The Defense Department and Innovation: An Assessment of the Technical and Policy Challenges of Airborne Boost-Phase Intercept

by

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Abstract

Technological innovation broadly is one of the major sources societal advance. In the realm of defense, it is of prime importance to the strategic interests of a nation. Defense innovation policy is the culmination of a variety of factors, including considerations of the future strategic environment, bureaucratic and organizational politics between military services and civilian agencies, and domestic politics. The differing degrees of influence of these inputs often helps to explain the resultant systems. A case study of particular interest in United States' defense innovation is the modern evolution of missile defense systems. Such evolution principally began under the Reagan administration in response to the threat from the Soviet Union and continues today to meet emerging missile threats. With the emergence of the North Korean ballistic missile threat, a new capability using unmanned aerial vehicles to intercept missiles during boost phase may increase capability to defend the United States from missile attack. To assess why such a system does not currently exist, the viability of such a system, and understand how to field such a system, the following framework is developed:

1. A historical analysis of the origins of current missile defense systems and the implications of its legacy
2. The establishment of a policy consensus of a shift in missile defense towards North Korea and the identification of a technological opportunity in boost-phase intercept
3. Building a political coalition to support the new boost-phase intercept system
4. Case studies on previous missile defense efforts to develop a good product.

This thesis identifies concurrency in acquisitions to provide rapid capability against emerging third-world missile threats as a prime reason for the lack of a current boost-phase intercept capability. Next, it shows that a system based on the MQ-9 Reaper could provide the capability to intercept notional intercontinental- and intermediate-range ballistic missiles from representative geographies in the near-term. Finally, it suggests a political coalition incorporating the combatant commands and the United States Navy due to operational and organizational interests to champion the development of such a system, incorporating recommendations to improve the acquisitions process.

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[1] Any opinions, findings, or recommendations expressed in this material are exclusively those of the author and do not necessarily reflect the views of the U.S. Navy, the Department of Defense, or the U.S. Government.

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List of Acronyms

ABL	Airborne Laser
ABM	Anti-Ballistic Missile
AHTK	Airborne Hit-to-Kill
ALHK	Air-Launched Hit-to-Kill
AMRAAM	Advanced Medium-Range Air-to-Air Missile
AO	Area of Operations
AOA	Analysis of Alternatives
BAM-S	Broad Area Maritime Surveillance
BMDS	Ballistic Missile Defense System
BSTS	Boost Surveillance and Tracking System
BMDO	Ballistic Missile Defense Organization
BPI	Boost-Phase Intercept

C2BMC	Command, Control, Battle Management and Communication
CC	Command Center
CCDR	Combatant Commander
CE	Capability Enhanced
CEC	Cooperative Engagement Capability
COCOM	Combatant Command
CONOP	Concept of Operation
EKV	Exoatmospheric Kill Vehicle
EO	Electro-Optics
FY	Fiscal Year
GAO	Government Accountability Office
GBI	Ground-Based Interceptor
GMD	Ground-Based Midcourse Defense
GEM	Guidance Enhanced Missile
GPALS	Global Protection Against Limited Strikes
GSTS	Ground-based Surveillance and Tracking System
ICBM	Intercontinental Ballistic Missile
IR	Infrared
IRBM	Intermediate-Range Ballistic Missile
JCS	Joint Chiefs of Staff
KV	Kill Vehicle
MAD	Mutually Assured Destruction

MDA	Missile Defense Agency
MRBM	Medium-Range Ballistic Missile
MTS	Multi-Spectral Targeting System
NCADE	Network-Centric Airborne Defense Element
NDAA	National Defense Authorization Act
NEI	Noise Equivalent Intensity
NIFC-CA	Naval Integrated Fire Control – Counter Air
NMD	National Missile Defense
OTA	Office of Technology Assessment
PAA	Planned Adaptive Approach
PAC	Patriot Advanced Capabilities
PACOM	Pacific Command
PIP	Predicted Intercept Point
PTSS	Precision Tracking Space System
SBI	Spaced-Based Interceptor
SDI	Strategic Defense Initiative
SDIO	Strategic Defense Initiative Organization (Office)
SSTS	Space Surveillance and Tracking System
SRBM	Short-Range Ballistic Missile
THAAD	Terminal High Altitude Area Defense
TMD	Theater Missile Defense
UAV	Unmanned Aerial Vehcile

WMD .... Weapon of Mass Destruction

Chapter 1. Framework and Methods for Assessing Defense Innovation

As technology continues to permeate further into every element of society, the mechanisms that drive the development of technology gain further importance. Such advances have given rise to tremendous achievements in a variety of fields. In some fields, such as healthcare, aircraft safety, and many others, these achievements are quite literally matters of life and death. The perhaps comfortable narrative characterizes the processes of innovation as the strictly rational "data driven" pursuit of optimal solutions to existing issues. Often, however, the reality of technological development tends to be much more complex. Like in other fields, these complexities drive the technologies and systems that militaries field, and such systems are matters of life and death both for the militaries that employ these systems and the nations that rely upon the employment of these systems for their security. Beyond the assessment of technological systems' ability to provide a desired capability, the politics and dynamics of bureaucracies, governments, and societies can greatly influence what technology is eventually developed.

Such complexities are present in the evolution of technology in Western militaries. Authors such as Barry Posen, Stephen Rosen, Owen Coté Jr., and many others studied at length the general conditions that resulted in the capabilities fielded by these militaries. To varying degrees, these works discuss the extent to which factors influence technological development. In some cases, assessments of the security environment and associated technological opportunities to meet security challenges dominate. In others, the power of civilian leaders or the competition within and between bureaucracies and military services explain the results. Taken as a whole, these works provide a variety of lenses to understand military developments.

The modern American military, under the Department of Defense, is a highly complex bureaucracy of four distinct military services and several different agencies. Different considerations dominate in different subsystems of the overarching organization. Such complexities require the consideration of individual elements of this apparatus. A relatively recent component of the Defense Department, the Missile Defense Agency (MDA), offers a unique perspective into the pursuit of technical systems. President George W. Bush created MDA in 2002 to direct the pursuit of missile defense capabilities. Because of the historical legacy preceding its creation, the political moment at the time of its birth, and technology required for missile defense, MDA offers an opportunity to understand further the dynamics of technology development. Such an understanding lends an opportunity to improve the process of technological development within the United States' pursuit of missile defense and provide increased capability to meet the security challenges of today.

To pursue the goal of fielding improved future missile defense capabilities, this work considered the factors that influence Defense Department acquisitions. Sapolsky et. al identified three obstacles to successful acquisition programs. The first condition requires a convergence of a policy consensus, an agreement that a security challenge needs addressing, and a technological opportunity to address that challenge. Second, a political coalition must be assembled and maintained to support and advocate for a program through its lifetime. Third, the program must field a good product that provides a capability (Sapolsky, 92-94, 2009). As a case study for utilizing this framework to understand the MDA process, this work considered the introduction of an airborne boost-phase intercept capability. Various authors have suggested such a system may offer missile defenses increased capability. This work aims to assess if such claims are correct, that an airborne system could intercept a ballistic missile in boost phase, and if so, why has the MDA not pursued such a system?

The work slightly modified the Sapolsky framework for the consideration of the boost-phase capability. Namely, it incorporated a historical analysis of the previous missile defense environment to characterize the progression and decisions that led to the current systems. Figure 1 shows the framework and the general methods applied.

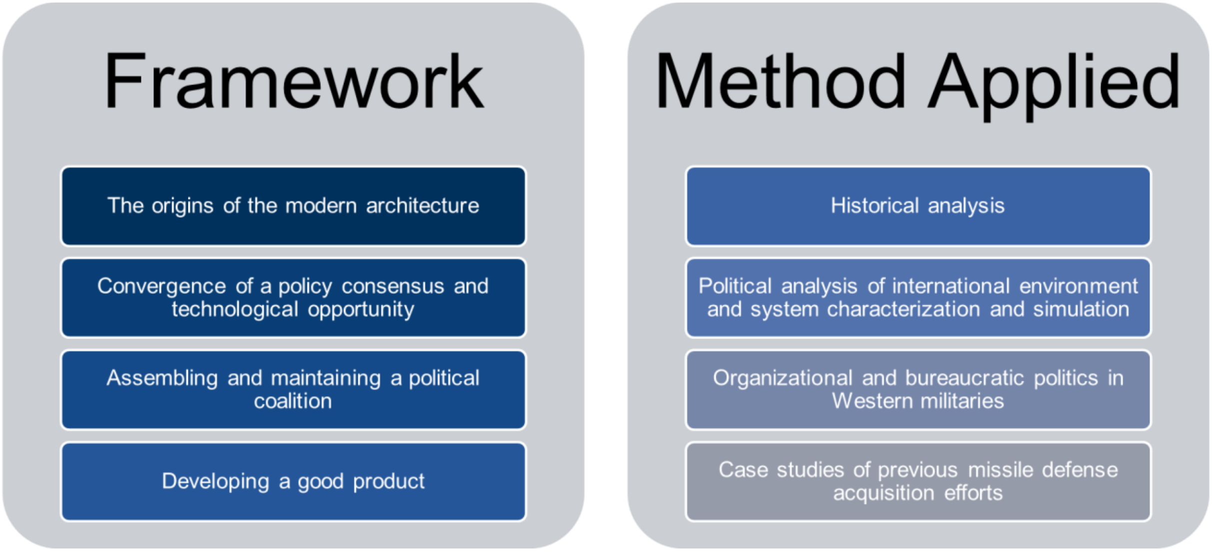

Figure 1. Framework and methods applied

This thesis first investigates the origins of the modern architecture through a historical analysis of an existing and extensive secondary source literature. Second, this thesis argues a new policy consensus regarding a shift in missile defense focus to North Korea, applying a political analysis of the international security environment, and highlights the technical opportunity unmanned aerial vehicles present for a boost-phase intercept capability, developing a system, and modeling the employment of such a system. Third, this thesis characterizes the environment at MDA and suggests a political coalition to support the development of a new system using the aforementioned organization and bureaucratic political analysis in Western militaries. Finally, this thesis makes suggestions on how to develop a good product, drawing lessons from previous case studies in missile defense acquisition efforts.

Chapter 2. The Origins of the Modern Missile Defense Architecture

With the proliferation of ballistic missile technology across the globe to nations that are potentially hostile to the United States and the current and future proliferation of nuclear weapons, the United States has elected to pursue a robust missile defense system. Starting with the deployment of the Patriot missile in the first Gulf War, American missile defense has evolved to include multiple systems intended to provide point, regional, and national defense capabilities, focusing on intercepting missiles after threat burnout. This architecture is a product of the strategic environment and political choices in the legacy of the Strategic Defense Initiative (SDI) program initiated under President Reagan, culminating in the deployment of a national missile defense system during the Bush presidency and its subsequent continuation in the Obama presidency.

2.1 A Brief Primer on Modern Missile Defense Architecture

The following section serves as a brief introduction to the classes of ballistic missiles threats and some of the options available for defending against them.

2.1.1 General Classes of Threats

While the classification criteria varies depending on source, ballistic missiles are generally categorized based on range. Ballistic missiles are generally classified into five classes, with four types of interest here. This thesis adopts the following classifications. The shortest-range ballistic missiles are Close-Range Ballistic Missiles (CRBMs), with ranges of less than 300 kilometers. Of greater interest to this thesis are Short-Range Ballistic Missiles (SRBMs), with ranges between 300 and 1,000 kilometers, Medium-Range Ballistic Missiles (MRBMs), with ranges between 1,000 and 3,500 kilometers, Intermediate-Range Ballistic Missiles (IRBMs), with ranges between 3,500 and 5,500 kilometers, and Intercontinental Ballistic Missiles (ICBMs), with ranges in excess of 5,500 kilometers. SRBMs and MRBMs are sometimes collectively referred to as Theater Ballistic Missiles (TBM) (National Research Council, 27, 2012). Figure 2 depicts trajectories for these classes of missiles, as well as current defensive systems to counter these threats, discussed in the next section.

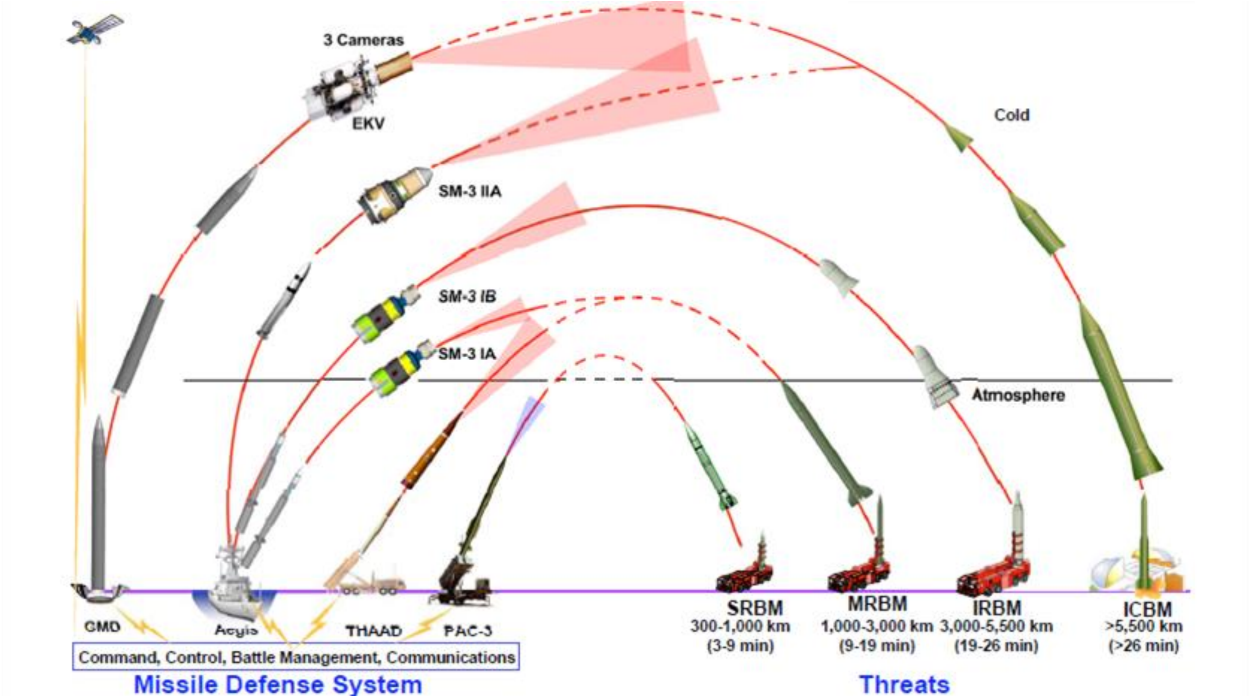

Figure 2. Classes of ballistic missiles and defensive systems[1]

2.1.2 ***Defending Against Ballistic Missile Attack***

For a defensive system to successfully engage a threat missile, it must perform the following tasks: detection, tracking, discrimination, fire control, homing, and negating the threat. Detection is identifying that a threatening missile has been launched. Tracking is repeatedly observing the location of the target to produce estimates of its future position. Discrimination is the process of selecting the threatening object, the warhead, from several possible objects such as the spent booster, debris, and countermeasures. Discrimination is necessary to prevent excessive use of interceptors and ensure engagement of the correct target. Fire control is determining where to intercept the threat with the available interceptors. Homing is guiding the interceptor to ensure that it arrives at the intercept point at the same time as the threat, updating the intercept point over time as necessary. Finally, negation is eliminating the destructive potential of the weapon, either through body-to-body contact (hit-to-kill), an explosive warhead, or other means (Masters,

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[1] Missile Defense Agency.

2014). These processes can be performed during three distinct phases of the threat missile's flight: boost, midcourse, and terminal.

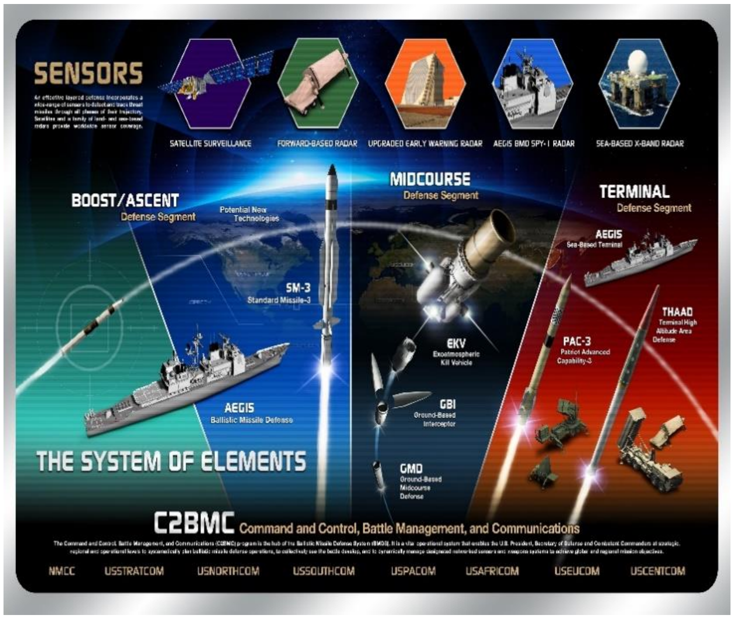

Figure 3. Ballistic missile phases of flight and defensive systems

Figure 3 depicts the various phases of flight and some of the modern systems or concepts available in those phases. Boost phase is the time while the rocket engines are still thrusting (the missile is "boosting"). Some sources consider ascent to be after burnout but prior to the deployment of countermeasures. However, ascent has physics challenges similar to midcourse, as the warhead has already separated from the booster. Ascent is, in many respects, simply "early midcourse." Midcourse is the time from the burnout of the missile boosters until the warhead reenters the atmosphere. The terminal phase of flight is when the missile and its deployed components reenter the atmosphere ("A System of Elements," 2015). In response to these myriad threats and to increase the robustness of the defensive system, the United States is pursuing a "layered" defensive architecture that provides multiple intercept opportunities in all phases of flight for a variety of missile threats by fielding multiple systems as a part of a "system-of-systems."

The United States has fielded several systems, together known as the Ballistic Missile Defense System (BMDS), to counter existing threats principally during the midcourse and terminal stages of flight. These systems are interoperable to allow a desired layered defense. Three systems serve as the principal Theater Missile Defense (TMD) assets. The Aegis system with the Standard Missile (SM)-2 and -3 is a ship-based system designed to detect and track ballistic missiles utilizing the onboard AN/SPY-1[1] radar. The SM-3 engages medium-range threats in midcourse while the SM-2 engages short-range threats in the terminal phase. SM-2 relies principally on a blast fragmentation warhead while SM-3 utilizes hit-to-kill to destroy threats. The United States had 33 deployed BMD-capable Aegis ships as of December 2014. Terminal High Altitude Area Defense (THAAD) is a land-based system that can engage missiles both inside and just outside the atmosphere. The system makes use of the Army Navy/Transportable Radar Surveillance-2 (AN/TPY-2[2]) for tracking and discrimination and then launches a hit-to-kill interceptor. The system is also rapidly deployable by land, sea, or air. Finally, the Patriot missile system has evolved from the original Gulf War era system, making use of an organic[3] phased-array radar, the AN/MPQ-53, to provide terminal defense. When combined with THAAD, Patriot can provide layered point defense. The Patriot system utilizes two missiles depending on the threat type: the Guidance Enhanced Missile (GEM) uses a blast fragmentation warhead and the Patriot Advanced Capabilities-3 (PAC-3) is hit-to-kill. For defense of the homeland, the current fielded system is the Ground-based Midcourse Defense System (GMD). GMD relies upon land-based radars and Aegis ships to provide tracking data and then engages threats in midcourse with the Ground Based Interceptor (GBI). The GBI deploys the Exo-atmospheric Kill Vehicle (EKV) to home to the target and hit-to-kill the threat. The Command, Control, Battle Management, and Communications (C2MBC) system connects these systems and provides coordination of missile defense engagements ("The Ballistic Missile Defense System," 2015).

2.2 The Progression from SDI to GMD

In order to understand the mechanisms by which missile defense systems have entered the United States' arsenal, an investigation of the emergence of modern capabilities provides insight into the technical environment and policy decisions that shaped fielded systems. The history of this development has important implications for understanding the political institutions and strategic considerations that affect the pursuit of missile defense. Further, this history also reveals what factors shaped the systems employed and why certain capabilities exist while others may not. In sum, technical factors have had less significance in historic missile defense choices

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[1] The AN/SPY-1 designation follows the format: Army Navy Joint Electronics Type Designation System/S - Water (surface ship), P - Radar, Y - Surveillance (target detecting and tracking) and Control (fire and/or air control), model number.

[2] Army Navy/T – Transportable, P – Radar, Y – Surveillance

[3] Organic is the military vernacular for a capability that is included in a given unit. For example, an aircraft carrier has "organic" aircraft, in that it carries those aircraft with it.

than other factors. The increased importance of nontechnical factors may be part of the reason why the current BMDS does not possess a boost-phase defense capability.

2.2.1 President Reagan: A Vision of Missile Defense

Though previous administrations launched missile defense efforts, the evolution of modern missile defense began largely during the Ronald Reagan presidency almost in a singular moment. On March 23, 1983, President Reagan gave a televised address announcing an effort to make nuclear weapons “obsolete” and “impotent” through the development and deployment of a missile defense system. The statement challenged the place of Mutually Assured Destruction (MAD) based on mutual vulnerability of the Soviet Union and the United States as the centerpiece of American strategic security policy and ignited the modern missile defense debate within the United States. This effort became known as the Strategic Defense Initiative (SDI), with the Strategic Defense Initiative Organization, alternatively Office, (SDIO) tasked to develop and implement the system. (Cho, 63, 2009; Van Hook, 7, 2002). SDI differed from previously considered ABM systems in proposing a layered defense architecture, enabling intercept of enemy ballistic missiles in all three phases of flight (Van Hook, 8, 2002). This was the first missile defense concept to introduce the idea of layering systems into a system-of-systems to provide greater coverage and increased intercept opportunities.

