UCAS to form the images and compare the measured spectra against a catalog on board the aircraft; if the result is a high likelihood that a threat agent exists, just the relevant information can be transmitted off board for additional analysis and verification. This type of ATC capability is being developed as part of the Hyperspectral Collection and Analysis System (HyCAS) ACTD program for MQ-1 Predator (Mercury Computer Systems Incorporated, 2006). However, HyCAS will not include an LWIR sensor.

An alternative to HSI is light direction and ranging (LIDAR). However, unlike HSI, LIDAR uses active sensing that would be detrimental to stealth.

A simpler approach to CBRN detection is to have the N-UCAS fly through a plume and collect samples to bring them back for testing against reagents. Because the aircraft may become contaminated, an unmanned aircraft in this application has the obvious advantage of eliminating risk of contaminating the pilot. Still, the aircraft has to be recovered and decontaminated. Although procedures are in place for CBRN decontamination of Navy aircraft, it is a complex and potentially hazardous task to perform on an aircraft the size of N-UCAS on the deck of an aircraft carrier, whether the aircraft is manned or unmanned (U.S. Army, 2006).

An alternative is to have the N-UCAS launch smaller UASs that will fly through the plume and collect samples, and then recover the small UASs on the N-UCAS. The concept of having one unmanned system launch another is sometimes referred to as "marsupial robotics," and many universities and laboratories are working to develop this type of technology (SPAWAR Systems Center Pacific website, 2003). However, the challenge of launching and recovering marsupial UASs in a penetrating environment with limited availability of communications for C2 and while maintaining stealth of the N-UCAS is not trivial.

An N-UCAS equipped for penetrating strike and CBRN detection applications could have significant tactical value for striking CBRN weapon sites of near-peer adversaries. As discussed, there are many challenges to developing a CBRN detection capability for an

N-UCAS. Although progress is being made to address each of these, the combined challenge is formidable. For this reason, we do not recommend CBRN detection as an application for N-UCAS in the 2025 time frame.

While CBRN is not a suitable application for N-UCAS, it is a promising application for other types of UASs. In fact, there are efforts to develop CBRN applications for ScanEagle, as discussed later in this chapter.

Summary of Recommended Applications for the N-UCAS

Our evaluation of operational N-UCAS applications is summarized in Table 4.4.

Navy VTUAS

While the BAMS UAS operates from shore and the N-UCAS would operate from carriers, Fire Scout VTUAS can operate from surface ships, offering those ships the additional advantage of a UAS. Fire Scout has well-defined applications for LCS in support of mine countermeasure, surface warfare, and antisubmarine warfare missions. However, with its electro-optical turret equipped with a laser designator and a small surface search radar, the MQ-8B could provide a wide spectrum of surface vessels with an over-the-horizon maritime surveillance capability. Further, the Fire Scout has sufficient payload capacity to provide for a modest armament. Armed variants of Fire Scout could be used to interdict a variety of small boat threats.

The A160T Hummingbird is a VTUAS under development by DARPA and Boeing. Flight tests are scheduled through the end of the decade. Although the aircraft is much larger than the Fire Scout with a footprint closer to that of a MH-60, it is expected to have higher altitude and payload performance. Higher altitude would allow the Hummingbird to have a greater LOS range capability. Higher payload performance could allow a wider range of sensor and weapon options.