President Reagan’s decision to pursue SDI was influenced heavily by the coalescing of the Joint Chiefs of Staff (JCS), namely through the concerted efforts of the Chief of Naval Operations, Admiral James D. Watkins. Watkins, in the midst of a debate in where to base the new MX ICBM, observed,

> We were reaching the point where we were losing our hat, ass, and overcoat at Geneva. We had no bargaining chips, no strength, with which to negotiate. The Soviets could just sit at Geneva and watch us throw away all of our chips right here in Washington. That’s one reason I wanted to influence the Joint Chiefs of Staff, so I worked hard…I felt so strongly we were headed into a strategic valley of death (Baucom, 184, 1992).

In response, Watkins led a review of strategic issues surrounding the MX program. After several months of meetings on the topic, he was convinced there was not an invulnerable basing mode for the MX to allow it to serve as an effective counterforce deterrent to Soviet missiles. However, Watkins believed America’s advantage typically stemmed from high technology and began to consider a technological remedy to the situation. Further, Watkins was a devout Catholic. At the time he was leading the strategic review, Watkins, and the other 50 million American Catholics, was influenced by the movement of Catholic bishops questioning the moral legitimacy of MAD. In a letter titled *The Challenge of Peace: God's Promise and Our Response,* the Catholic Church declared its support for the freeze movement, advocating for a halt in the testing, production, and deployment of nuclear weapons. The letter began producing effects even prior to its publication, particularly as sailors and officers started to leave the Navy citing moral concerns articulated by the letter. Finally, as Watkins prepared for the JCS meeting with President Reagan on February 11, 1983, he met with a group of high-level advisers, namely missile defense advocate Edward Teller. Teller was able to convince Watkins that missile defense offered the ability to use technology to move beyond the MX basing debate in the short-term and a long-term shift to a more morally palatable deterrence, indicating the technology could be developed in 20 years (Baucom, 184-189, 1992).

Watkins proceeded to convince the rest of the JCS of the merits of missile defense in a meeting on February 5, 1983. The collapse of the dense pack MX basing mode moved Air Force Chief of Staff General Charles A. Gabriel to agreement, and the Chairman of the JCS, Army General John William Vessey Jr., supported missile defense on the grounds of previous support for Army ballistic missile defense plans and moral concerns surrounding MAD (Baucom, 190, 1983). Finally, in the February 11th meeting, the unanimous support of the JCS as well as support from the National Security Adviser Robert C. McFarlane convinced President Reagan to pursue missile defense, and he directed the JCS and McFarlane to develop a proposal. President Reagan would continue to push the JCS for the missile defense proposal in the run-up to his speech, either on political advice or due to his own sense of the strategic crisis. The final push that led to the announcement of SDI was McFarlane gaining the support of science adviser George Keyworth and the subsequent revelation to and handling objections from other key government officials (Baucom, 192-195, 1992).

The SDI announcement came at a particular political moment, allowing a political coalition to coalesce around the concept. Specifically, the announcement came in the context of a Soviet missile build up, suspicions of Soviet SALT violations, and improvements to the Moscow ABM system. These factors converged to create a strategic desire for SDI (Cho, 63, 2009). Support for the program came from various corners. SDI fit within the broader political goals of the Republican Party, namely a build-up of United States' defense capabilities and technologies and enamored a great deal of public support, drawing from Reagan's singular skill as an orator and declining support for the MAD doctrine. The military as a whole supported the SDI program because it offered defense of strategic missile sites, decreasing the vulnerability of strategic weapons. Finally, SDI garnered the support of defense contractors viewing potentially lucrative contracts supporting the deployment of an expansive system (Van Hook, 9-10, 2002).

2.2.1.1 Exploration and Opposition

The announcement of SDI served mainly as a statement of policy that the United States intended to field a missile defense system. However, specifics of the system had yet to be decided or largely investigated. Released later in 1983, the interagency report, combining the Defense Technologies Study and the Future Security Strategy Study, recommended an architecture of lasers, sensors, and interceptors based on the ground, in the air, and in space and exploration of the suggested concepts within a couple of years. The report was generally regarded as a recommendation for necessary research to support a missile defense system vice a commitment or an endorsement of a specific architecture (Cho, 65-66, 2009). With fears of increasing Soviet capability, President Reagan subsequently approved the acquisition of the Strategic Defense System Phase I architecture after two and a half years of research and development in 1987. The Phase I architecture contained six subsystems: a spaced-based interceptor and two sensors, a ground-based interceptor and sensor, and a battle management control system (Jones, 2, 2002).

However, institutions outside of the Reagan administration expressed skepticism in the feasibility of the SDI system. Analysis from independent universities, the Union of Concern Scientists, and the Office for Technology Assessment (OTA) depicted a far less optimistic projection of SDI viability. While the Reagan administration continued to project confidence, it did not commit to a specific architecture beyond the Phase I subsystem definitions. The uncertainty in SDI goals and architecture shifted the debate to ideology surrounding the system, rather than specifics of the system and their technical merits (Cho, 67, 2009). Further, its place within the overarching strategic strategy of MAD was complicated by competing administration statements. Specifically, the public face of SDI as omnipresent and capable of defending the entire United States was often far more optimistic than reports delivered to Congress. Defense Under Secretary for Policy Dr. Fred Ikle suggested in Congressional testimony that an intermediate step for SDI was defense against limited ballistic missile attacks (Cho, 70, 2009).

Additional political issues began to arise for the SDI program. First, it presented issues with respect to the Anti-Ballistic Missile (ABM) Treaty of 1972. Article I of the ABM Treaty restricted the United States and the Soviet Union from the development and deployment of an ABM system. Article III created two exceptions: point defense of the capital and an ICBM launch site, later reduced to one site by the 1974 ABM Protocol (Van Hook, 5, 2002). Article V restricted the development, test, and deployment of sea, air, space, or mobile land-based systems. SDI, with the expansive proposed architecture in Phase I, would ultimately require withdrawal from the ABM Treaty (Van Hook, 11, 2002). Second, contractor base interest eventually waned as the prospect of an actual deployment decreased. The lack of clarity surrounding a planned deployment prevented the solidification of support as corporations did not have an understanding of what to expect from SDI (Van Hook, 12-13, 2002). Finally, additional fears also existed from the fear of fueling an arms race, limited capability of the system, and due to the lack of technological maturity (Van Hook, 14, 2002). The sum total of the political and technical complications was the lack of a commitment to deploy a missile shield by the end of the Reagan presidency. However, the vision and narrative created by Reagan around SDI in many ways precipitated the attitudes and policy positions on missile defense and set the environment that eventually led to the missile defense system of today.

2.2.2 President George H.W. Bush: Missile Defense in a New World Order

President George H.W. Bush entered office a less ardent supporter of missile defense than President Reagan did. Further, the strategic environment during his tenure would change dramatically, leading to significant changes in the direction of the United States' missile defense programs.

2.2.2.1 Early Decisions

Early in his presidency, the H.W. Bush administration decided to restructure Phase I of SDI for budgetary and technical reasons in FY 1989. The new plan consisted of seven elements: 1) Boost Surveillance and Tracking System (BSTS), 2) Space Surveillance and Tracking System (SSTS), 3) Ground-based Surveillance and Tracking System (GSTS), 4) Command Center (CC), 5) Ground-Based Radar (GBR), 6) Ground-Based Interceptor (GBI), and 7) Space-Based Interceptor (SBI) which eventually evolved into the Brilliant Pebbles program and associated Brilliant Eyes sensor element. BSTS was targeted for a two-year deployment timeline, and SSTS was targeted for 1994 (Cho, 78, 2009). Despite the decline of the Soviet Union and the dramatic fall of the Berlin Wall in 1989, uncertainty in the strategic environment in the post-Cold War Era furthered a desire for the maintenance of United Stated strategic policy centered not on first strike, but missile defense and massive retaliation. SDIO director George Monahan advocated for SDI for three principal reasons in 1990: the remaining Soviet threat; political instability in the Soviet Union; and the proliferation of ballistic missiles, citing a CIA analysis estimating 15 countries could have ballistic missiles by 2000 (Cho, 82-83, 2009). His analysis was an early indication of future concern over the expansion of the ballistic missile threat beyond the Soviet Union. However, Democrats dominated Congress during the Bush presidency, seeking to draw down defense spending. Further, it was deeply skeptical of SDI due to constant changes in architecture and its chilling effect on arms reduction negotiations, electing to use the continued decline of the Soviet Union and "the peace dividend" to reduce SDI spending (Cho, 231-234, 2009).

2.2.2.2 The Gulf War and the "New World Order"

The collapse of the Soviet Union and changing global circumstances led to a rapidly changing strategic environment during the second half of the H.W. Bush term. With the announcement of the "New World Order" in his January 1991 State of the Union Address, President H.W. Bush refocused the United States on developing mechanisms for maintaining peace. MAD, in some respects, became less useful as a strategic doctrine as concern shifted to Third World and accidental launches of ICBMs (Cho, 83-84, 2009). The speech came in the context of the Gulf War, in which Iraq's launch of 90 Scud missiles at Saudi Arabia and Israel caused 25 percent of United States' casualties and almost destabilized the coalition by drawing Israel into the conflict. Further, it caused the intelligence community to reevaluate the threat from ballistic missiles and associated Weapon of Mass Destruction (WMD) payloads. These shifts in perspective culminated in President H.W. Bush redirecting SDI in the 1991 State of the Union Address:

> Looking forward, I have directed that the SDI program be refocused on providing protection from limited ballistic missile strikes, whatever their source. Let us pursue an SDI program that can deal with any future threat to the United States, to our forces overseas, and to our friends and allies (Hoene, 1, 1996).

This new order produced significant changes in types and number of threats the United States faced. The collapse of the Soviet Union reduced the likelihood of a massive nuclear missile exchange, but, in the opinion of United States' Air Force Lt. Col Hoene of the National War College, "the new world order is now more threatening, albeit on a more limited basis, than before" (Hoene, 3, 1996).

Almost overnight, the focus of strategic concerns and missile defense in particular shifted to concern over the proliferation of missiles to Third World or rogue states. Dr. Keith Payne, a BMD supporter, cited Muammar Al Qadhafi (the leader Libya), Saddam Hussein (President of Iraq), and Abu Abbas (head of the Palestinian Liberation Front) as entities with stated desires to use ballistic missiles against the United States, if possible. He also contended that other delivery mechanisms commonly cited, such as suitcase bombs or shipping containers, would not necessarily be preferred by these entities (Cho, 85, 2009). As Qadhafi stated after the 1986 American bombardment of Tripoli,

> If they know you have a deterrent force capable of hitting the United States they would not be able to hit you. Because if we had possessed a deterrent, missiles that could reach New York, we could have hit in the same moment. Consequently, we should build this force that they and others will no longer think about an attack (Hoene, 5-6, 1996).

Further, apparent success of the Patriot in "hitting a bullet with a bullet" against the Scud missile increased optimism regarding the technical feasibility of SDI (Cho, 80, 2009). The SDI concept, following reorganization, became known as Global Protection Against Limited Strikes (GPALS) and retained elements of the SDI Phase I space-based architecture inherited from the Reagan-era, but parred it down to the constrained budget environment and emphasized ground-based systems to capitalize on Patriot's success (Cho, 80, 2009). The shift to GPALS represented a shift away from the Cold War doctrine of containment and deterrence through MAD to a strategy of deterrence and defense utilizing missile defense (Hoene, 1, 1996).

Not all entities agreed to the continued focus on an SDI-type national missile shield. Congress took a different view of the implications of the Gulf War, believing that the more significant threat was posed to American forces deployed to a specific theater and increased funding for TMD programs in response to the Gulf crisis, in opposition to the Pentagon request (Cho, 235, 2009). Further, technical evidence was presented indicating poor Patriot performance in the Gulf War, namely from Dr. Theodore Postol at MIT. Despite these issues, the image of Patriots destroying Scuds in flight created powerful Congressional support, leading to the insertion of the Missile Defense Act of 1991 into the defense authorization bill (Cho, 237, 2009). The Act passed the Senate relatively easily and survived conference as a political chip to negotiate a decrease in the number of B-2 purchases called for by the House (Cho, 241, 2009). This act marked the first legislative mandate for a limited ballistic missile defense system, a marked policy change under the H.W. Bush presidency from SDI. It required deployment of a cost-effective system by 1996, or as soon as technologically feasible, compliant with the ABM Treaty (Cho, 77, 2009). An interesting note, though, is the strong Congressional appetite for SDI came largely in opposition to public opinion. Only one-third of respondents in a *Los Angeles Times* survey in 1992 favored SDI development, indicating that public support may not have been as strong as support in Congress (Cho, 245, 2009). In sum, "the important policy statement to deploy an ABM system by 1996 was a product of Congress' initiative and legislative effort" (Cho, 246, 2009).

However, in response to technical uncertainty and the beginning of START, Congress delayed deployment until 2002 from the original 1996 date and maintained the requirement that the architecture be within the ABM Treaty (Cho, 242, 2009). While an architecture was ultimately not deployed during the H.W. Bush presidency, the transition from SDI to the GPALS system and the subsequent support of Congress for missile defense represented significant policy steps towards the architecture of today.

2.2.3 *President Clinton: Security, Politics, and Missile Defense*

The presidency of William Clinton saw a significant evolution in support for missile defense. The strategic environment continued to evolve in ways that increased the perceived need for a missile shield. Politics also significantly altered through the two Clinton terms in ways that produced significant impacts on the eventual course of the missile defense architecture.

2.2.3.1 An Early Emphasis on Theater Missile Defense

The Gulf War and employment of the Patriot missile against the Scud engendered support for TMD. National Missile Defense (NMD), the new designation for the GPALS concept under President Clinton, did not enjoy such universal support, as President Clinton quickly moved away from the concept (Hoene, 1, 1996). On May 13, 1993, President Clinton renamed SDIO the Ballistic Missile Defense Organization (BMDO), demoting its standing within the defense hierarchy (its director reported to an Under Secretary, not Secretary), and refocused on TMD after the post-Cold War "Bottom-Up Review" of defense capabilities. Under this organization, the improved Patriot system, the Aegis TMD components, and THAAD were developed and remain significant elements in the missile defense architecture of today (Jones, 3, 2002). BMDO also sought to maintain an ability to rapidly deploy an NMD system while advancing technology, though it did not commit to a specific architecture (Van Hook, 16, 2002).

Congress also indicated its preference for theater defenses over national systems. FY 1993 budget reductions focused efforts on TMD, with the near-term push centered on improvements to the Patriot system, mid-term analysis of TMD options such as THAAD, PAC-3, and Aegis, and the elimination of SBI and significant cuts to the Brilliant Eyes, the follow-on to the SSTS program (Cho, 90-91, 2009). A 1993 amendment to the 1991 Missile Defense Act sought the advancement of a more capable theater system than the Patriot and laid the framework for THAAD. However, some critics noted THAAD was capable as a strategic defensive system, whose use or test would violate the ABM treaty, reigniting debates around NMD (Van Hook, 17, 2002). In subsequent years, Congress further indicated its distaste for NMD and funded it below the levels requested by the Clinton administration (Cho, 248-249, 2009). Congress also pushed for a strict interpretation of the ABM Treaty, requiring the Secretary of Defense to review the Navy Upper Tier, an exoatmospheric missile defense system, and the Brilliant Eyes programs for ABM Treaty compliance. Further, Congress revised the Missile Defense Act to make NMD deployment an option rather than mandatory (Cho, 249, 2009).

2.2.3.2 Back to NMD: Proliferation and the Contract with America

President Clinton and the Democratic controlled Congress significantly reduced efforts towards developing an NMD system during the early part of his presidency. However, political and strategic requirements began shifting to reverse that course. In testimony before the Senate in January 1994, the Director of Central Intelligence, James Woolsey, stated “ballistic missiles are becoming the weapon of choice for nations unable to strike their enemies at long range” (Hoene, 5, 1996). In light of these analyses, President Clinton issued Executive Order 12938 on November 14, 1994, declaring a national emergency stemming from the threat from ballistic missiles and associated nuclear, chemical, and biological WMDs. The following year, on November 8, 1995, President Clinton reiterated the magnitude of the threat, stating,

> On November 14, 1994, by Executive Order 12938, I declared a national emergency with respect to the unusual and extraordinary threat to the national security, foreign policy, and economy of the United States posed by the proliferation of nuclear, biological, and chemical weapons (‘weapons of mass destruction’) and the means of delivering such weapons. Because the proliferation of weapons of mass destruction and means of delivering them continues to pose an unusual and extraordinary threat to national security, foreign policy, and economy of the United States, the national emergency declared on November 14, 1994, must continue in effect beyond November 14, 1995. Therefore . . . I am continuing the national emergency declared in Executive Order No. 12938 (Hoene, 2, 1996).

However, the declaration and associated executive orders did not fundamentally alter President Clinton’s policies surrounding missile defense. Political changes would prove to be the force that brought NMD back to prominence. The Republicans gaining control of the House in 1994, led by Representative Newt Gingrich and his “Contract with America,” including support of a NMD system, led to renewed Congressional support of deploying a system. Such a requirement was included in the FY 1996 Defense Authorization bill. President Clinton vetoed the bill over concerns of technological lock-in to a particular architecture and due to the unrelated restriction prohibiting placing American forces under UN command for peacekeeping missions. A subsequent compromise led to an increase in BMD funding of $600 million but no deployment mandate (Cho, 253, 2009).

Beyond serving as a useful piece of political opposition and a conservative cause from the Reagan presidency, changes in the security environment substantiated a desire for a defensive shield. In a paper for the Institute of National Strategic Studies in 1995, Robert Joseph and Keith Payne indicated strong evidence of the ballistic missile threat to the United States increasing, and without an immediate American response, the "threat will outpace the nation's ability to deploy effective defense" (Hoene, 2, 1996). Further, the purchase of Russian and Chinese missile hardware by Iraq, Libya, Iran, Syria, and North Korea demonstrated an intent to acquire ballistic missiles by a variety of nations (Hoene, 5-6, 1996).

Representative Curt Weldon (R-PA) articulated the proliferation concern in 1996: "Twenty-five countries have or are developing weapons of mass destruction, [and] a similar number of countries have or are seeking to acquire ballistic missiles" (Hoene, 5, 1996). Hoene's analysis again reflects the belief that several Third World nations may threaten the United States by the turn of the century, which indicated the need to field an NMD system prior to the threat materializing to prevent vulnerability (Hoene, 3, 1996). Additional fears also existed that threats may emerge faster than anticipated, as technology transfer between states may accelerate the rate at which nations can acquire ballistic missile systems (Hoene, 5, 1996).

In addition, policy makers viewed MAD as of decreasing relevance in a multipolar world. As Henry Kissinger, a principal architect of the ABM Treaty, stated, "MAD was barely plausible with one nuclear opponent and makes no sense in the multipolar world" (Hoene, 7, 1996). Further, Joseph and Payne argued in 1996 "the conditions necessary for deterrence – mutual familiarity, understanding, communication, etc. – are less likely to pertain in the existing environment than in the bipolar structure of the past" (Hoene, 8, 1996). Finally, Saddam Hussein's use of Scuds to terrorize local populaces necessitated the protection of population centers vice merely strategic forces, as the survival of strategic forces no longer sufficiently deterred an opponent attack. This lack of a defense and therefore a deterrent fueled fears that the United States may be less able to respond to regional aggression by states with ballistic missile systems (Hoene, 8, 1996). Finally, there was an increasing degree of technical optimism surrounding NMD. Again, the analysis of Hoene indicated the belief that rapid fielding of an NMD system was possible due to recent developments in technology (Hoene, 3, 1996). With advances from SDI and TMD systems, Henry Cooper and Stephen Hadley suggested an NMD system could be deployed in four to seven years, and Hadley further suggested the cost of the system to be between $5 billion and $15 billion, "affordable, especially when considered against the cost of the destruction of just one US city" (Hoene, 10, 1996).

2.2.3.3 Towards Deploying a System

The renewed emphasis from Congressional Republicans continued after the compromise in the FY 1996 budget. In February 1996, Defense Secretary William Perry advocated a shift from "technology readiness" to "deployment readiness" for the NMD program, establishing the "three-plus-three" development plan but maintaining that missile defense would focus on the

PAC-3 and the Navy lower-tier systems over THAAD and the Navy Upper Tier system. The "three-plus-three" plan consisted of three years of technology development and testing for necessary components, and then an assessment of capabilities and the threat environment culminating in a deployment decision. If the administration decided to deploy, the system would be deployed in three years (Cho, 254-255, 2009). However, 75 percent of BMD funds remained slated for TMD, as the Clinton administration remained focused on TMD (Cho, 92, 2009). The delay of the THAAD and Navy Upper Tier systems may have indicated a fear over the ABM Treaty implications of those two systems.

In response to the delay of the THAAD and Navy Upper Tier systems, Congressional Republicans sued the administration in the District Court of Columbia. Though dismissed on the basis of the suit being premature for judicial resolution, the Court warned the executive branch, "the Court does not believe the executive can blatantly defy the Congress where the national security interest may be at stake" (Cho, 257, 2009). The statement also suggested the future involvement of the court if the executive strayed from Congressional desires (Cho, 258, 2009). In striking a middle ground, Clinton increased funding to TMD systems, including the Patriot, THAAD, and Navy upper tier systems and maintained the structure of the "three plus three" plan (Van Hook, 18, 2002). The Clinton administration broke the deployment plan into three stages. C-1 consisted of 20 interceptors stationed in Alaska and a new X-band radar by 2005, providing defense against a simple attack. C-2 would consist of 100 interceptors and new X-band radars in Alaska, Great Britain, and Greenland by 2007, providing capability against tens of warheads and simple countermeasures. Finally, C-3 would consist of 250 interceptors in Alaska and North Dakota and an additional X-band radar on the United States' coastline and possibly in South Korea by 2010 or 2011, providing capability against advanced warheads and countermeasures (Jones, 13, 2002). This delineation of architecture indicated the shape of the eventual deployed BMDS. However, President Clinton's commitment to the architecture did not appear resolute. In March 1997, President Clinton and President Yeltsin of Russia signed an executive agreement setting the TMD demarcation at defense against missiles with less than 3,500 kilometers of range and speeds of 5 kilometers per second. The presented Clinton architecture would clearly violate the ABM Treaty under this definition, angering Congressional Republicans (Cho, 260, 2009).