Table 4.4
Stoplight Chart of Applications for the N-UCAS

Application	Advantages for N-UCAS	Disadvantages for N-UCAS	Comments
Penetrating strike	Range, stealth, no danger to crew	Vulnerability of C2 data links	LPI data links could reduce vulnerability
Penetrating ISR	Range, stealth, no danger to crew	Vulnerability of data links for ISR products	LPI data links could reduce vulnerability
COMINT collection	Stealth	Large number of antennas required is detrimental to stealth	Useful secondary mission for high-threat environment
ELINT collection	Stealth	Antennas required are detrimental to stealth	Low data rate required for transmittal of data
Air-to-air combat	Range, stealth, no danger to crew, g-forces	Latency; vulnerability of C2 and sensor data links	Not useful in dogfight; manned/unmanned less ambitious
Airborne electronic attack	Stealth, range	Self-jamming; POD weight/power; LO compromised	Potentially useful in niche applications
SEAD	Close approach reduces kill-chain	Limited airborne electronic attack capabilities	Weaponized platform for niche applications
Close air support	Range, stealth		UASs already do it
CBRN detection	Range, stealth, no danger to crew	Accommodating sensors in stealth design and decontamination of aircraft are challenging	Sample collection may be good application for STUAS

Navy STUAS

The goal of the Navy and Marine Corps STUAS/Tier II UAS program is to provide persistent ISR support for tactical-level maneuver decisions and unit-level force defense and protection for Navy ships and Marine

Corps land forces. For the Navy, it is envisioned to be complementary to other, more-capable, tactically oriented, heavily tasked UASs. It will be capable of launch and recovery from an austere, unprepared surface, so it may provide UASs operational capabilities to surface ships that are unable to support a larger platform, such as Fire Scout. (U.S. Navy, 2008). The Boeing/Insitu ScanEagle is one potential candidate for an STUAS; it offers limited ISR capabilities in a high-endurance platform that can be launched and recovered from a wide spectrum of ships.

In 2005, the Navy signed a $14.5 million contract with Boeing to provide ISR coverage with ScanEagle during Naval Expeditionary Strike Group missions and security for oil platforms in the Persian Gulf. The current payload is EO/IR, but a small SAR has also been developed. In Iraq, ScanEagle supports counterinsurgency by providing Marine Corps units information on enemy concentrations, number of personnel, vehicles, and activity that seems suspicious. It has also been used for border and oil pipeline monitoring and has demonstrated voice communication relay. An STUAS could be employed in similar applications for the Navy, such as providing information on number of personnel or extending LOS communications in support of maritime interdiction operations, over-the-horizon surveillance, and tracking vessels in support of missions to counter small boat attacks or piracy.

Additionally, a CBRN detection and tracking capability is being developed for the ScanEagle STUAS (see "ScanEagle to Detect Biological Agents," 2006; and Fein, 2007). The aircraft is equipped with a low-data-rate satellite communication system to allow it to perform the CBRN mission from beyond LOS. The aircraft would fly through a suspected plume created after an attack (by another asset or means) on a suspected CBRN weapon site, to collect samples to be brought back for offboard analysis. The aircraft is not designed to be stealthy, but its small size and slow speed may make it challenging for an adversary to detect and identify it. The small size and light weight of the aircraft may simplify recovery and decontamination, and the relatively low cost may make attrition of the aircraft palatable if recovery is deemed unsafe (for instance, it could be landed or crashed into the CBRN weapon site).

Fire Scout, a large and much more capable UAS designed for a broader range of applications, could certainly perform many of the tasks envisioned for an STUAS. However, it would operate from a more limited variety of ships, and may not be as cost-effective for these specific applications.[18]

Nonstealthy Carrier-Based UAS

Much of DoD's insatiable appetite is for the nonstealthy, MAE strike UASs, such as Predator, Reaper, Avenger, and SkyWarrior. The Army and Air Force have found tremendous utility in these platforms for strike missions. Their endurance attributes allow them to loiter and be effective against time-sensitive targets. It stands to reason that the Navy might find similar utility in these platforms operated from the decks of carriers. These platforms might have advantage in conflicts where carrier resources are first on the scene or where access to air bases is limited.

Carrier-capable versions of Predator have not been fielded. Reaper and Avenger have a size that does not exceed that of an E-2C Hawkeye, and they therefore could physically fit on board an aircraft carrier. Wing structures and landing gear may have to be modified to deal with the intense stress of catapult launch and arrested recovery, the size and placement of the vertical stabilizers may have to change, and a tail hook may have to be added.