2.2.3.4 The Rumsfeld Commission and the Missile Defense Act of 1999

The turning point in the emergence of a policy consensus regarding the deployment of a NMD system began during the initial fights between Congressional Republicans and President Clinton. Evidence emerged suggesting that North Korea was planning a nuclear capability, and Pakistan and India acquired ballistic missile capabilities. A National Intelligence Estimate in 1995 concluded the continental 48 states would be safe from ballistic missile attack for 15 years.

Fearing political pressure resulted in the omission of Alaska and Hawaii from the findings, Congress initiated the bipartisan Rumsfeld Commission to investigate the ballistic missile threat, headed by former Secretary of Defense Donald Rumsfeld (Cho, 96-97, 2009).

1998 proved to be a particularly decisive year in driving a Congressional interest in a NMD system. The year saw demonstrations of ballistic missiles and nuclear capabilities by India, and the pursuit of nuclear material and missile demonstrations by Pakistan. In addition, Iran tested the Shahab-3, which could reach Israel, Turkey, and Saudi Arabia. Further, North Korea launched the Taepodong-1, demonstrating 1,250 kilometers of range (Cho, 97-98, 2009). The Rumsfeld Commission also released its findings, stating Third World countries could have ICBMs by 2003. In response, Secretary of Defense William Cohen, a moderate Republican senator appointed to replace Secretary Perry in late 1996, advocated increasing NMD commitment by $6 billion and committing to deploy in June 2000, two years earlier than called for in the original three-plus-three plan (Van Hook, 18-19, 2002). The report also argued the need for a long-term solution as missile defense developed, namely deterrence against rogue states is not applicable because:

1. Rogue states' smaller arsenals are more vulnerable to preemptive strike, leading to a "quick trigger finger," or a greater willingness to more rapidly use ballistic missiles
2. They have nothing to lose and are more inclined to risk a massive retaliation as a result
3. They do not expect chemical or biological retaliation in response to such an attack.

The report recommended a fixed, United States based defense to ensure homeland defense with little or no warning, a boost-phase option before countermeasure deployment, and a flexible and deployable element for boost or terminal defense (Jones, 13, 2002). The recommendation for fixed defenses providing all-aspect[1] coverage against threats with little warning would have decisive implications for architecture, as it essentially required a midcourse system to provide such broad coverage. Flexible solutions for boost and terminal defense, however, could be based either on land, at sea, in space, or abroad aircraft, depending on the size of the systems.

In the wake of the Rumsfeld Commission report, Senator Thad Cochran (R-MS) began to introduce legislation to further NMD efforts. After several unsuccessful attempts in 1998, Senator Cochran achieved veto-proof majorities in the Senate and House (97-3 and 317-105, respectively) on the 1999 Missile Defense bill. The bill's language called for deployment "as soon as technologically feasible" with no timetable or architecture, attracting Democrats to a

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[1] Defense against threats inbound from any direction.

system that could possibly fit within the ABM Treaty. Further, on the face, it preserved Congressional review of a deployment and allowed for continued arms negotiation. Finally, the security developments highlighted by the Rumsfeld report served to break the previous Democrats filibuster coalitions (Cho, 261-262, 2009). Senator Chris Dodd (D-CT) summarized the initial opposition,

> The current plan calls for the Defense Department, by the year 2000, to research and develop such a system and then be able to deploy it within three years….In the absence of a current long range ballistic missile threat from a rogue state, this is the most reasonable policy….What [the accelerated timeline in Senator Cochran's bill] would have done is lock this nation in to buying a yet-to-be-developed system against an unknown threat for an unidentified sum of money….This bill would have had a detrimental impact on arms control agreements (Dodd, S10855-S10856, 1998).

Representative Gil Gutknecht (R-MI), argued a common emotional appeal of an NMD system,

> I remember the Cuban missile crisis. I remember fallout shelters. I remember the drills we had to do when I was a child to protect us from a nuclear attack…. It is time for us to build a national missile defense to protect our children… I want our kids to grow up happy and carefree, not practicing what to do when nuclear missiles are launched at us. Let us build a national defense. Let us do it for our kids (Gutknecht, H5301-H5302, 1998).

Representative Ron Packard (R-CA) articulated two driving components of the support for the new NMD deployment: security and political appeal, stating before Congress

> It is of the utmost importance to enact a national antimissile defense system as soon as possible…. This legislation would answer the emerging threat posed to the United States by the development and deployment of ballistic missiles around the world…. the irresponsibility that this Administration has shown in helping to kill this much needed legislation is appalling and puts every American family at risk (Packard, E1706, 1998).

Henry Kissinger, testifying before Congress on May 26, 1999, illustrated the prevailing view on security implications and relied on a moral appeal,

> I believe it is strategically and morally necessary to build a missile defense: strategically, because of the proliferation of weapons of mass destruction and the missile technology to deliver them; morally because the doctrine of Mutually Assured Destruction which I have opposed in my writings for at least thirty years, is bankrupt (Van Hook, 30-31, 2002).

The call for deployment in the 1999 Missile Defense Act was made before the assessment on technical feasibility was complete. Repeated test failures and a lack of progress from funding after Secretary Cohen's Quadrennial Defense Review in 1997 displayed the technical immaturity of the NMD system. The language of the Act somewhat acknowledged this and signaled a desire to continually pursue the system until it was technologically feasible (Cho, 94, 2009). While signing the Act, President Clinton announced a deployment decision would be made in the summer of 2000 based on four criteria (Jones, 14, 2002):

1. Is the technology ready?
2. How will a defensive system affect relations with Russia and China?
3. Is an appropriate system affordable?
4. Does a threat to U.S. soil really exist?

In September of 2000, President Clinton opted to allow his successor to decide on deployment, citing technological uncertainty. The decision alleviated political pressure during an election year. Further, the decision came late enough to prevent significant opposition from Congressional Republicans running campaigns (Cho, 263, 2002). NMD progressed significantly during the Clinton presidency primarily through the advocacy of Congressional Republicans, culminating in a mandate for a deployment and significant indications on the shape of the architecture. However, a final deployment decision fell to the winner of the 2000 presidential campaign. Further, complications remained surrounding the ABM Treaty and its implications for NMD.

2.2.4 President George W. Bush: The Final Push and Architecture Implications

George W. Bush succeeded President Clinton, inheriting the uncertain NMD environment. While campaigning, President W. Bush stated the goal to "build effective missile defenses, based on the best available options, at the earliest possible date." In December of 2001, less than a year into his presidency, President W. Bush withdrew from the ABM Treaty to free the United States to develop and test a missile defense system pursuant to this campaign pledge (Jones, 2-3, 2002). In January 2002, Secretary of Defense Donald Rumsfeld, the chairman of the Rumsfeld Commission which advocated for a missile defense system, elevated BMDO to agency level, renaming it the Missile Defense Agency (MDA), marking missile defense as a primary national priority. President Bush charged MDA with defending American and allied forces at home and abroad through the employment of a layered missile defense system (Van Hook, 22, 2002).

Further, President Bush tasked the MDA with developing and deploying a system as quickly as possible, exempting it from the standard Department of Defense acquisition regulations (Sessions, 25, 2008). These standard regulations stipulate that:

1. A requirements process that establishes utility of a system against a specific threat or meets a strategic goal
2. An acquisition process that compares alternatives on the basis of cost and efficacy to the proposed system.

Requirements are set through the Joint Capabilities Integration and Development System (the most recent being the CJCS 2015) and acquisitions are guided by the Defense Acquisition System as codified by Defense Directive 5000 known by its shorthand "DOD5000." These regulations dictate that programs with over $480 million in research and development costs or estimated program costs over $2.79 billion constitute a "Major Defense Acquisition Program," subjecting the program to a higher level of scrutiny. However, Secretary Rumsfeld placed MDA in charge of both development and oversight and exempted it from the standard testing and operational capability demonstrations prior to purchase typically required of major programs, allowing all funds to be designated as research and development. He furthered directed MDA to "use prototype and test assets to provide early capability" (Grego, 10, 2016). In trying to meet the compressed timeline placed by the W. Bush administration, the MDA pursued a highly concurrent, "spiral development" strategy in which a system was developed and incrementally improved while simultaneously fielded (Grego, 15, 2016). Senator Jack Reed (D-RI) remarked in 2002 that the process led to "the suspicion this is as much to avoid scrutiny of the program as to shield us from adversaries" (Grego, 11, 2016). Despite several specific changes to process such as creating the Missile Defense Executive Board in 2007, the requirement for yearly reports from the MDA director, and the increase of the role of the Joint Staff and the services in advising the MDA in 2008, President Obama continued to exempt the MDA from the DOD5000 acquisition process (Grego, 12, 2016).

2.2.4.1 Motivating Factors for Architecture and Rapid Deployment

Several factors motivated the reason to deploy as soon as possible. Smaller arsenals of threat nations means missile defense systems can possess greater deterrent and defensive power (Sessions, 24, 2008). Further, proliferation of ICBM technology to third world countries necessitated a missile shield, as does the possibility of a terrorist launched missile (Van Hook, 25-26, 2002). The 9/11 terrorist attacks created popular support for a defensive system and reduced the relative importance of arms control. Further, the attacks mitigated foreign opposition, as world leaders were less inclined to oppose American defense decisions in the wake of the attacks (Jones, 3, 2002). The attacks also did not reduce the perceived need for strategic defense systems to focus attention on unconventional delivery mechanisms. Representative Christopher Shays (R-CT) articulated in a hearing on missile defense on July 16, 2002, "in securing our nation in a volatile world… [terrorists] should not blind us to the emerging peril posed by nations developing and proliferating missile technologies" (Jones, 4, 2002).

Specific missile threats also continued to materialize. North Korea possessed and launched the Taepodong-1 in 2002 and was feared to be developing a successor TD-2 with the capability to hit any location in the United States. North Korea also exported missile technology to fund their emerging nuclear program, fueling worries of a WMD-armed missile within range of the United States. Further, Iraq violated United Nations' sanctions in testing missiles, but intelligence sources assessed it would require foreign assistance to field a missile system, possibly from a nation like North Korea. Iran also displayed interest in WMDs and missile technology, and its perceived political instability raised concerns over its possession of such systems (Jones, 5, 2002). Further, President Bush expressed fears of linkages between these nations in his 2002 State of the Union Address, identifying an "axis of evil" between the three nations ("Bush State of the Union Address", 2002).

Progress in the underlying technology also increased confidence in the ability to rapidly deploy a system. Despite concerns from the Union of Concerned Scientists regarding test methodology, namely unrealistic signatures of decoys, there were five successful intercepts in eight attempts by 2002, furthering optimism in the system (Jones, 10, 2002). Further, success with other hit-to-kill systems such as PAC-3, Aegis Sea-Based Terminal, and THAAD gave administration officials confidence in the future success of the ground-based missile defense program. Digging began on silo holes for an anticipated 50 to 200 missiles by the 2004 opening of the Fort Grealy, Alaska, interceptor site, prior to the demonstration of the interceptors themselves (Jones, 12, 2002). In the view of CDR Christi-Lynn Jones at the US Army War College, the ground-based system met the Clinton criteria for deployment. Namely,

1. Successful tests have been completed, demonstrating existing technology as a base for future deployments despite issues with discriminating warheads from decoys
2. Russia has already accepted the United States' withdrawal from the ABM Treaty. Further, protection against rogue states is a greater concern
3. While the probability of attack was low, the number of threats was proliferating and one attack would be catastrophic. Cost could be contained by utilizing existing technology and platforms (Jones, 18-19, 2002).

With this uncertain and developing threat in mind, the Bush administration pursued a layered system, with technologies to intercept in any phase of flight (Jones, 8, 2002). However, the nature of the threat and the uncertainty in the location of launch led to a midcourse-centric defensive system, as a midcourse system provides the ability to protect a large area from a limited number of launch locations (National Research Council, 10, 2012). As Senator Jeff Sessions (R-AL) would state in 2008, "the centerpiece of the present architecture is the GMD system" (Sessions, 26, 2008). The administration also eventually developed plans to place GBIs in Europe to provide capability against threats launched from the Middle East.

The MDA still pursued complimentary systems to layer a boost capability with the persistent midcourse option, namely through the Kinetic Energy Interceptor (KEI) and the Airborne Laser Programs (ABL). The KEI program aimed to create a missile with higher acceleration than existing interceptors. These interceptors would be deployed to areas of concern when needed and supported by existing sensors within the BMDS architecture (National Research Council, 32-33, 2012). The ABL program aimed to capture the perceived advantages of lasers for boost-phase intercept, namely the ability to project high energy over long ranges nearly instantaneously, by placing a high-energy chemical laser onboard a modified Boeing 747-400F. The aircraft would patrol near potential threat locations, identifying launches with onboard sensors and then engage those threats (National Research Council, 35-37, 2012).

2.2.4.2 Difficulties in Development and Deployment

The development of GMD over the years would prove difficult. From 1999 to 2016, the system would only have nine successful intercepts in 17 attempts ("Ballistic Missile Defense Intercept Flight Test Record," 2016). In the assessment of the Union of Concerned Scientists,

> This dire state is the result of rushing a system into the field to meet a timeline imposed by considerations other than technical maturity while exempting it from the usual rules that provide oversight and accountability for the development of major military systems (Grego, 33, 2016).

Acutely illustrating the higher weight placed on factors other than technical maturity, at the point of the initial W. Bush deployment decision, only five out of nine intercept testes were successful, including two failures the week before announcing the deployment (Willman, 2014). The MDA would not have a successful test of the deployed system until 2007, three years after deployment. In addition, only 67 percent of the hardware and 62 percent of the software in the deployed EKV, the Capabilities Enhanced-I (CE-I), was tested at deployment (Grego, 20, 2016).

Issues with the EKV plagued the GMD system. Again, the Union of Concerned Scientists assessed “reliable kill vehicles are the key to a working ballistic missile defense, but the United States is accepting a high level of risk from problem-ridden and untested hardware to keep on an artificially strict schedule” (Grego, 25, 2016). An improved version of the EKV, the CE-II, was developed to replace obsolete components of the CE-I, but again was deployed prior to testing in January 2010. The first successful test of the CE-II would come in 2014, 5 ½ years after deployment (Grego, 22, 2016). Further, both versions of the EKV were non-modular, leading to difficulties in repair and replacement of problematic components (Willman, 2014). In addition, the complex design of the vehicle led to issues in ensuring quality control. The Inspector General found in 2014,

> A combination of cost constraints and failure-driven program restructures has kept the [GBI] program in a state of change. Schedule and cost priorities drove a culture of “Use-As-Is” leaving the EKV as a manufacturing challenge. With more than 1,800 unique parts, 10,000 pages of work instructions, and 130,000 process steps for the current configuration, EKV repairs and refurbishments are considered by the [GMD] program to be costly and problematic and make the EKV susceptible to quality assurance failures (Grego, 23, 2016).

Nearly all 24 of the deployed CE-I KVs were deployed prior to a flight test. Further, a 2007 program to fix known issues in the EKV culminated the failure of a 2013 test due to EKV failure. In 2014, the Government Accountability Office (GAO) found that the MDA had not adequately fixed the issue causing the problems (Grego, 21, 2016). The MDA further deployed interceptors with a known design flaw in the guidance unit despite the fact that the fault was observed in eight tests over the course of nine years and ultimately deployed a fix prior to establishing with certainty the root cause of the issue (Grego, 24, 2016). These faults were accepted and ultimately deployed primarily as a result of the desire to field as quickly as possible. As the Under Secretary of Defense for acquisition, technology, and logistics, Frank Kendall III, summarized at a defense industry conference in February 2014,

> We recognize the problems we have had with all the currently fielded interceptors. The root cause was a desire to field these very quickly and very cheaply….We are seeing a lot of bad engineering, frankly, and it was because there was a rush (Willman, 2014).

Despite these setbacks, the nation’s commitment to missile defense, particularly midcourse defense of the homeland through GMD, remained strong. Per Senator Sessions, “Many hostile states are actively pursuing sophisticated ballistic missile capabilities” (Sessions, 23, 2008). Mike McConnell, the Director of National Intelligence at the time, stated in 2006 that the

Taepodong-2 probably has the capability to deliver a nuclear sized payload to the United States. In addition, the missile threat continued to be perceived as coming from multiple actors. 120 foreign ballistic missile launches occurred in 2007, with Iran and North Korea demonstrating advanced capabilities, and Syria and Pakistan expanding the number and range of missiles. In the words of General B.B. Bell, commander of United States forces in Korea, North Korea is "a threat that cannot be ignored" (Sessions, 23, 2008). Further, testimony to Congress from General Bantz J. Craddock, commander of Army forces in the European Combatant Command, on March 13, 2008, indicated that Iran could deploy an ICBM by 2016 and that the lack of coverage against such a threat necessitated a "third-site" for interceptors in Europe. Again, Senator Sessions summarized the fear of a multitude of actors, "if Iranian President Mahmoud Ahmadinejad and North Korean dictator Kim Jon Il believe that ballistic missiles are still relevant in the post 9/11 world, it would behoove us to act as if they are. Today we face a much broader range of missile threats than we did during the Cold War, posed by a much more diverse, and less predictable, group of enemies" (Sessions, 24, 2008). Finally, changes in the behavior of Congress indicated the bipartisan support for missile defense. Even after the Democratic Party won majorities in both chambers of Congress and the presidency in 2008, funding to missile defense was decreased by just 3 percent, indicating a bipartisan commitment to missile defense vice merely a conservative cause (Sessions, 29, 2008).

2.2.5 President Barack Obama: Incremental Change

Despite changes to the structure of several programs, the Obama administration remained committed to the midcourse elements of missile defense. Boost-phase capabilities were completely removed from the development of the architecture. In 2009, the Obama administration cancelled the KEI program, citing that the expected capabilities of the system would not be consistent with the strategy for defending against those threats. Spiraling costs and delays may have also played a role. The ABL program was also cancelled in 2011 after the range limitations inherent in the system would require placing a large, vulnerable aircraft near hostile territory indefinitely, eliminating its operational capability (National Research Council, 32-33, 2012). Meanwhile, the GMD and terminal systems continued development, and the Obama administration announced the Phased Adaptive Approach (PAA) in September of 2009 to provide a defensive capability against the Iranian ballistic missile threat to both Europe and the United States. The short-term focus of this program on European defense against Short-Range Ballistic Missiles (SRBMs) and Intermediate-Range Ballistic Missiles (IRBMs) reflected a shift in Iranian development towards shorter-range missiles (National Research Council, 79, 2012). Though the plan ultimately shifted away from utilizing the GBI of the GMD system, the plan eventually culminated in the deployment of midcourse capable Aegis ships to the Mediterranean

Sea and the construction of Aegis ashore sites in the Romania and eventually Poland (Browne, 2016). Both of these systems utilize the SM-3 missile to intercept threats in midcourse.

2.3 Summary

In short, strategic and political forces from the initial proposition of SDI through the current architecture resulted in a BMDS focused on all-aspect defense utilizing midcourse defensive systems. Midcourse systems provided, in the view of policy makers, the most persistent option for defense from a possibly unknown threat. In addition, terminal defenses provided an additional layer of protection to deployed forces and high-value facilities. Development issues and operational constraints precluded the deployment of boost-phase systems within the defensive architecture. A final observation through the totality of this process is the small degree to which technology analysis played within the progression of the missile defense architecture. Often, architecture decisions were made prior to technology assessments. In the view of one study,

> The analysis of the security perspective demonstrated that among threat, technology, and cost, the level of threat or new developments in the strategic environment was the most powerful factor in shifting US defense policies. The success or failure of ABM tests certainly enhanced or dampened support for missile defense efforts. However, technology was not a central element in missile defense debates because operational capability in the future could not be predicted, and judgements of achievability proved to be a function of expectation (Cho, 272, 2009).

Chapter 3. A New Policy Consensus and a Technological Opportunity – Modern Threats and the Relevancy of Boost-Phase Intercept

With an understanding of the origins of the current missile defense architecture, understanding the evolving geopolitical and technical environments is necessary for advancing this architecture. A continuing evaluation of evolving threats around the world will aid in the tailoring of security policy to meet these threats, while an eye towards technology helps in the identification of emerging capabilities. Joining these two pieces of analysis to find areas of policy consensus and technological opportunity will aid in the creation of systems that match the strategic demands of the United States and the tactical demands of her warfighters.

As this section aims to demonstrate, the continuing and increasingly capable North Korean ballistic missile and nuclear programs require a shift in missile defense policy to a greater consideration of this threat. The Obama administration's 2010 Ballistic Missile Defense Review stated missile defense should "dissuade [Iran and North Korea] from developing an intercontinental ballistic missile (ICBM), deter them from using an ICBM if they develop or acquire such a capability, and defeat an ICBM attack by such states if deterrence fails" (Grego, 34, 2016). The relative growth of North Korea in comparison to other ballistic missile threats enables a shift in strategy from a pure reliance on midcourse intercept for defense of the homeland to the fielding of boost-phase capabilities as a part of layered architecture to improve defense of the homeland in depth.

3.1 The Emergence of the North Korean Threat

Perhaps the single most powerful motivator for a shift of missile defense strategy towards North Korea is the continued emerge of their missile and nuclear arsenal, particularly relative to other possible threats around the world. Representative Joe Wilson (R-SC) identified the North Korean threat, highlighting, "The growth of North Korea's testing medium- and long-range missiles . . . and their rapidly proceeding nuclear program" (Wilson, H2250, 2017). Representative Gerald E. Connolly (D-VA) concurred, stating,

> It is undeniable that North Korea's nuclear and ballistic missile programs have accelerated in recent years. In 2016 alone, the regime conducted two nuclear tests and

> more than 20 missile tests. In its most recent test, North Korea simultaneously launched four intermediate-range ballistic missiles toward the Sea of Japan, three of which landed within Japan's exclusive economic zone (Connolly, E457, 2017).

The following illustrates that threat, seeking to build a policy consensus solidifying its place as the primary missile threat to the United States and the possibility of using a boost-phase kill capability to counter it.

3.1.1 A Legacy of Ballistic Missile Development

North Korean missile development began with a reported purchase of Egyptian Scud missiles in 1976, producing its own modified version by 1984, the Hwasong. A derivative, the Hwasong-6, missile has been sold to Iran. In April 2016, The International Institute for Strategic Studies assessed the medium range Nodong to be "a proven system which can hit all of South Korea and much of Japan" ("North Korea's Missile Programme," 2017). Further, the North Korean arsenal includes a range of short-, intermediate-, and long-range missiles. Most significant to the United States may be the Tapeo Dong-2 (TD-2), which may possess the ability to strike the Pacific Northwest and was demonstrated several times in its space launch configuration (Cohen, 8, 2012).

The development of the TD-1, the shorter-range relative of the TD-2, and TD-2 began in the early 1990s, with the objective of launching a 1,000-1,500 kilogram payload 1,500 to 2,000 kilometers and 4,000 to 8,000 kilometers, respectively. The fielded TD-2 possesses an assessed range of 4,300 kilometers with a possible reduced payload version having a 6,700 kilometers range (Hildreth, 1-3, 2007). The space launch version, the Unha, successfully placed a satellite into orbit in February 2016 ("North Korea's Missile Programme, 2017). This launch marked the fourth demonstrated launch vehicle and may indicate a degree of familiarity with long-range rockets (Panda, 2017). However, prowess with space launch vehicles does not necessarily translate into ballistic missile design acumen. Michael Elleman and Emily Werk of the Arms Control Association discount the extent to which a demonstrated launch vehicle indicates the ability to field an ICBM:

> The Unha-2 or -3 could serve as a springboard for the development of an ICBM, but the history of long-range missile development by other countries, including the Soviet Union, the United States, China, and France indicates that satellite launch activities have limited impact on missile programs. No country has converted a satellite launch rocket into a long-range ballistic missile (Tucker, 2017).

The more developed short and intermediate range systems place American military facilities and allies in South Korea, Guam, Okinawa, and Japan at risk (Hildreth, 3, 2007). Further, as early as 2000, senior American officials identified the threat posed to the United States' homeland by North Korean missile capabilities. As Robert D. Walpole, the National Intelligence Officer for Strategic and Nuclear Programs for the Central Intelligence Agency, stated in testimony before a Senate Subcommittee hearing on February 9, 2000,

> Although the majority of systems today are short- or medium-range ballistic missiles, North Korea's three-stage Taepo Dong-1 space launch vehicle launch heightened sensitivities and moved earlier projections of the threat from hypothetical to real. If flown on a ballistic trajectory with an operable third stage and reentry vehicle, the TD-1 could indeed deliver a small biological or chemical payload to the United States, albeit with significant inaccuracy. . . .They need not be highly accurate; the ability to target a large urban area is sufficient. They need not be highly reliable, because their strategic value is derived primarily from the implicit or explicit threat of their use (Walpole, 2008).

3.1.2 Towards a Capable ICBM

Recent developments indicate that North Korea may be on the verge of fielding an ICBM with greater capability than the TD-2. As the Republican Senator Sessions suggested in 2008, President Obama also suggested early in the transition that North Korea should be the Trump administration's top priority, indicating a degree of bipartisan concern for the emergence of the North Korean threat (Panda, 2017). Additional advances fueled President Obama's concern over the North Korean threat. During his presidency, North Korea conducted five nuclear tests and launched satellites into orbit in December 2012 and February 2016. In April 2016, North Korea successfully launched a ballistic missile from a submerged submarine (Dodge, 2016). The rate of North Korean missile and nuclear tests has also increased under Kim Jong-un, who assumed power from Kim Jong-il in 2011. Figure 4 depicts the number of North Korean nuclear and missile tests from 2001 to the present (Sanger, 2017).

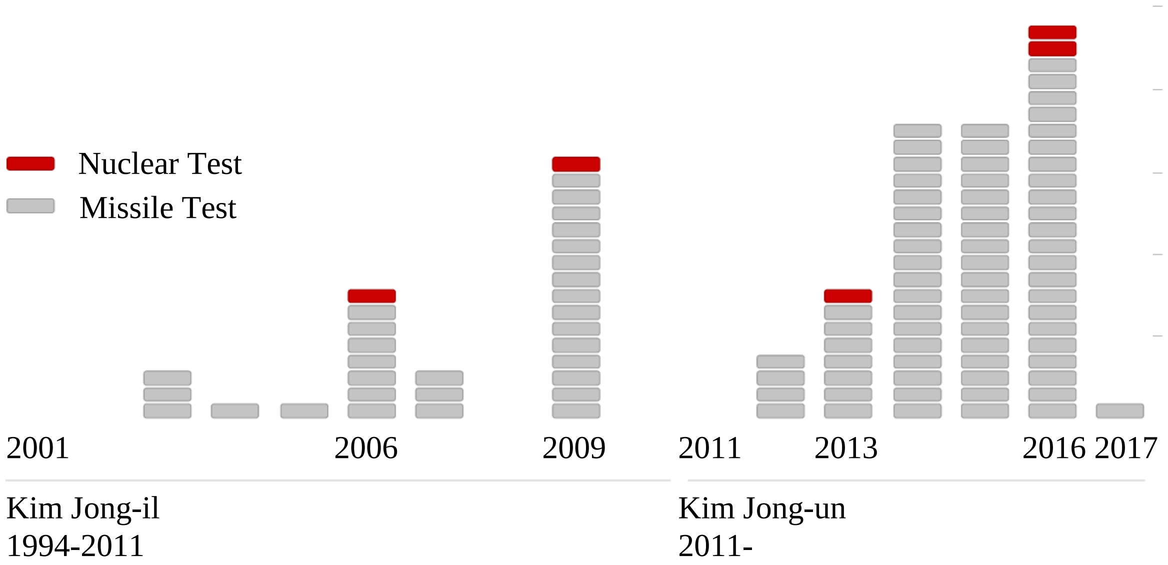

Figure 4. North Korean missile tests[1]

The culmination of the various technical developments indicates a system moving towards an operational capability. A 2015 Department of Defense assessment found that a new missile, the KN-08, if successfully developed would likely be able to reach much of the United States (Panda, 2017). The road-mobile KN-08, harder to hit pre-emptively by nature of its ability to be launched from a variety of locations, reportedly possesses a range of 6,700 kilometers, with April 2016 photos showing a new rocket engine purported to be able to propel the missile to the United States (Tucker, 2017). In April 2016, John Schelling at the John Hopkins School of Advanced International Studies stated,

> If the current ground test program continues and is successful, flight tests of a North Korean ICBM could begin in as little as a year. Moreover, Pyongyang may be able to deploy this delivery system in a limited operational capability by 2020 (Tucker, 2017).

Additional independent arms controls experts agree that North Korea is making rapid progress to develop an ICBM. Per Melissa Hanham, an East Asia researcher at the Middlebury Institute of International Studies at Monterey, “they are very far along in their ICBM testing project. Probably we will see that they will do a flight test in 2017” (Brumfiel, 2017). Such a test is in the stated policy agenda of Kim Jong-un. He announced in his New Year’s address final preparations of a ballistic missile test, coming in the context of progress on the submarine-

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[1] Figure from Sanger, 2017.

launched KN-11, the intermediate-range Hwasong-10, and progress towards test flights of the KN-08 and other long-range designs (Panda, 2017). Indeed, North Korea successfully tested a ballistic missile, the Pukguksong-2, an apparent upgraded version of the submarine-launched missile tested in August of 2016, off their east coast on February 13, 2017 (Park, 2017). Further, some analysts have suggested North Korea may have miniaturized a nuclear warhead. However, it remains unclear if such a warhead could survive the g-forces of launch and such claims have yet to be verified (Brumfiel, 2017; Park, 2017).

3.1.3 Provocative Behavior, Political Change, and Policy Implications

In addition to, and perhaps a compliment of, a commitment to ballistic missile development, North Korea's behavior is decidedly more provocative than other potential missile threats. In addition to nuclear and missile tests, and the continuation of a potentially provocative space program, North Korea committed three violent provocations since from 2009 to 2012: an exchange of naval gunfire with South Korean ships in November 2009, sinking the South Korean cruiser Cheonan in March 2012, and shelling the South Korean island of Yeonpyeong in November 2010. Iran's provocations during this time were decidedly less violent. Further, North Korea has increased its rate of provocations between 2002 and 2012 (Cohen, 19-21, 2012). By contrast, other potential missile threats have become less threatening to the United States. Due to political upheaval and uprisings, Libya no longer presents a significant missile threat to the United States and its allies, while Syria presents a less likely threat while waging a civil war. Similarly, Iraq also no longer poses a threat in the aftermath of the 2003 American invasion.

The most challenging threat outside of North Korea is likely Iran. However, unlike North Korea, Iran does not possess a present nuclear capability nor appears likely to attain one after its agreement to the Joint Comprehensive Plan of Action, or more commonly the Iran Nuclear Deal. Further, Iran appears to be adhering to the deal, shipping over nine tons on uranium out of the country and slashing its number of centrifuges as stipulated by the deal by August of 2016 (Dolan, 2016). The head of the United Nations atomic energy watchdog also stated in December 2016 that Iran continued to display commitment to the deal ("Iran Adhering to Nuclear Deal Terms," 2016). While Iran continues to pursue ballistic missile programs, stoking tensions with the United States (Morello, 2017), a nuclear-tipped Iranian missile system appears far less likely than a North Korean one.

In sum, the progress North Korea has made on its offensive missile systems relative to other potential threats and its continued aggressive behavior should elevate its priority within American missile defense strategy.

3.2 Boost-Phase Intercept in the Context of North Korea

The transition in strategic focus from all-aspect, persistent defense against a potentially unknown threat to the much more geographically constrained North Korea allows for the consideration of alternative defensive architectures. In particular, Boost-Phase intercept (BPI) may provide an increase in the capabilities of the present BMDS when considered in the context of the North Korean threat. BPI is attractive for several reasons but is also complicated by several factors, with the driving constraints of attacking missile burn time and the speed of the interceptor (Barton, xxi, 2004). However, the particular considerations around defense against a North Korean missile enable the possible viability of a BPI system.

The principal advantage of BPI in general is its ability to alleviate the need to perform midcourse discrimination. A boosting ballistic missile presents a large target with a bright signature, making detection and engagement easier compared to dimmer midcourse targets. In addition, countermeasures are generally not deployed during boost, presenting a unitary target for engagement (National Research Council, 30, 2012; Van Hook, 23, 2002). The ability to avoid midcourse discrimination is particularly valuable, as all midcourse intercepts require some degree of discrimination and, per a 1999 National Intelligence Estimate, countermeasures should be available to countries that possess the ability to build long-range missiles (Grego, 32, 2016). A benefit of air-launched BPI is that interceptors for boost are smaller and will likely prove cheaper to produce compared to larger midcourse surface-launched interceptors. Admiral Gorney, commander of United States North Command, opined in 2015 that the United States will always be on “the wrong side of the cost-curve” due to high-tech interceptors generally proving more expensive. Five other high-level officers supported the notion, suggesting the present approach is cost-ineffective (Grego, 11, 2016). The smaller and generally cheaper boost-phase interceptors allow for higher production rates, which further drives down cost and increases the number of threats that can be intercepted (Corbett and Zarchan, 2010).

In addition to its standalone capabilities, a BPI system would also provide the benefit of a layered defense for the homeland, increasing the number of available shot opportunities against a threat missile similar to capabilities against shorter-range systems provided by layering Aegis, THAAD, and Patriot in theater defense contexts. A credible BPI capability would also create an additional, less obvious benefit through layering. One retired officer, reflecting on the GMD system defending the American homeland, stated, “The system is not reliable. We took a system that was still in development – it was a prototype – and it was declared to be ‘operational’ for political reasons.” (Willman, 2014). The previously traced out desire of the W. Bush administration to rapidly field a capability resulted in a highly concurrent development process that deployed untested interceptors, which required substantial efforts to improve later. These pressures continued in the Obama administration. In March 2013, Secretary of Defense Hagel announced the fielding of 14 more interceptors in response to the increasing North Korean threat, reducing resources available for development (Grego, 24, 2016). A boost-phase capability against the North Korean threat would substantially reduce the pressure to field an immature midcourse system, allowing for purposeful improvements to the GMD to improve the overall capabilities of American missile defenses.

Boost phase also presents unique challenges. Due to the short duration of threat missile boost, no more than five minutes for most threats and as small as three minutes for faster burning solid-propellant threats, the engagement timeline is extremely short to detect, track, and engage a threat. Further, the system must be in range of the threat trajectory at the time of launch, necessitating continual observation and persistent systems. The KV must be able to deal with the significant stress associated with engaging a rapidly accelerating threat (National Research Council, 30, 2012). Finally, natural impediments such as weather conditions affect boost-phase systems operating within the atmosphere to a greater extent than exoatmospheric midcourse systems (Van Hook, 23, 2002). These complications sum to constrain boost-phase systems to very specific geographic conditions, namely a sufficiently small country to allow assets to be within range of a boosting trajectory and features such as allied countries or open water for the basing of interceptors. In addition, local commanders must possess release authority for weapons since the compressed engagement timeline does not allow for communication to higher authorities (National Research Council, 31, 2012).

North Korea presents a geographic advantage for a boost-phase system compared to employing such a system against an Iranian threat. This advantage stems principally from the relatively small size of North Korea and its proximity to several seas that enable the persistent basing of interceptors (Wilkening, 47, 2004). Figure 5 depicts a side-by-side comparison of the geographies of Iran and North Korea from the eye altitude of 3,000 kilometers.

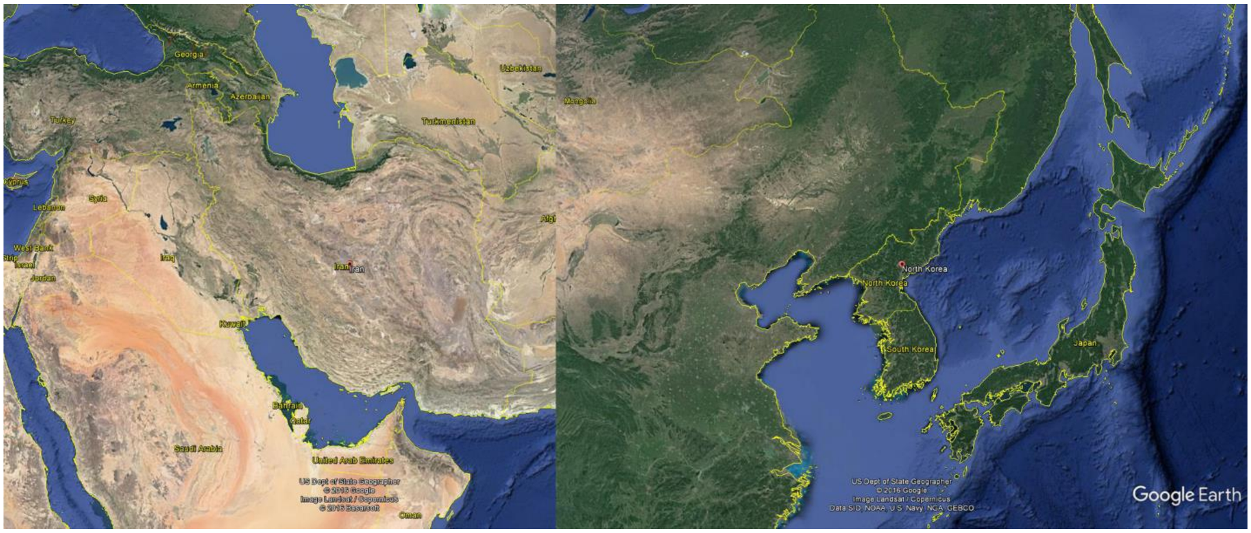

Figure 5. Comparison of Iranian and North Korean geography from eye altitude of 3,000 kilometers

The graphic demonstrates the relative accessibility of North Korea, with larger surrounding bodies of water and a smaller landmass. North Korea has a landmass of 46,500 square miles compared to the 636,400 square miles of Iran and borders the large, accessible Sea of Japan rather than the much more constrained Caspian Sea and Persian Gulf. As a result, a BPI system is much more likely to be able to reach threat trajectories from North Korea (Karako, 114, 2017).

3.3 Previous Work Assessing Boost-Phase Intercept Systems

Previous open-sourced studies considered the feasibility and practicality of BPI and investigated a variety of approaches, including the use of interceptor missiles or directed energy and the consideration of land, sea, air, and space-based launching platforms. These studies have reached varying conclusions over the viability of BPI. While its report focused mainly on surface-based interceptors, the American Physical Society (APS) concluded that defense of the United States homeland may be possible from land-, sea-, and air-based interceptors against slower burning, liquid fueled ICBMs with a burn time of 240 seconds but likely not against similar range but faster burning solid fueled missiles with burn times of 170 seconds or less (Barton, xxi, 2004). Analysis from Dean A. Wilkening at Stanford University indicated that air-based interceptors with a mass of 1,500 kilograms could provide intercept capability against IRBMs (burn time of 199 seconds), solid-propellant ICBMs (burn time of 180 seconds), and liquid-propellant ICBMs (burn time of 240-290 seconds) from 400-650, 430-600, and 600-1,000 kilometers, respectively. Mike Corbett, the former Director for Advanced Technology Weapons at MDA from 2006 through 2009, and Paul Zarchan, a technical staff member at Massachusetts Institute of

Technology Lincoln Laboratory, based upon the threat models in the 2004 APS report, concluded kinetic hit-to-kill interceptors launched from airborne platforms (either manned or unmanned) directed by an infrared search and track sensor suite could perform boost, ascent, and terminal engagements of threat missiles. Existing systems in both the Sniper pod currently used by United States aircraft and by the Distributed Aperture System on the F-35 possess such sensor capability (Corbett and Zarchan, 2010). However, the National Research Council (NRC) disagreed with the findings of these studies. Based upon analysis of threat models also developed by the 2004 APS report, the NRC found that a platform carrying interceptors would either need to be stationed in operationally infeasible locations in North Korea or China to intercept missiles in boost phase. Further, even interceptors with high burnout velocities of 6.0 kilometers per second would struggle to intercept solid-fueled ICBMs (National Research Council, 49-52, 2012).

3.4 Considered Threat Models

To assess the utility of a BPI system, this work generated trajectories for a range of notional threat models within a constructed political scenario. The models and scenario were selected to reflect the challenges and relevant geography indicative of boost-phase intercepts. To reflect the variety of ballistic missile threats, this work considered models for a medium, intermediate, and intercontinental-range missiles. Preliminary analysis indicated that short-range missiles burnout too quickly, at too low an altitude for an interceptor built for exoatmospheric intercepts to be useful, and thus are not considered below. In addition, to capture the effect of a missile with a shorter burn time, this work considered models for both a liquid and solid-fueled ICBMs.

Table 1 through

Table 4 show select parameters for the four threat models, referred to as M-1, R-1, L-1, and S-1 for the MRBM, IRBM, liquid-propellant fueled ICBM, and solid-propellant fueled ICBM, respectively (Wilkening, 61, 2004).

Table 1. MRBM model, M-1, select parameters, payload mass = 1,000 kg, nominal range = 1,340 km

Attribute	Units	Stage 1
Stage mass	kg	19,000
Mass fraction		0.85
Cross-sectional area	m^2	1.13
Thrust	kN	429
I_{sp}	s	257
Burn time	s	95

Table 2. IRBM model, R-1, select parameters, payload mass = 500 kg, nominal range = 4,750

Attribute	Units	Stage 2	Stage 1
Stage mass	kg	18,000	52,000
Mass fraction		0.84	0.83
Cross-sectional area	m^2	1.39	4.52
Thrust	kN	350	1,315
I_{sp}	s	290	263
Burn time	s	114	85

Table 3. Liquid-fueled ICBM model, L-1, select parameters, payload mass = 400 kg, nominal range = 10,700 km

Attribute	Units	Stage 2	Stage 1
Stage mass	kg	15,000	95,000
Mass fraction		0.83	0.87
Cross-sectional area	m^2	1.77	3.14
Thrust	kN	240	1,655
I_{sp}	s	290	293
Burn time	s	147	143

Table 4. Solid-fueled ICBM model, S-1, select parameters, payload mass = 800 kg, nominal range = 14,500 km

Attribute	Units	Stage 3	Stage 2	Stage 1
Stage mass	kg	4,000	12,000	29,000
Mass fraction		0.84	0.87	0.89
Cross-sectional area	m^2	1.54	1.77	2.00
Thrust	kN	160	495	1,225
I_{sp}	s	290	290	291
Burn time	s	60	60	60

Generally, the range of a missile increases as its burn time increases. However, the faster burning solid propellant ICBM breaks this trend. S-1 was included to determine the effect of decreasing the burn time of a threat missile on the capability of the BPI system.

The following constructed canonical scenario reflects the constraints placed on a BPI system by enemy defenses, geographic considerations, and geopolitical realities. In this scenario, the fictionalized People's Republic of Florida is interested in increasing its clout through the acquisition of a credible ballistic missile arsenal, including the M-1, R-1, L-1, and possibly S-1 missiles. The missiles were launched from near Miami, FL, a location selected to present the most challenging trajectories to any defensive systems for the ICBM launches, namely by having the trajectory fly over land for the duration of its boosting flight. Three targets of varying ranges were selected to demonstrate the effect of changing trajectories. Table 5 shows the details of the scenario, and Figure 6 depicts the ground tracks of the resultant missile trajectories.