While an N-UCAS could provide similar capability, a nonstealthy strike platform would likely have overall lower acquisition and operating costs than a LO N-UCAS. The Navy might benefit from a mix of N-UCASs and nonstealthy, carrier-based and strike-capable UASs to meet its mission needs.

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[18] TheDoD budget for fiscal year 2007 included $37.6 million for procurement of four Fire Scout UASs, or about $9.4 million each (see DoD, 2006). STUAS cost estimates were not available to us. However, given that the procurement cost of the candidate platform ScanEagle is reportedly two orders of magnitude less, at $100,000 each, it is reasonable that STUASs will cost far less than the more capable Fire Scout VTUAS (Garamone, 2005).

CHAPTER FIVE

Conclusions and Recommendations

We recommend communication relay as a traditional military application for Navy UASs. Communication relay mitigates kinetic and noise-jamming threats to satellite communication uplinks. This will benefit fleet assets that are highly dependent on satellite communication resources, including other UASs. The BAMS UAS is particularly well suited to communication relay application because of its high altitude and long endurance attributes, and the Navy has considered this application for the BAMS UAS.[1] However, a communication relay payload would compete for the size, weight, and power needed for the BAMS UAS sensors to support its primary role in providing persistent ISR. This could be addressed by developing a modular payload capability for the BAMS UAS, so that it could be configured with multiple sensors to support its primary ISR roles or reconfigured with a combination of communication relay and fewer sensors for a more limited ISR role. Another alternative is to use the BAMS UAS for the air-to-air links only, and another platform, possibly a manned platform, for the air-to-satellite link. As shown in Chapter Four, the air-to-air links require much less payload power than the air-to-satellite link, making more power available for sensors.

We recommend that the Navy support efforts to develop robust, LPI tactical data links and gear those efforts to meet the specific needs

1 Low-rate initial production vehicles are likely to include a basic communication relay package that leaves space for spiral development of a more capable communication relay package. See Richfield, 2007.

of UASs. Development of this technology could be an enabler for LO UASs such as the N-UCAS.

We also recommend penetrating strike, suppression of enemy air defenses, ELINT collection, and close air support as primary applications for the N-UCAS. Robust, LPI tactical data links are necessary to enable the N-UCAS for these applications. We recommend that the Navy not invest in developing air-to-air combat capability for the N-UCAS because it will likely be less effective than manned aircraft in this application. We do not recommend the Navy explore the utility of N-UCAS in CBRN detection applications, although using other UASs, such as ScanEagle, for this mission is worth consideration. The reasons are the challenge of incorporating a suitable sensor into a stealthy design and challenges associated with decontamination of aircraft upon recovery on an aircraft carrier. Additionally, we see only limited utility of N-UCASs for penetrating ISR, COMINT collection, and airborne electronic attack applications.

We recommend that the Navy consider development of nonstealthy, carrier-based, MAE UASs for many of the applications also considered for the N-UCAS. We note that the Army and Air Force have found great utility in this class of UAS (although it is non-carrier-based), especially for strike applications against time-sensitive targets in more-benign threat environments where LO characteristics are not needed. While the N-UCAS could be used for these applications, a nonstealthy UAS may have a cost advantage because it will not require LO materials, and may have performance advantages in a benign environment because the design is not constrained for LO shaping. If the challenges of operating a UAS from a carrier are addressed in the UCAS-D program, the lessons learned would be applicable to a nonstealthy UAS as well. The Navy should then consider a mix of LO N-UCASs and nonstealthy but carrier-capable strike platforms to meet its prioritized mission needs in a cost-effective manner.