Table 5. Canonical scenario details

Launch	Miami, FL – 26.845°N, 80.221°W		
Missile	M-1	R-1	L-1 / S-1
Target	Marsh Island, LA	Chinese Theater, Hollywood, CA	Point Hope Airport, AK
Latitude/Longitude	29.536°N, 91.870°W	34.102°N, 118.341°W	68.347°N, 166.782°W
Ground Range	1,305 km	3,725 km	7,120 km

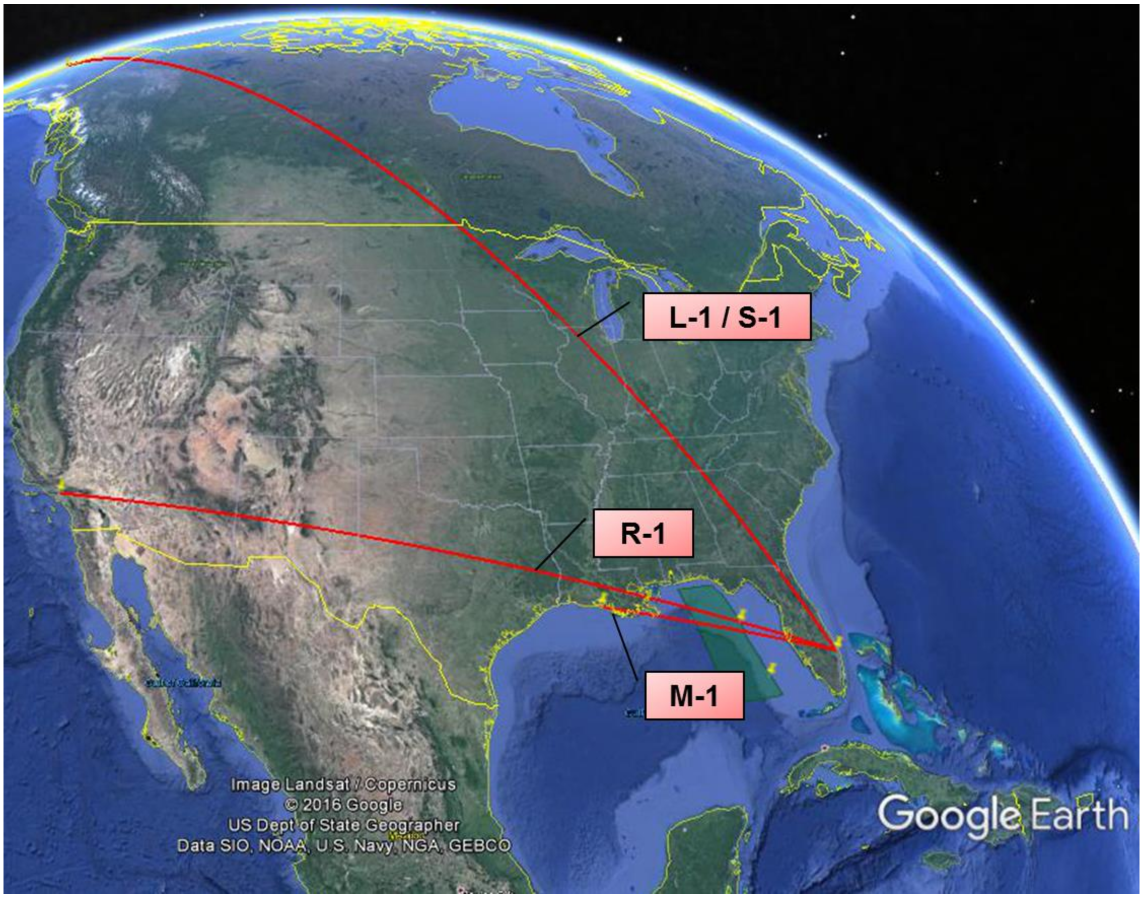

Figure 6. Ground tracks for M-1, R-1, L-1, and S-1

Appendix A describes the process for generating ballistic trajectories including boost from the models and canonical scenario in detail. In summary, the missiles boost vertically for the first kilometer of flight, perform a gravity turn until dynamics pressure falls below 24 Pa to allow maneuvers with structural loading, and then utilize Lambert guidance until burnout. M-1, due to its lower altitude operation, initiates Lambert guidance 70 seconds after launch rather than at the dynamic pressure threshold. All four missiles, including the solid propellant missile, terminated thrust after achieving sufficient velocity to reach the target. Figure 7 depicts the resultant boost range-altitude profiles.

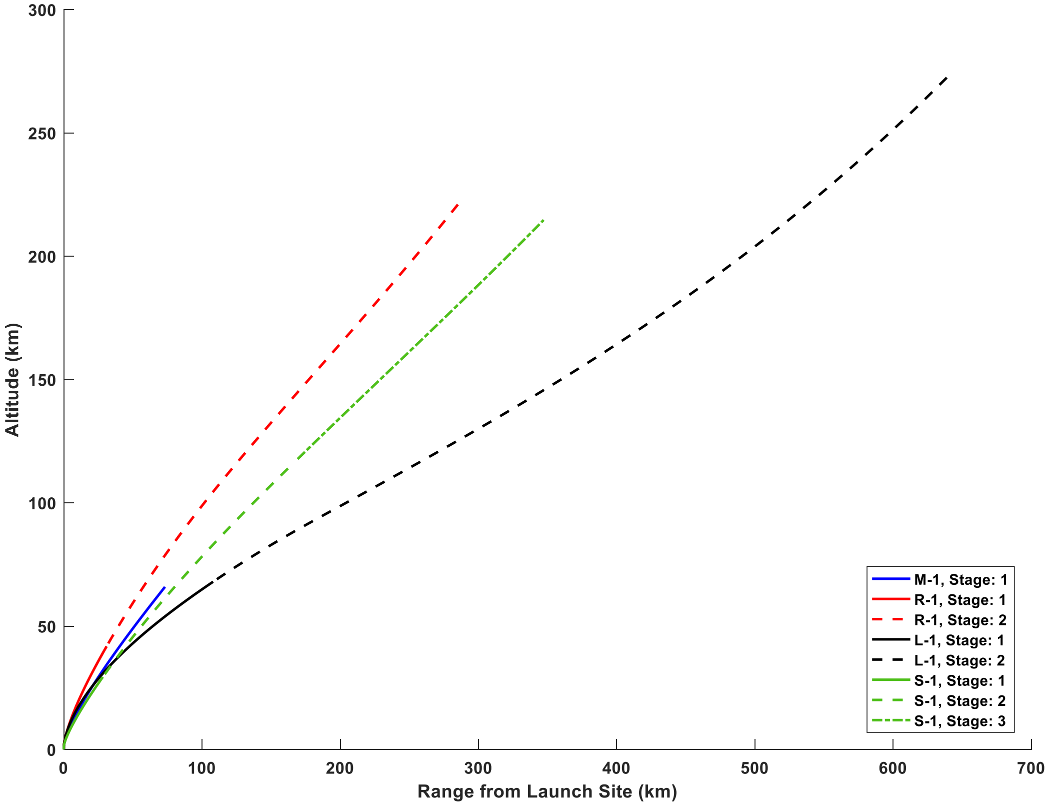

Figure 7. Threat range-altitude profiles during boost

The burnout altitude and ground range covered during boost is generally consistent with the burn time for a given threat, with M-1 burning out at the lowest altitude and at the shortest range and L-1 at the opposite extreme. Generally, trajectories that cover less ground range are more difficult for BPI systems to intercept, as they cannot get close enough to the threat due to operational considerations, such as the threat of enemy defensive action or geographic constraints.

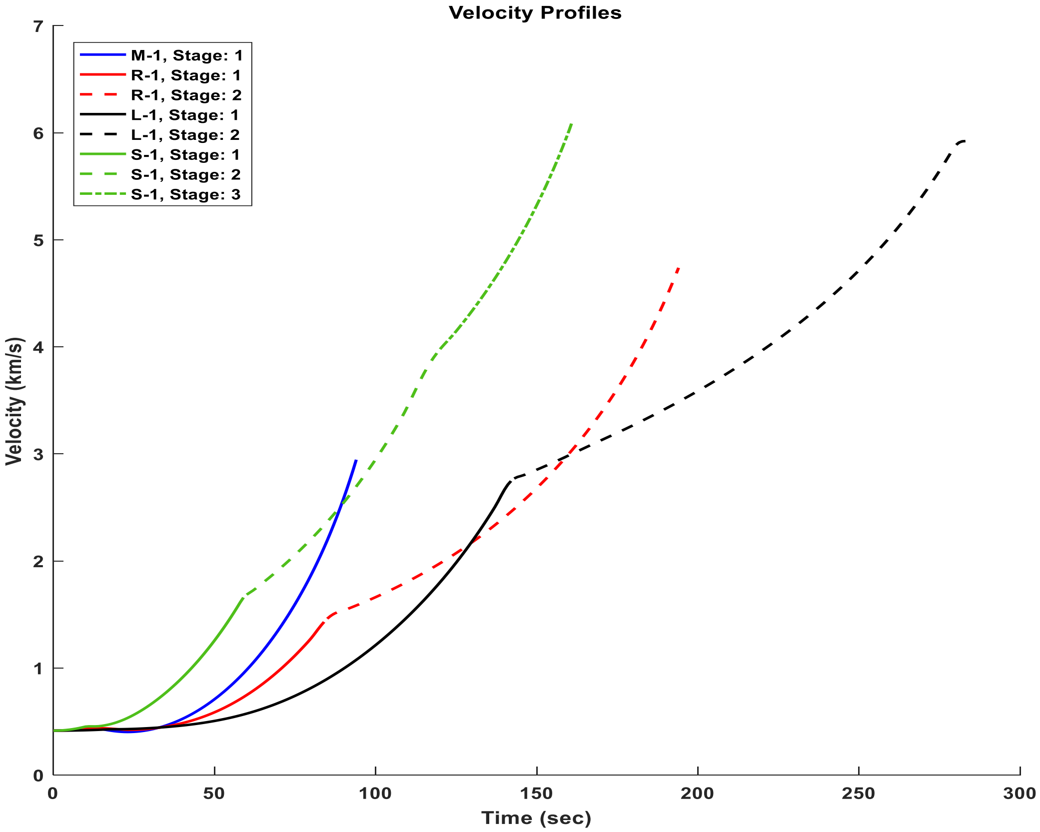

Figure 8. Threat velocity profiles during boost

Figure 8 displays the velocity profile of the threat missiles through boost. M-1 boosts for the duration of its capability, burning out 95 seconds after launch. The other threats achieved the requisite velocity early, burning out at 199 seconds, 280 seconds, and 160 seconds for R-1, L-1, and S-1, respectively. The burnout times for the trajectories of interest determined the amount of time available for the BPI system to perform an intercept of the threat. In addition, burnout velocity largely determines the range of the missile, so shorter-range threats having a lower burnout velocity is expected.

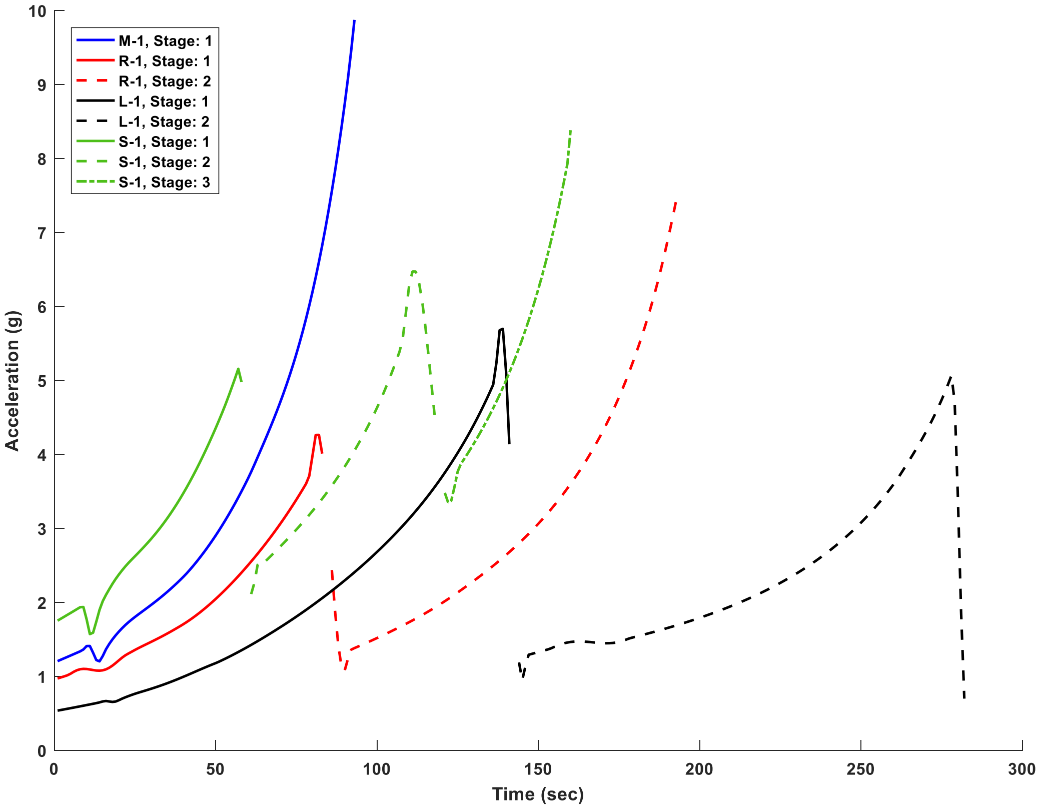

Figure 9. Threat acceleration profiles during boost

Figure 9 displays the acceleration profiles for the four threat missiles. Jump discontinuities reflected staging events, where the missile released spent stages to reduce the amount of dead weight carried, while sharp discontinuities during a stage represent a transition from one guidance regime to another. For example, the hitch exhibited by all four missiles around 15 seconds is the transition from the initial portion of flight directly vertical to the gravity turn. The later in-stage discontinuity is then the transition from the gravity turn to Lambert guidance. The magnitude of the threat acceleration drives the divert velocity and acceleration requirements of the intercepting KV, such that missiles that achieve greater acceleration represent a more challenging target.

To facilitate simulation of detection and tracking by an infrared sensor, rocket plume signatures were generated for threat models. This work implemented a simplified one-dimensional plume model in the mid-wave portion of the spectrum, from 2.8 to 4.8 microseconds where the atmosphere attenuates the signal significantly less. Figure 10 depicts the physical concept of a one-dimensional model, and Appendix B contains a detailed description of the modeling process. In short, cross-stream effects were assumed rapid and negligible relative to the downstream axis. As such, plume properties such as temperature and irradiance depending only on downstream distance from the nozzle (Simmons, 113-115, 2000).

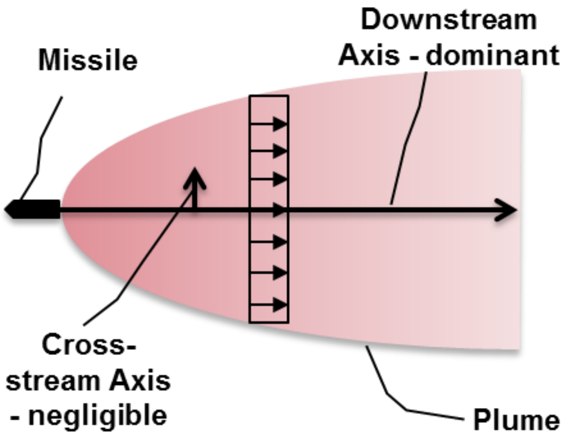

Figure 10. One-dimensional plume model[1]

Figure 11 displays the resultant exhaust plume intensities up to 60 kilometers of altitude. Above this altitude, the one-dimensional model's validity degrades. This work assumed that by the time the missile broke this altitude, the seeker onboard the interceptor would acquire the threat missile and no longer rely upon updates from the sensor onboard the platform. This assumption simplified the modeling process while capturing the necessary sensor performance in long range tracking necessary for engaging a ballistic missile in boost phase.

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[1] Figure from Simmons, 2000.

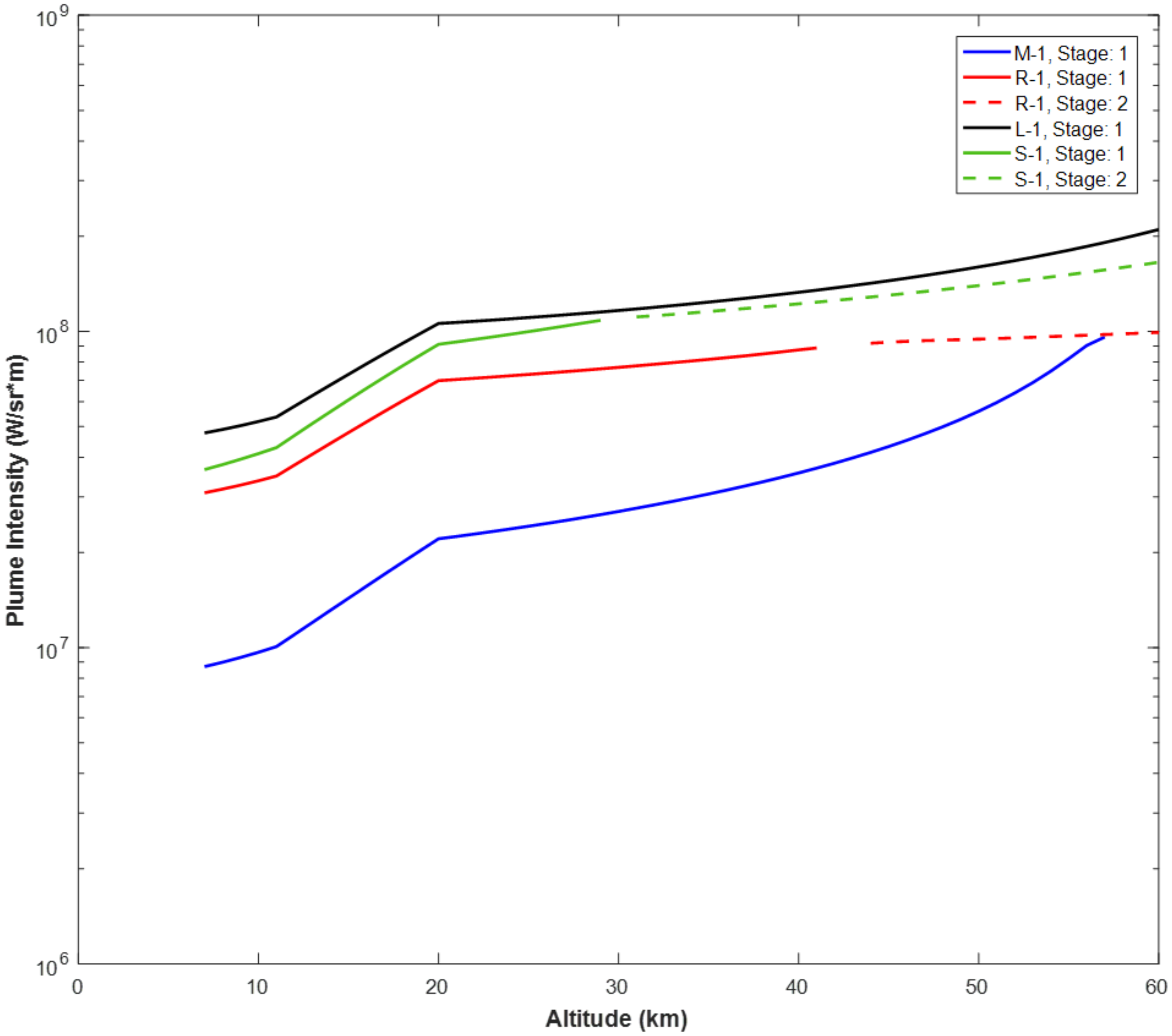

Figure 11. Threat exhaust plume radiance profiles

3.5 Creating an Airborne Boost-Phase Intercept System

In order to assess the capability of a BPI system, a notional system was developed with the intent of identifying the potential ability of such a similar system if fielded. This work aimed to identify a system that is capable of being fielded in the near-term for at reasonable cost compared to other elements of the ballistic missile defense system. As such, components were selected principally based on technical maturity, to minimize both the development time and cost. This work considered three principal components of a BPI system: the platform, the sensor, and the interceptor. Based upon the previous work on BPI and on a review of operationally useful and potentially cost-effective options, this work considered an airborne BPI system. Airborne was selected as the basing option due to the reduced drag of launching an interceptor at high altitude leading to higher performance and allowing interceptors to be based farther from potential launch sites (Wilkening, 53, 2004). Airborne also allows a greater degree of operational flexibility due to the mobility of aircraft.

3.5.1 The Platform

Requirements for the platform were principally payload, or the weight of ordinance the aircraft is capable of carrying, and endurance, or how long the aircraft is able to stay airborne "on-station."[1] Previous studies considered utilizing manned tactical aircraft, useful due to a large payload that allows for the carriage of either more numerous or larger interceptors (Wilkening, 44, 2004). Large UAVs were also considered, such as the Global Hawk, due to their long endurance (greater than 24 hours) and high operating altitudes (60,000 feet), which both present attractive attributes for an airborne BPI system (Wilkening, 28, 2004). However, Global Hawk, or the maritime version for the Navy, the MQ-4C Triton, are not presently configured for weapons carriage and would require significant modification in order to do so. Such modifications would take additional time and increase the cost of any airborne BPI system.

Given that the desired system should be as inexpensive as possible and available in the near-term, this work considered a medium sized UAV that captured some of the benefits of both manned aircraft and large UAVs. The MQ-9 Reaper represents an ideal tradeoff between these two classes of aircraft. The Reaper has moderate persistence and operates at more moderate altitudes than the Global Hawk or Triton but has the demonstrated ability to carry up to 1,700 kilograms of weapons on multiple wing stations. Further, the aircraft has a demonstrated operational capability in multiple theaters of combat, indicating the maturity of the platform ("MQ-9 Reaper," 2015).

3.5.2 The Sensor

The second component to consider was the sensor used for detecting and tracking the launch of the threat missiles. The principal concerns were the weight and accuracy of the sensor, to allow for carriage onboard the Reaper and to generate quality tracks useful for cueing interceptors rapidly. Two principal classes of sensors are available: airborne radars and Electro-Optics (EO). Airborne radar offers the ability to generate timely tracks of threats with one aircraft (Wilkening,

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[1] In a position useful for the desired mission of the aircraft.

54, 2004). However, to have sufficient ranges, an airborne radar would be too large to place onboard the Reaper. This weight constraint drove the consideration of EO sensors, specifically operating in the infrared (IR) region. Because EO/IR systems typical operate as passive sensors, stereo tracks by two or more aircraft triangulating a target are necessary.

The Reaper as presently equipped carries the Multi-spectral Targeting Systems-B (MTS-B), which provides detection capabilities in the short- and medium-wave regions. In 2016, the MDA demonstrated the capability of utilizing two Reapers to track a ballistic missile. The Reapers carried an upgraded version of the MTS, the MTS-C, which adds a long-wave IR sensor capable of tracking "cold bodies," allowing the aircraft to maintain a track through boost into the midcourse phase (Stevenson, 2016). Again, such a demonstrated capability illustrates the maturity of the system, decreases the amount of development necessary to field such a system, and enables the more rapid fielding of a capability. With such considerations in mind, this work considers the usage of a notional EO/IR sensor similar to the MTS-C, with a Noise Equivalent Intensity (NEI) of 10^{-11} Watts per square meter (Buss, 30-8, 2005) and a diffraction limited angular accuracy of $8.8*10^{-6}$ radians. The diffraction limit is given by $\text{diffraction limit} = \frac{\lambda}{D}$, where λ is the wavelength being measured and D is the aperture size of the sensor. Aperture size is assumed to be half the size of the turret of the MTS-B sensor of 0.55 meters ("AN/DAS-1," 2016). The reference wavelength from the spectral band the sensor was 4.8 micrometers.

3.5.3 The Interceptor

The final element of the BPI system to select was the interceptor that would negate the threat. Two principal approaches have been considered for airborne BPI, namely Airborne Hit-to-Kill (AHTK), which utilize a fast missile to achieve body-to-body contact with a threat missile, and directed energy approaches that rely upon a laser in order to disable the threat. Previous programs have studied and attempted to implement these approaches in the past. The discussed ABL program utilized a chemical laser housed in a 747 to achieve intercepts of ballistic missiles. Industry proposed two AHTK concepts. The first was the Air-Launched Hit-to-Kill (ALHK) based upon an airborne version of the PAC-3 from Lockheed Martin. Second, Raytheon proposed the Network-Centric Airborne Defense Element (NCADE) based upon a modified Advanced Medium-Range Air-to-Air Missile (AMRAAM) (National Research Council, 38, 2012). MDA pursued the NCADE concept to a greater extent than the ALHK, with a December 2007 test successfully demonstrating the seeker planned for utilization onboard the NCADE, intercepting a short-range ballistic missile surrogate and indicating a degree of maturity with the technology. The NCADE was also attractive due to similarities existing with the AMRAAM, namely the same profile depicted in Figure 12, allowing for carriage by a variety of aircraft in the United States arsenal including UAVs ("Network Centric Airborne Defense Element," 2017).

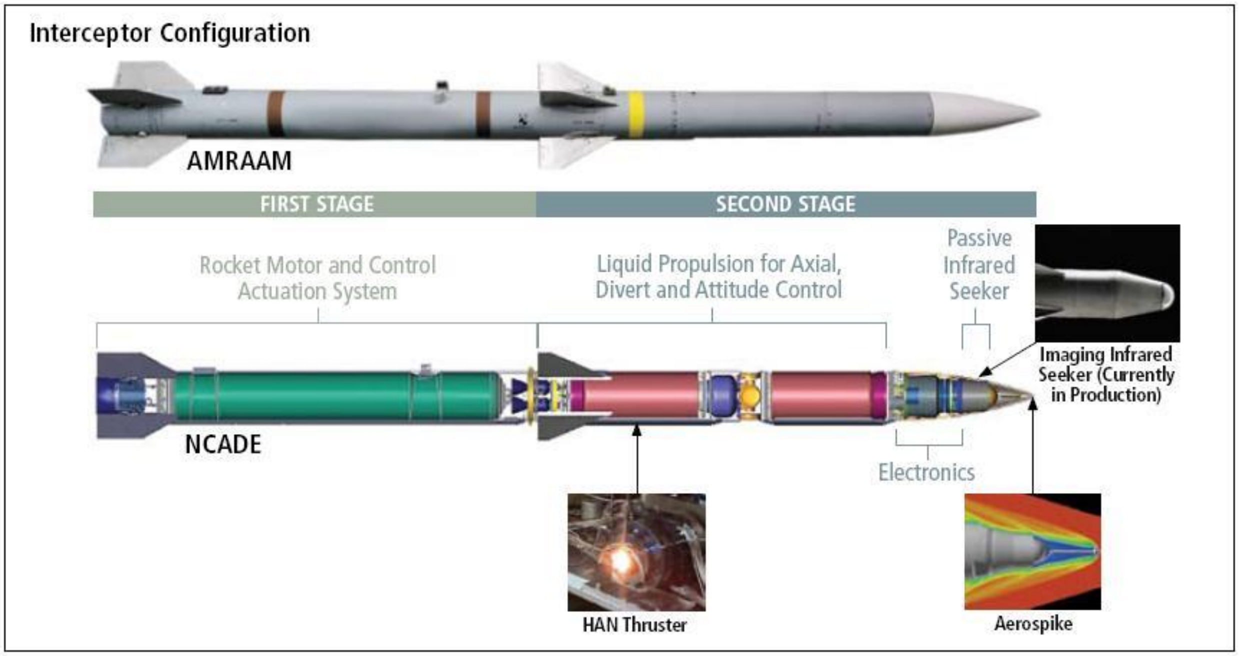

Figure 12. Comparison of AMRRAM and NCADE

An alternative approach is the use of newer directed energy technology. MDA has recently expressed renewed interest in utilizing lasers for BPI, considering the use of solid-state lasers abroad high altitude UAVs. However, such a system remains relatively far-term, with a low-power demonstrator slated to fly in 2021, with experiments and alternatives reviewed in 2018-19 (Freedberg, 2015). An operational capability would require a higher-power system than will be demonstrated, indicating such a capability is longer term than 2021. Further, such a system may require a service to champion a new aircraft development program, as current UAVs in the inventory have neither the payload nor altitude capability desired by the MDA (Personal Communication with Defense Executive, 2016). Such a program would further increase the cost and complexity in fielding such a system.

While directed energy provides many advantages for BPI, namely the propagation of the "interceptor" at the speed of light, such a capability appears to be mid- to far-term. In keeping with the desired goal of a near-term, lower cost system to provide more immediate capability, this work considered an AHTK interceptor. However, the previous concepts did not provide sufficient range or velocity for usage against emerging threats with operationally useful ranges (National Research Council, 39, 2012). An AHTK system with increased mass closer to the class of 2,000-pound bombs currently carried by American tactical aircraft may provide useful capability, similar to the SM-3 Block 2 missile currently fielded (Corbett, 101, 2010).

To provide the desired increased capability, this work modified the design of the NCADE to make use of the entire available payload onboard the Reaper, referring to this redesigned interceptor as “I-1.” The Reaper is capable of carrying 1,400 kilograms of ordinance externally (“MQ-9 Reaper,” 2015). In order to allow for the carriage of two missiles, one under each wing, the interceptor mass was set at 700 kilograms. A KV was sized to carry 5 kilograms of optics, 3 kilograms of deadweight, based on a notional focal array based upon the demonstrated NCADE capability, and 8.9 kilograms of fuel to achieve 2 kilometers per second of divert velocity for homing on the threat. The total KV weight is 16.9 kilograms. A two-stage design was utilized to achieve higher burnout velocity, with mass optimally distributed between the two stages to maximize ideal burnout velocity. Table 6 contains the final parameters of the interceptor, and Figure 13 shows a hypothetical profile of the missile compared to the AMRAAM and GBU-12, a laser-guided bomb currently carried by the Reaper.

Table 6. Interceptor “I-1” Parameters

Attribute	**Units**	**Stage 2**	**Stage 1**
Diameter	meter	0.273	0.359
m_{wet}	kg	121.2	700
m_{dry}	kg	29	208.1
m_{KV}	kg	16.9	
Thrust	kN	30.9	65.9
Burn time	seconds	8	20

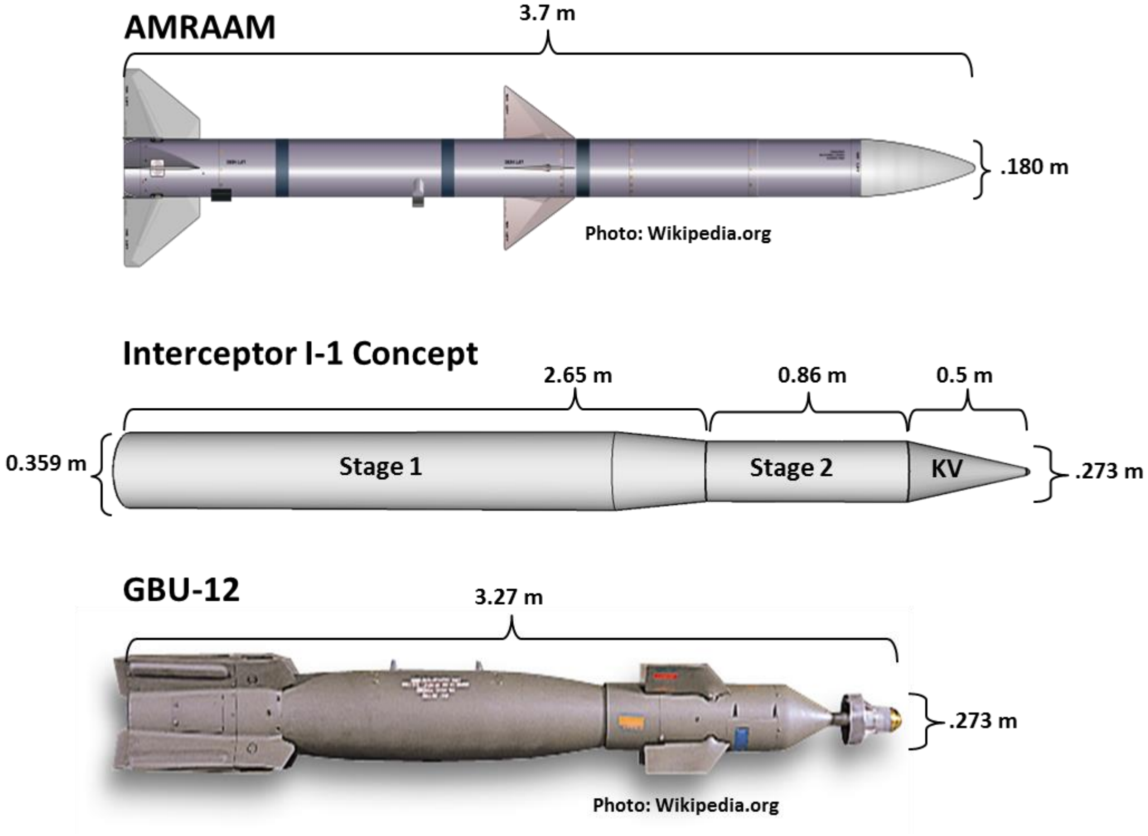

Figure 13. Comparison of AMRAAM, I-1, and GBU-12

3.6 Airborne Hit-to-Kill System Concept of Operations

To assess the capability of the developed AHTK system, a Concept of Operations (CONOPs) for the system was constructed. CONOPs included where to station the aircraft and processing a kill-chain from detection through negating the threat with the interceptor. A primary consideration in developing the CONOPs was reflecting realistic operational and political constraints, such that the assessed performance of the AHTK system would reflect performance in real-world scenarios.

3.6.1 Setting the Area of Operations

Technical considerations, such as the operating altitude of the Reaper, and political considerations, such as territorial concerns over where aircraft could operate, constrained the employment of the system. Three constraints shaped the Area of Operations (AO) in general:

1. Aircraft needed to be stationed outside of the range of Surface-to-Air Missiles (SAMs) to ensure the survival of the aircraft. Based on a survey of possible threats, this necessitated a standoff range from SAM sites of 200 kilometers.
2. Aircraft must operate outside of the territorial waters of non-allied countries, necessitating that aircraft remain 12 nautical miles from the coast of such countries.
3. Aircraft cannot overfly allied countries to avoid political concerns over operating armed drones of allied nations.

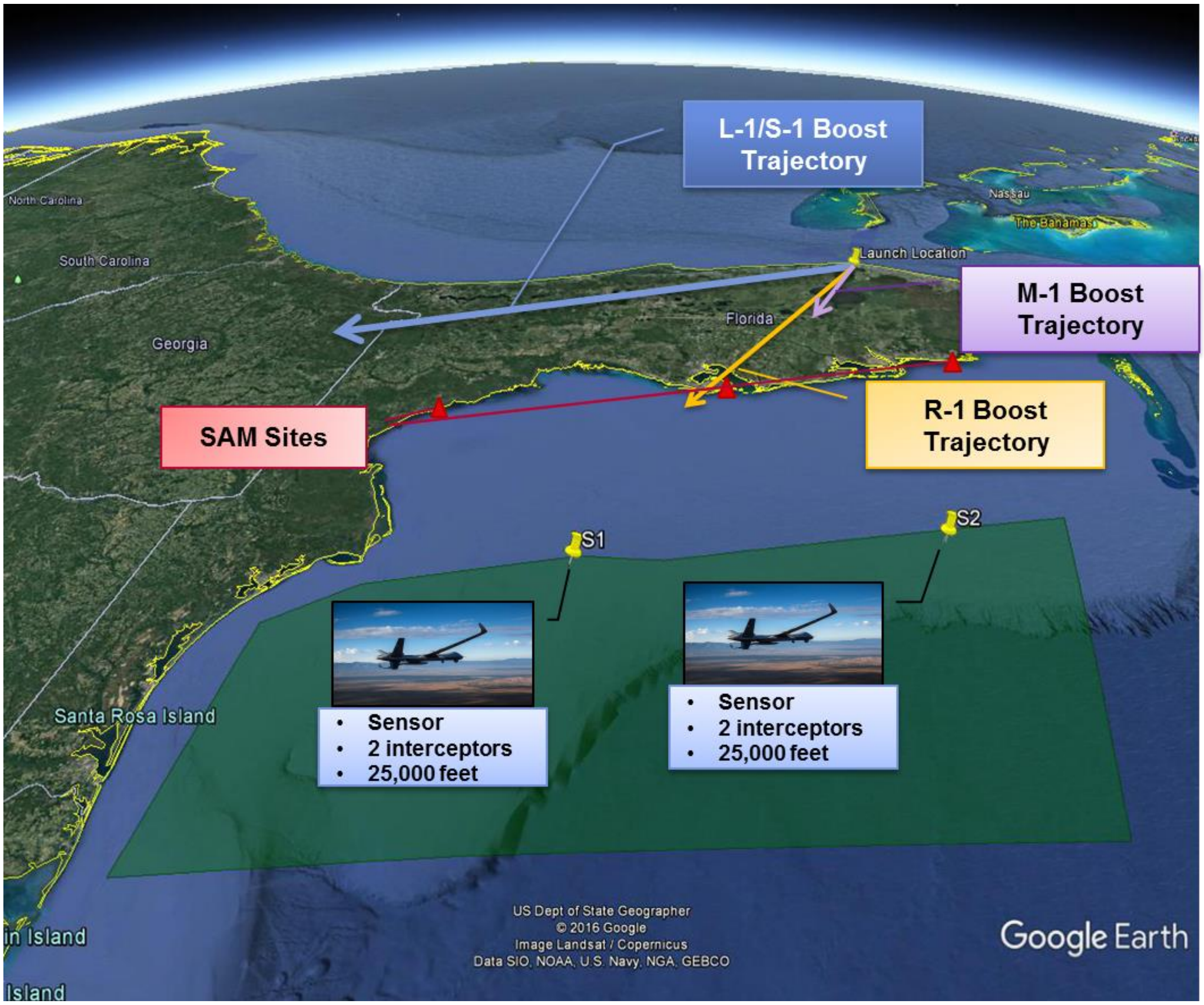

Figure 14. AHTK system notional area of operations

Figure 14 depicts the notional AO in which the AHTK system could operate along with the notional stationing of two aircraft, referred to as S_1 and S_2. The shaded green area represents the area that aircraft could safely operate persistently. Also shown are the approximate boost ground tracks of the various classes of threat missiles as well as the location of SAM sites. In this scenario, with Florida acting as the aggressor nation, the location of SAM sites influenced the shape of the AO, as well as avoiding direct overfly of the “pan-handle” Western part of the state. The geography of other countries did not influence the shaping of the AO as there are not countries in the area of interest in the Gulf of Mexico that constrained the employment of aircraft.

3.6.2 Notional Kill Chain

A BPI system utilizes a somewhat simplified kill chain compared to the one presented in Section 2.1.2, as discrimination is not necessary in a boost-phase system. Removing discrimination from the process, Figure 15 depicts the kill chain for the AHTK system.

Figure 15. AHTK kill chain

Detection occurred after two conditions were met. First, threat missile broke the cloud cover, assumed to be at 7 kilometers of altitude (Wilkening, 6, 2004). Second, both EO/IR sensors onboard the UAVs needed to obtain a sufficient signal from the threat missile’s plume in order to exceed the noise within the sensor. To perform tracking, an extended Kalman filter was implemented making use of the measurements from the two EO/IR sensors. Appendix C describes the filter in detail. Fire control required projecting the location of the threat at the time of intercept. A three-term Taylor series, given by Equation (1), predicted the location of the intercept point from the state estimates provided by the Kalman filter (Zarchan, 908, 2012).

$$r_{pip} = r_k + v_k t_f + \frac{1}{2} a_k t_f^2 \qquad (1)$$

r_{pip} is the radius of the Predicted Intercept Point (PIP), r_k is the threat track radius at time t_k, v_k is the track velocity, a_k is the track acceleration, and t_f is the time-of-flight of the interceptor launched from the platform closest to the PIP. Notably, the acceleration remains constant throughout the projection. As a result, the acceleration of the threat will introduce some error that needs to be corrected by the KV. Further, threat maneuvers will introduce further errors. Time-of-flight was found by iteratively calculating the PIP and the required t_f until both answers converged to a stable solution. The interceptor was launched when the projected covariance of the track at the time of intercept was within the divert capability of the KV after a minimum track time of 10 seconds, to reflect the time required for a real-world system to verify the track as legitimate. The interceptor boosted vertically for the first 10 seconds of flight to reduce atmospheric drag, and then utilized Lambert guidance for the remaining 18 seconds of boost. Finally, the interceptor deployed the KV after burnout, which homed via augmented proportional navigation attempting to remove any PIP errors and negate the threat via hit-to-kill (Zarchan, 895, 2012).

3.7 Assessing System Performance

With the threat models and scenario developed, a system assembled, and corresponding CONOPs implemented, this work characterized the performance of the system against the threats. The following sections depict two sets of system performance. The first is the nearer-term configuration of the system based upon the Reaper operating at an altitude of 25,000 feet (7.26 kilometers). In order to assess the effect of launch altitude, a second set of performance data was generated for a launch altitude of 55,000 feet (16.8 kilometers), similar to the operating altitude of the MQ-4C Triton.

3.7.1 Interceptor Flyout Fans

Flyout fans generally depict the kinematic performance of a given interceptor, showing the altitude and range combinations an interceptor can reach in a given amount of time. Figure 16 and Figure 17 show the flyout fans for I-1 when launched at 7.26 and 16.8 kilometers, respectively. The blue lines show possible interceptor trajectories, while the dashed contours indicate the missile position for a given time after interceptor launch.