The Navy and Marine Corps are currently leasing STUAS-class aircraft. For the Navy, STUASs could (1) provide information on number of personnel in a battle area; (2) extend LOS communication in support of maritime interdiction operations; and (3) track vessels in support of the mission to counter small boat attacks and pirates. Larger and more-capable platforms designed for a broader range of applications, such as Fire Scout, could be used for the applications envisioned for STUASs. However, they would not operate from the same broad range of Navy ships and may not be cost-effective in these specific applications. If these applications are important to the Navy, then the STUAS/Tier II UAS program to acquire, own, and operate these platforms should move forward.

Because we have not provided an exhaustive list in this monograph, potential nontraditional missions that make sense for UAS in the future may not have been included. As UASs become more versatile and widely operated, there may be more missions that make sense for UASs.

APPENDIX

Summary of Equations Used in Analysis of Communication Systems

This appendix provides a summary of the equations used in our evaluation of communication systems. We used a link budget equation to estimate the performance of communication links, the performance of SATCOM jammers, and the performance of passive detection systems.

The link budget equation we summarize relates the transmitter power, transmitter antenna gain, power losses in the channel and transmit and receive systems, receiver figure of merit, the ratio of energy per bit to noise power spectral density, and data rate of a one-way wireless communication link between a transmitter and a receiver. The link budget equation and variants of it are described in many standard texts on communications.[1]

Let P_t denote the transmitter power in watts (W), G_t denote the transmitter antenna gain (unit-less), L_t denote the total power losses (unit-less), R_f denote the receiver figure of merit in one-over-degrees-Kelvin, E_b / N_0 denote the signal-to-noise ratio per bit in units of one-over-bits, k denote Boltzmann's constant in watt-seconds-per-degree-Kelvin, and d denote data rate in bits per second (bps). Then one form of the link budget equation is

$$d = \frac{P_t G_t R_f}{L_t \left(E_b / N_0 \right) k}. \tag{1}$$

[1] See, for example, Proakis, 2001, pp. 315–318; and Elbert, 1999.

This form of the link budget equation relates the data rate in bits per second that can be achieved in the link to the transmitter power and antenna gain, receiver figure of merit, losses, and signal-to-noise ratio per bit. The link budget equation can be resolved for any of the variables. Most of the variables are self-explanatory and do not require any additional description. The receiver figure of merit, R_f, is the ratio of the receiver antenna gain and the receiver noise temperature in degrees Kelvin. It is commonly listed as a specification for a receiver. For a wireless RF link, the total power loss, L_t, may have many contributions, including free-space loss, atmospheric attenuation, attenuation due to rain, pointing losses due to misalignment of the transmit and receive antennas, polarization mismatch losses, and unplanned systems losses in the transmit and receive systems. Designers of communication systems usually allow some margin in the total power loss for unplanned system losses. Let r denote the range between the transmit and receive antennas and λ denote the signal wavelength (in the same system of units). Then the free-space loss, denoted L_f (unit-less), is given by

$$L_f = \left(\frac{4\pi r}{\lambda} \right)^2 . \tag{2}$$

Atmospheric losses and losses due to rain will vary with signal frequency, altitude, and other factors. Estimates of expected atmospheric losses and losses due to rain are given in Belcher (1990) and Elbert (1999).

The higher the signal-to-noise ratio per bit, E_b / N_0, the lower the ratio of incorrectly received symbols to the total number of symbols transmitted on the communication link. This ratio is called the *symbol error probability*. Hence, E_b / N_0 provides a measure of quality of service (QoS). Trade-off curves are available to designers of communication links that specify the value of E_b / N_0 required to achieve a desired symbol error probability. The trade-off curve will vary depending on the modulation waveform chosen for the communication link. A key consideration in choice of modulation waveform is the trade-off between power and spectral efficiency for a given symbol error probability. Some waveforms have high spectral efficiency, meaning that little bandwidth in Hz is required for a given data rate in bps, but these waveforms achieve spectral efficiency at the expense of more power required for a given QoS. Trade-off curves are available in standard textbooks on communications.[2]

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[2] For instance, see Proakis, 2001, p. 282.

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