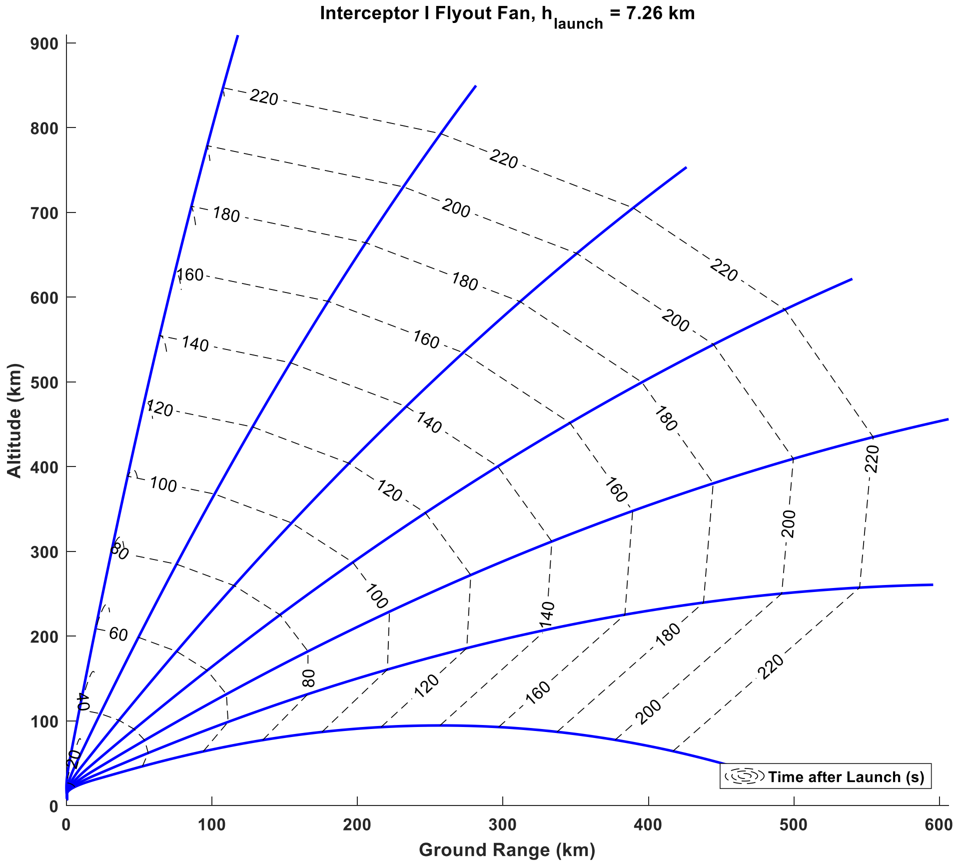

Figure 16. I-1 flyout fan with 7.26 kilometer launch

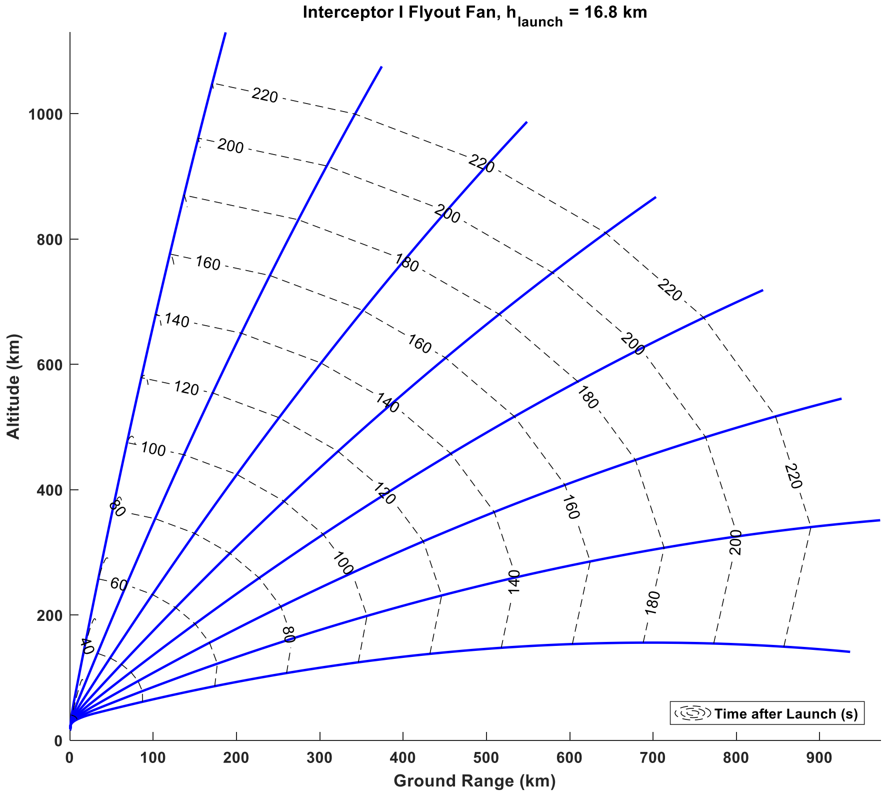

Figure 17. I-1 flyout fan with 16.8 kilometer launch

The range of the interceptor is greatest when flying to intercepts at altitudes greater than 100 kilometers, reducing the influence of atmospheric drag on the trajectory, but lower 600 kilometers, where gravity drag plays a greater role. Further, the higher launch altitude produces a significant increase in kinematic reach, increasing the maximum range achieved 220 seconds after launch from approximately 550 kilometers to 880 kilometers. This increase in performance is the result of a significant decrease in atmospheric drag, increasing the interceptor burnout velocity and therefore increasing the kinematic reach.

3.7.2 Example Intercepts

While interceptor flyout fans can illustrate kinematic capabilities of an interceptor and provide rapid insights into the coverage against a given threat, details such as sensor tracking performance and KV divert requirements can be lost when relying solely on flyout fans. As such, this work simulated a series of engagements to assess further the AHTK capability. The following section presents an example engagement against L-1, illustrating the timeline and interceptor flyout to illuminate further the kill chain as a dynamic process. Figure 18 depicts a notional engagement timeline.

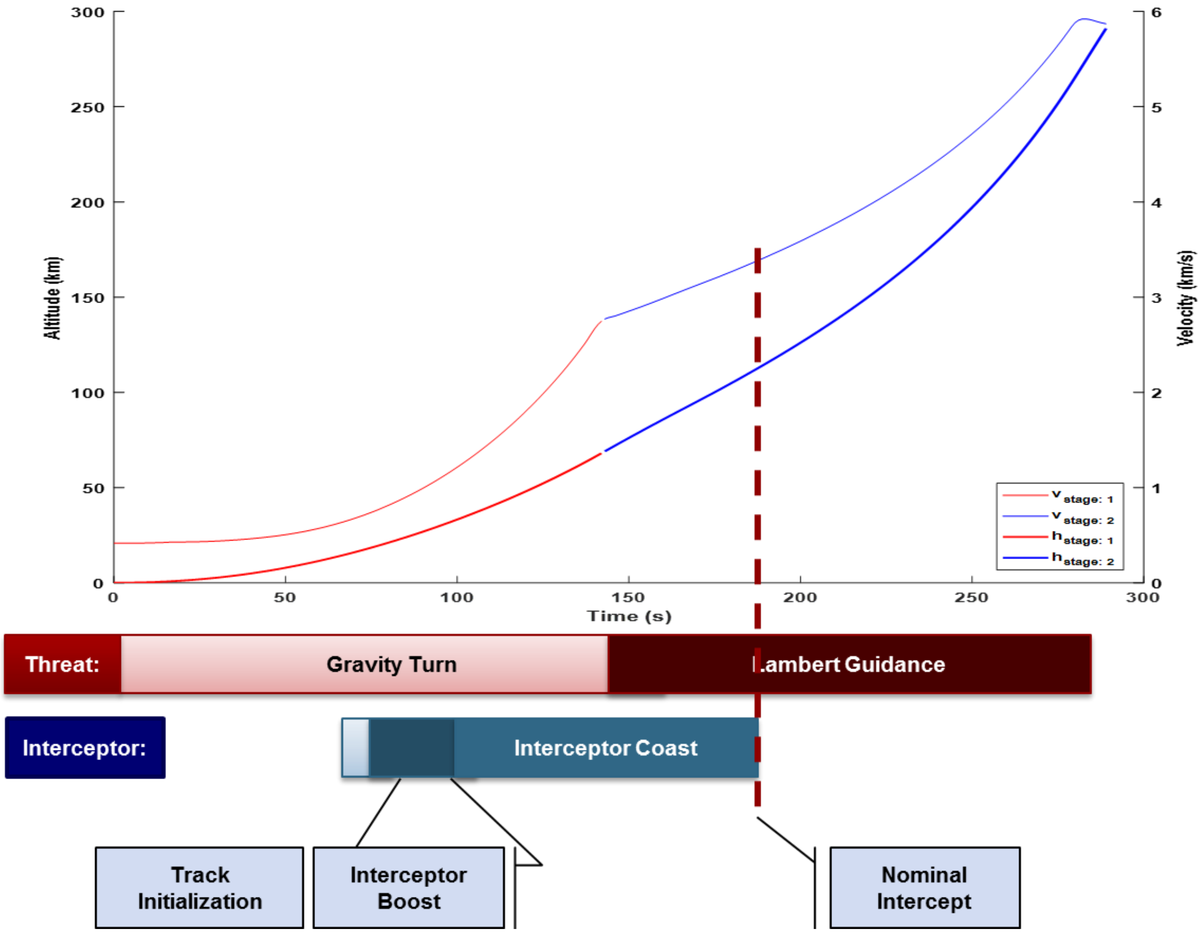

Figure 18. Notional engagement timeline

As previously discussed, the threat changes guidance technique during boost, transitioning from a gravity turn to Lambert guidance. The Kalman filter is required to maintain track through this maneuver and can incur errors around the time of transition. The tracker provides updates to the interceptor through interceptor boost. The KV must correct any remaining PIP errors post burnout.

In order to reduce the computational load when simulating a series of engagements, divert velocity requirements were estimated at interceptor burnout vice simulating the entire flyout of the KV and integrating the resultant accelerations. Further, by not simulating through the homing portion of the engagement, this simulation did not require estimates of seeker performance. Thus, estimates in this manner eliminated the need to either extend the one-dimensional plume model to altitudes beyond its validity or implement a new model. Zarchan demonstrated that Equation (2) provides a conservative estimate of the KV required divert velocity, ΔV_{KV}, resulting from PIP errors (PIP_{error}, in meters) and threat maneuver (Zarchan, 903, 2012). In the following, t_f is the time of flight for the KV and $n_{t,max}$ was the maximum acceleration of the threat, taken as a conservative 10 g's for all tracks.

$$\Delta V_{KV} = \frac{1.5 * PIP_{error}}{t_f} + \frac{1}{4} * n_{t,max} * t_f \qquad (2)$$

Figure 19 depicts the PIP errors and resultant divert velocities for an example intercept timeline. This timeline held t_f at a constant 100 seconds when calculating divert velocity requirements.

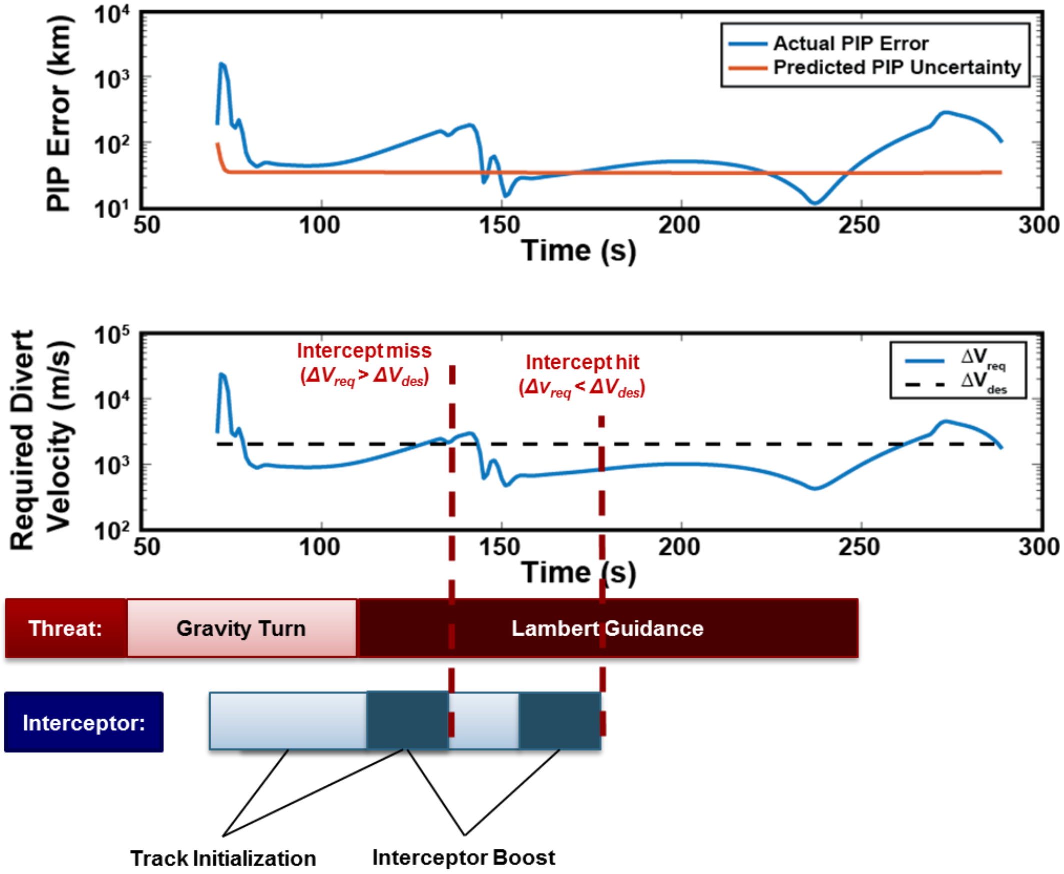

Figure 19. PIP Error and KV required divert velocity for example intercept timelines

Generally, the PIP error and required divert velocity decrease over time as the tracker refines its estimates. However, PIP error increases around 140-150 seconds due to the threat transitioning from a gravity turn to Lambert guidance and the staging event. This occurs because the extended Kalman filter and the Taylor series PIP prediction are not tuned to address this behavior. As a result, intercepts may prove difficult near staging events or guidance transitions. Further, the PIP error increases near the end of the threat's flight, as the velocity and acceleration of the threat outpace the Taylor estimate for the PIP. A further feature of the PIP error is that the system is not able to assess accurately its own uncertainty in its PIP estimates. The upper chart illustrates that the actual PIP error varies over time and is often in excess of the predicted PIP uncertainty from the tracker. As a result, an interceptor may be launched and burnout at a time when the PIP error results in a required divert velocity that exceeds the capability of the KV. The lower chart shows an example, as an interceptor that burnouts out at approximately 145 seconds would not have sufficient divert velocity to correct the error and would miss. However, an interceptor that burned out later, as illustrated at 175 seconds, would have sufficient divert velocity and would hit the target. In short, threat maneuvers can result in either threat leakage or interceptor wastage, as interceptors miss the target and either require committing additional interceptors or result in the threat passing the defensive system.

3.7.3 Stationing Options to Counter the Considered Threats

To assess locations within the AO that provide the ability to successful intercept a threat, this work simulated a series of engagements while varying the position of the interceptor within the AO. The location of one aircraft, S_2, was held constant and not allowed to launch interceptors, such that all intercepts were launched from S_1. The location of S_1 was varied across a range of locations, incrementing by a half degree of latitude and longitude through the grid, and an engagement was simulated at each location. An intercept was deemed feasible if the KV required divert velocity was below the design capability of 2 kilometers per second, the intercept occurred before the threat burned out, and the interceptor occurred above 60 kilometers where an exoatmospheric KV could operate. Endgame is neglected, as the KV will possess 2 to 3 times the acceleration of the threat at this point. This analysis is a feasibility assessment and does not account for the fact that some interceptors may be wasted if planned intercepts occur during staging events or maneuvers. This procedure was repeated for each class of threat missile with the aircraft at operating altitudes of 25,000 feet and 55,000 feet, again to assess any performance gains from the increase in altitude. Figure 20 and Figure 21 depict the capability of the AHLK system against the notional ICBM L-1 with interceptor launch altitudes of 7.26 and 16.8 kilometers, respectively.

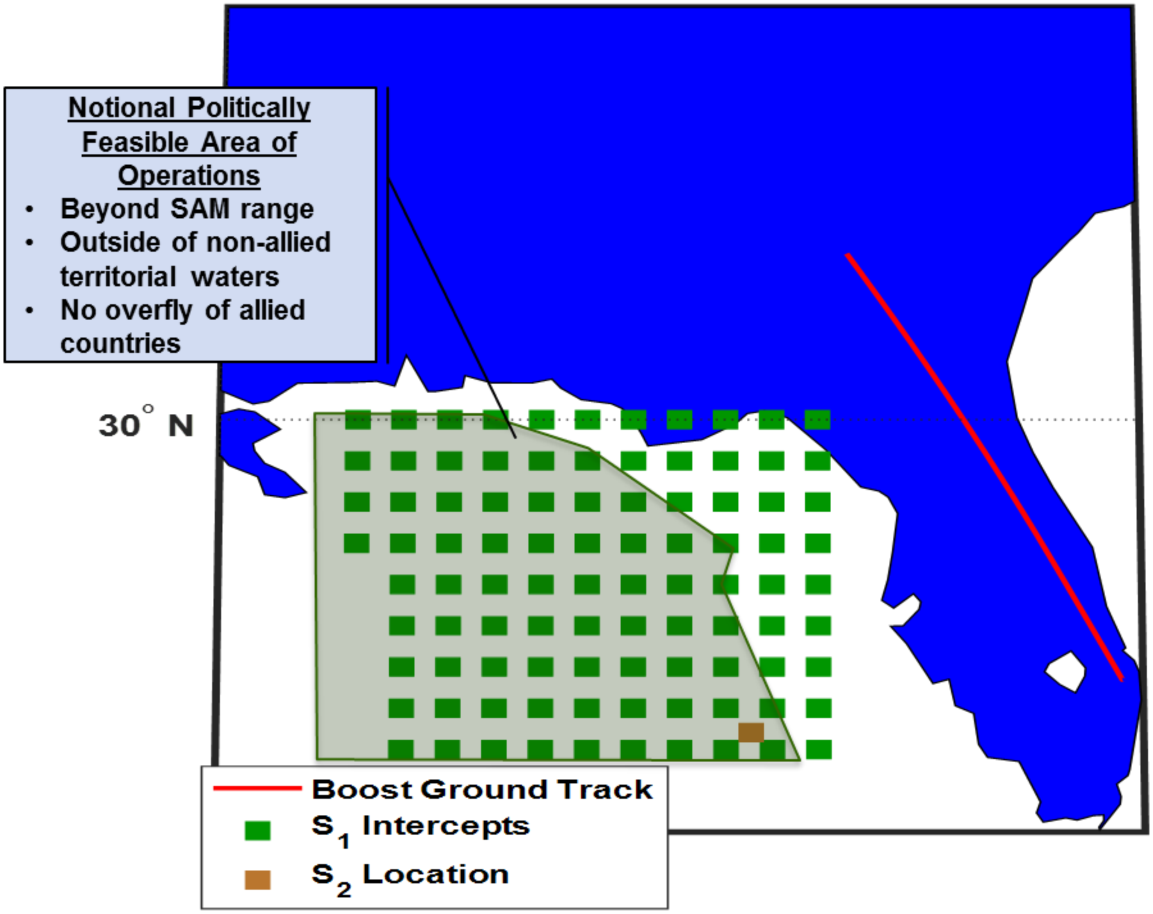

Figure 20. Feasible intercept basing locations against notional ICBM, L-1. Interceptor launch altitude = 7.26 kilometers

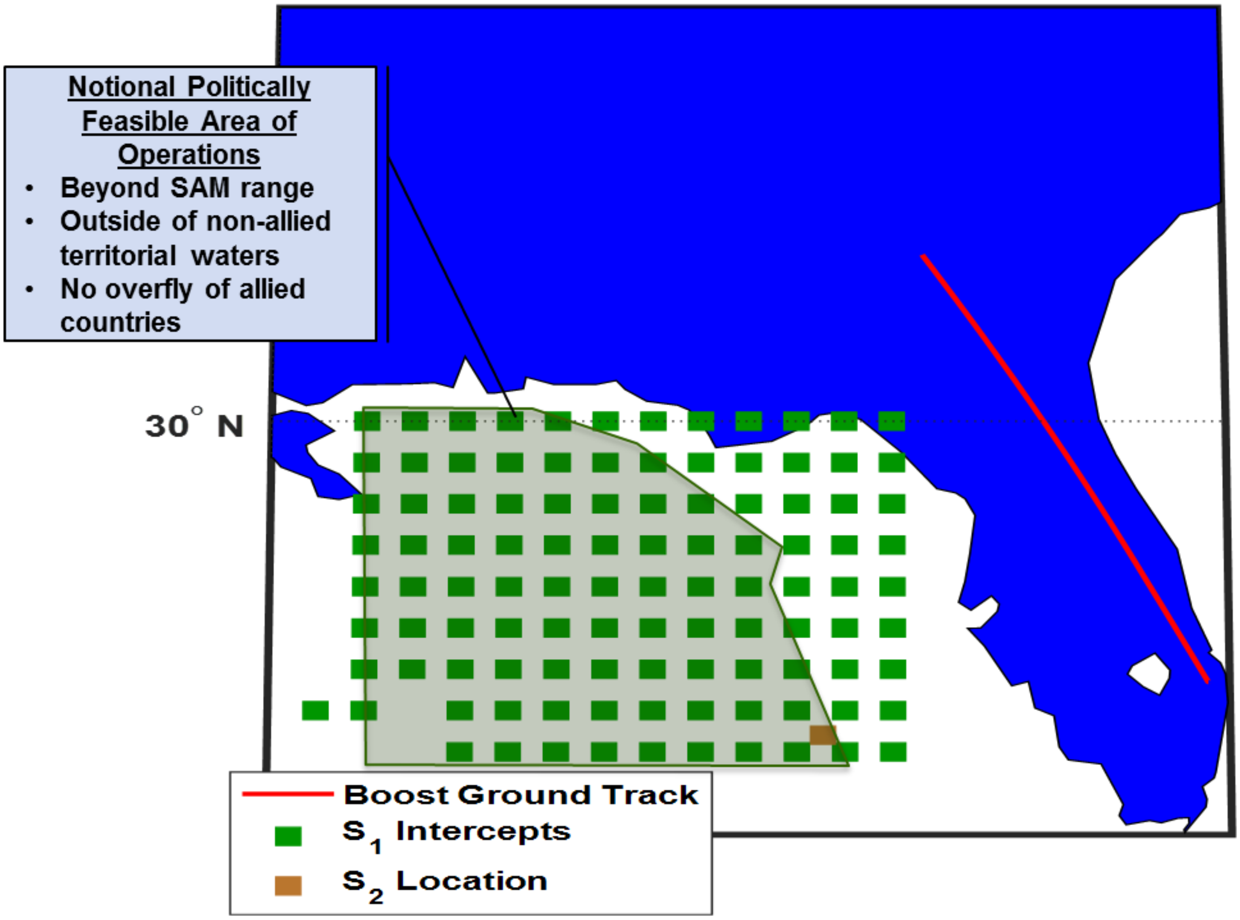

Figure 21. Feasible intercept basing locations against notional ICBM, L-1. Interceptor launch altitude = 16.8 kilometers

The AHLK system provides a significant capability against L-1, allowing for a wide range of basing options across the AO. The system could achieve a standoff range significantly greater than is required, indicating a high degree of survivability when countering the liquid-fueled ICBM. In addition, the higher launch altitude provided some increased capability, allowing feasible intercepts to occur from locations a half-degree in longitude further west. This is less than the kinematic improvements indicated by the flyout fans would predict, indicating that the tracking performance and divert velocity requirements may play a greater role in determining coverage than the increased kinematic performance.

Figure 22 and Figure 23 depict the capability of the AHLK system against the notional ICBM S-1 with interceptor launch altitudes of 7.26 and 16.8 kilometers, respectively.

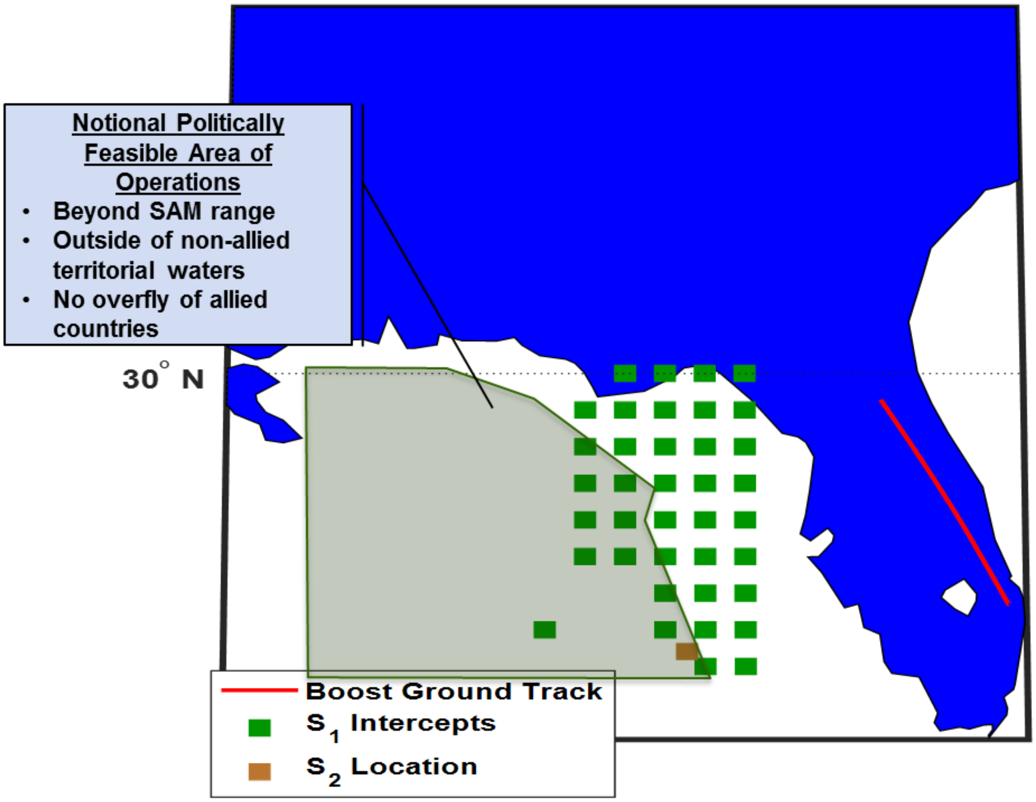

Figure 22. Feasible intercept basing locations against notional ICBM, S-1. Interceptor launch altitude = 7.26 kilometers

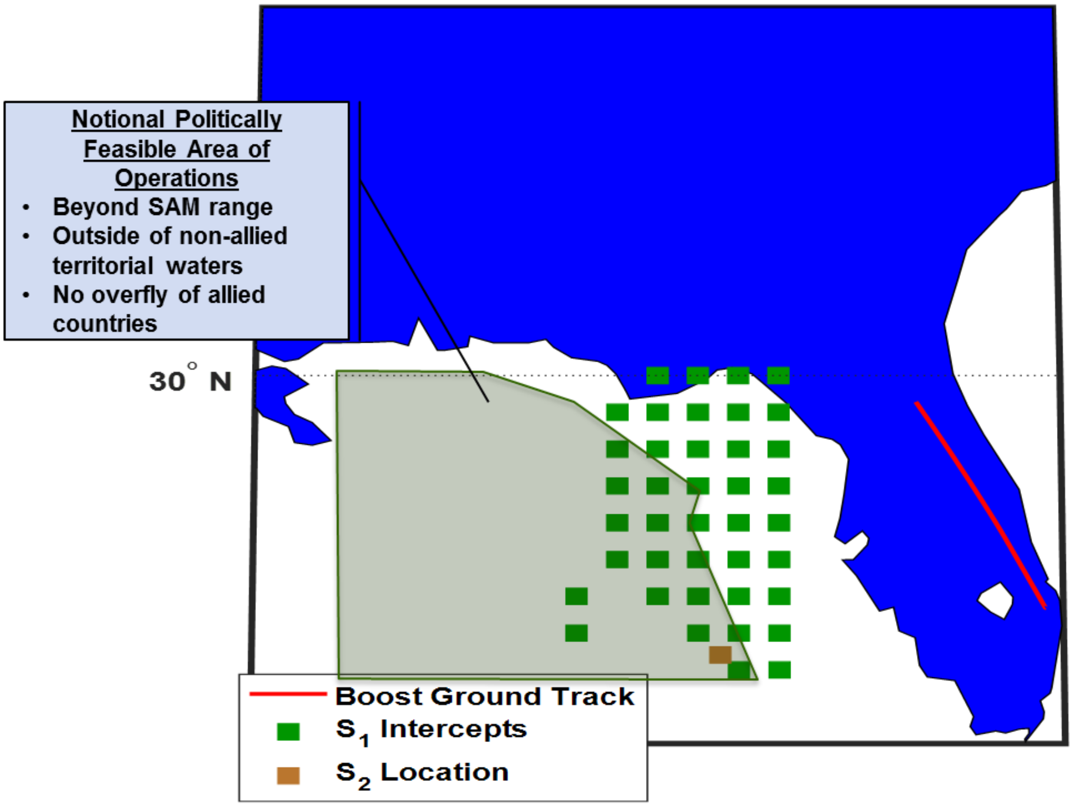

Figure 23. Feasible intercept basing locations against notional ICBM, S-1. Interceptor launch altitude = 16.8 kilometers

The faster burn time of the solid-propellant S-1 significantly decreased the standoff range for the ALHK system. However, the ALHK system still can conduct feasible intercepts from the AO, indicating capability even against faster burning ICBMs. Such a capability is significant, as the natural response to a BPI system would be to engineer faster burning ICBMs to stress the system. Stationing the aircraft at a higher altitude only provided marginal improvements in stationing options, specifically locations in the southwest of the feasible intercept area. This is again less than the kinematic improvements in interceptor performance predict, indicating that divert velocity and timeline requirements are the more stressing factors.

Figure 24 and Figure 25 depict the capability of the AHLK system against the notional IRBM R-1 with interceptor launch altitudes of 7.26 and 16.8 kilometers, respectively.

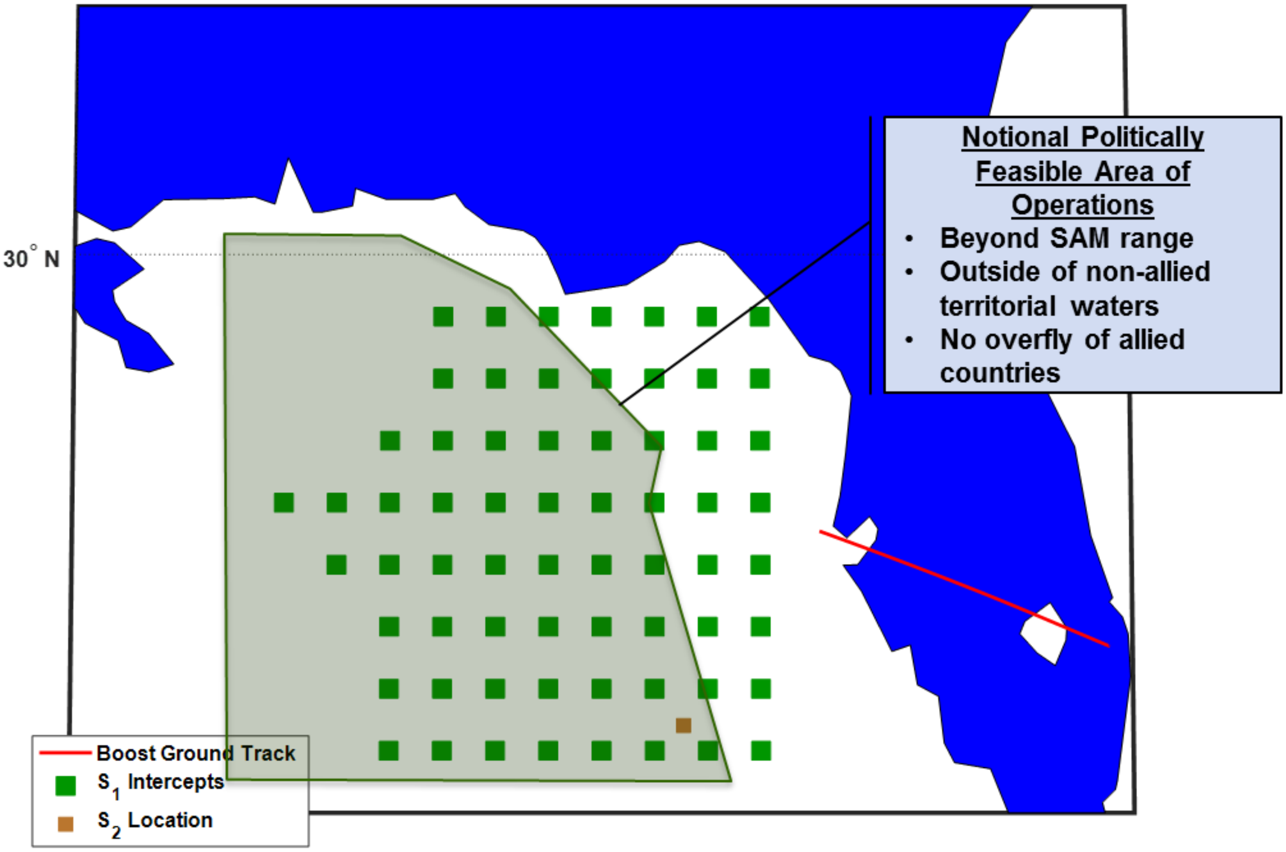

Figure 24. Feasible intercept basing locations against notional IRBM, R-1. Interceptor launch altitude = 7.26 kilometers

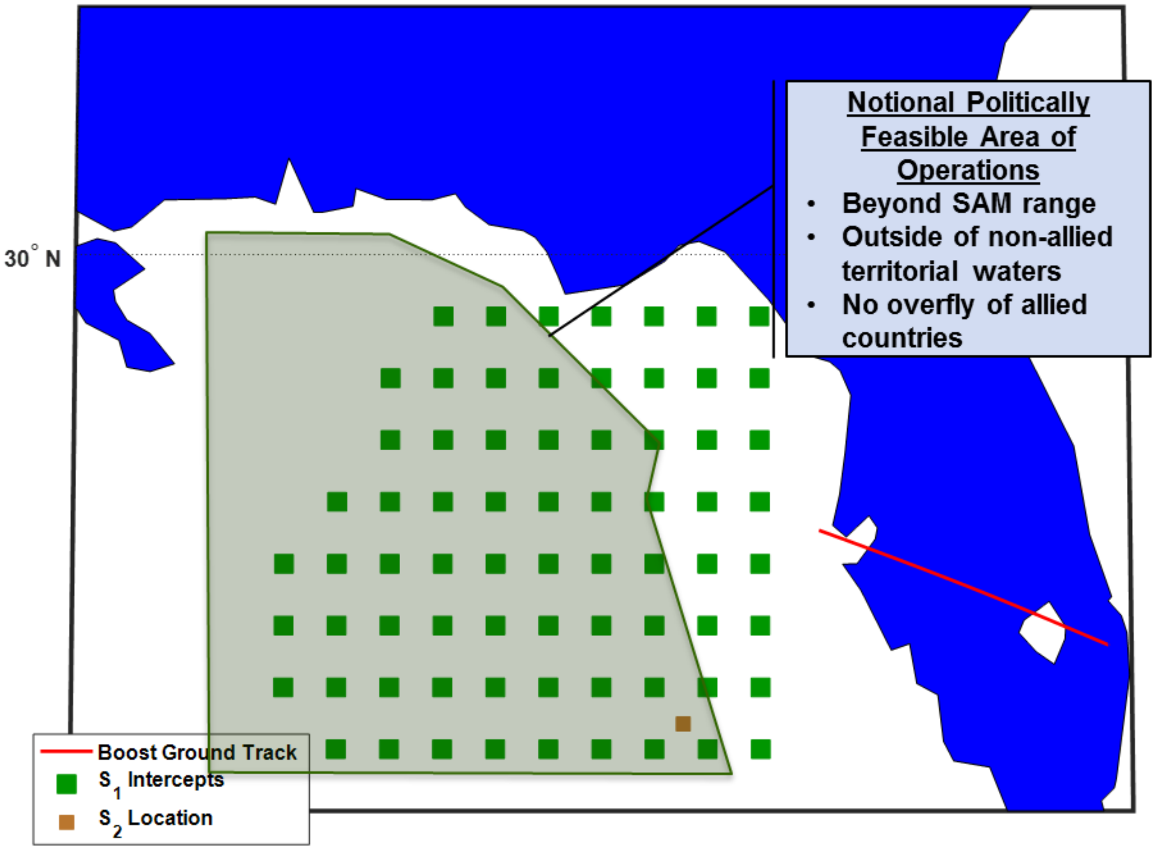

Figure 25. Feasible intercept basing locations against notional IRBM, R-1. Interceptor launch altitude = 16.8 kilometers

The ALHK system exhibited capability against the IRBM, R-1, allowing for a variety of stationing options across the AO at both launch altitudes. A significant contributing factor in the large extent of coverage is the more favorable geography of R-1's trajectory, which flies directly at the AO rather than flying overland and away from the AO like the ICBM trajectories. Such favorable geography allows for improved ALHK performance as it reduces the range the interceptors must fly to reach the target, particularly compared to the similar, though faster, burning S-1. Again, increasing the launch altitude does not significantly increase stationing options, adding some options to the southwest of the feasible area but actually removing the western most option at 7.26 kilometers of altitude. This further supports the notion that divert velocity and timeline constraints are imposing a more significant constraint than the difference in kinematic performance at these altitudes.

Figure 26 and **Error! Reference source not found.** depict the capability of the AHLK system against the notional MRBM M-1 with interceptor launch altitudes of 7.26 and 16.8 kilometers, respectively.

Figure 26. Feasible intercept basing locations against notional MRBM, M-1

The AHTK system did not provide any capability against the notional MRBM M-1 from either launching altitude. This stems from the short boosting time for M-1, slightly longer than half the burn time for the next shortest threat, S-1. Further, despite favorable geometry of M-1's trajectory boosting towards the AHTK AO, it only covers about one-third the ground range of R-1 and thus does not sufficiently close with the AO to provide any feasible intercepts. Finally, M-1 burned out at a low altitude that precludes many or all intercepts by an exoatmospheric KV. As such, defense against such a threat would require midcourse or terminal defenses.

3.8 A Brief Consideration of Cost

While this work did not explicitly develop costing estimates, other sources indicate such a providedsystem may prove cheaper than other defensive options in both cost to field and in cost per intercept. Wilkening assessed the cost of an AHTK system capable of countering an enemy inventory of 100 ballistic missiles. The system was sized to maintain three defensive stations with 240 total interceptors airborne at given time onboard Global Hawk UAVs (similar to the Triton), with one interceptor per aircraft and a total inventory of 700 interceptors. The analysis assumed that all the aircraft would be acquired specifically for the BPI system. The cost of similarly sized air-launched cruise missiles was used as the cost surrogate for the interceptor. A separate airborne radar supported the system provided tracking data, requiring eight total aircraft to maintain two 24-hour radar orbits. His estimate placed the total acquisition cost at $12.9 to $20.7 billion in 2017 dollars, not considering operating costs or development costs (Wilkening, 44-45, 2004). The National Research Council estimated the twenty-year lifecycle costs, considering development, acquisitions, and operating costs, of an AHTK system, utilizing modified F-15Cs (manned fighter aircraft), at $11.7 to $19.7 billion in 2017 dollars. The assessment considered an interceptor that was approximately the same size as the I-1 considered in this work, and considered procuring 1,000 total interceptors. The CONOPs assumed maintaining a fleet of 100 modified F-15Cs in constant air patrols, similar to the CONOPs of the UAV system proposed in this work (National Research Council, 227-236, 2012). The National Research Council would likely prove to be a better estimate of the cost of the AHTK system propose in this work, given its much more granular consideration of development costs, its more realistic procurement scenario of using modified aircraft, and a similarly sized interceptor. Further, the system proposed here may prove less expensive than this estimate, as the MQ-9 is about 9 times cheaper to operate on a per flight-hour basis ($4,762 versus $41,921) (Thompson, 2013).

3.9 Summary

In developing a new policy consensus, this chapter presented the emergence of the North Korean ballistic missile threat, presenting a dangerous pattern of behavior and technical development particularly when compared with other ballistic missile threats around the world. This chapter then suggested boost-phase intercept as presenting a possible means of gaining additional capability against such a threat due to the particular geography of North Korea. This chapter then presented a series of notional threat models, a notional canonical scenario, and a notional airborne hit-to-kill system to counter such threats. Finally, while finding the system did not provide capability against a notional MRBM, this chapter demonstrated the capability of such a system in countering notional liquid- and solid-fueled ICBMs and IRBMs.

Chapter 4. Fielding the Technology: Building a Political Coalition and Developing the Product

The natural question following the technical analysis of BPI feasibility is, if this system is feasible and effective, why has it not already been pursued? Further, what can advance this technology over these considerations? This chapter seeks to address both questions. The historical MDA decision-making environment precluded the opportunity for innovative and off nominal alternatives to gain traction. A new political coalition that relies upon the interests of the combatant commanders and the integrated warfare approach of the Navy could prove successful in pushing for a new system.

The success of any defense acquisitions program is rooted in the ability to develop a political coalition that will support and defend the development of that product from nascence to deployment. A variety of factors underlies these coalitions, from rational analysis of threats and the possible application of technology to meet these threats to personal and organizational interests. Missile defense is no exception to this rule. Proposing the adoption of a new technology and corresponding strategy requires understanding the historical dynamics that operate in the missile defense sector, namely through the decision makers in MDA, and identifying mechanisms that will allow for overcoming these historical barriers.

4.1 The Historical Missile Defense Agency Environment

As seen from the history of missile defense systems in the United States, particularly homeland defense, policymakers have emphasized deploying capabilities rapidly to meet emerging threats. In the pursuit of these rapidly fielded capabilities, the W. Bush administration exempted MDA from standard Defense Department oversight and acquisition regulations, and the Obama administration continued this policy. Further, the concern over a variety of threats from differing geographies necessitated a focus on midcourse to provide the capability to counter the various threats. As a result, the historical MDA environment precluded the consideration of alternative strategies, such as boost-phase intercept, due to two principal dynamics, namely a hurried decision-making environment and mechanisms that were opaque to outside decision makers. Such an environment is not conducive to allocating resources for the study and pursuit of innovative strategies that depart from the current portfolio under development, nor is it flexible to respond to inputs from outside organizations.

4.1.1 A Sense of Urgency and the Impact on Acquisition Efforts

Barry Posen's *Sources of Military Doctrine* argues that civilian leaders impart pressure onto military organizations, resulting in audits that determine doctrine as lacking with civilians sometimes intervening to change that doctrine (Cote, 335, 1996). This dynamic is apparent in the development of missile defense systems, particularly long-range defensive systems. The concern of policymakers at the end of the Clinton administration and during the W. Bush administration that the threat would emerge prior to our fielding of defensive systems produced the significant time pressures on military acquisitions, particularly through the MDA, to field capabilities. Obama administration demands to defend Europe from regional threats also produced similar effects. Both the presidential directive in 2002 to create a homeland missile defense system and task MDA to develop it and the presidential announcement in 2009 for United States missile defense in Europe created tight periods for MDA to deploy systems. Tightening budgets and a mandate for additional deployed interceptors further increased pressure on the capability to field robustly capable systems (GAO, 1, 2013). Further, as previously demonstrated, these decisions were largely made independent of technology maturity. This hurried decision making environment produced negative effects by causing premature decisions on which systems to field and concurrent development, testing, and fielding of those systems without the consideration of alternative strategies to midcourse defense.

4.1.1.1 A Pattern of Concurrency in Development

Concurrency, and its consequences, has been a part of missile defense efforts since their inception, with several programs including GMD affected. These efforts limit the effectiveness of MDA efforts to field robust capabilities. As GAO stated in 2013, "MDA acquisitions have faced significant cost growth, schedule delays, and/or performance shortfalls due to a highly concurrent acquisitions approach" (GAO, 4, 2013). Again, a 2015 GAO report summarized, "Since 2002, MDA has developed, demonstrated, and fielded a limited homeland and regional ballistic missile defense capability, but has fallen short of its goals, in part, because of its acquisition practices" (GAO, 9, 2015). For example, PAA has been a more recent victim, where MDA pursued a highly concurrent strategy. The MDA pursuit of a concurrent approach represents a rational response to two incentives. First, highly demanding timelines imposed by civilian decision makers necessitates concurrent development to meet the demands. The Presidential plan for European PAA illustrates these pressures, as the demand for rapid employment demands concurrent development (GAO, 17, 2013). Second, military acquisition programs generally have an incentive to concurrently develop systems to lock-in the program. As Harvey Sapolsky argues, "The military services believe that once production starts, their favored weapons gain near-irreversible momentum – so the services rush through the development phase or even finish it concurrently with full-rate manufacturing" (Sapolsky, 90, 2009). Missile defense efforts also potentially exhibit this dynamic, as some concurrently developed systems remain a principal part of the system. However, the cancellation of the ABL and the KEI programs stand counter to this perspective.

In general, successful defense acquisition programs and commercial development projects make use of a knowledge-based approach, where the program advances from stage to stage sequentially based upon the amount of information known about the technology. By demanding a gathering and demonstration of knowledge, knowledge-based development eschews concurrency.

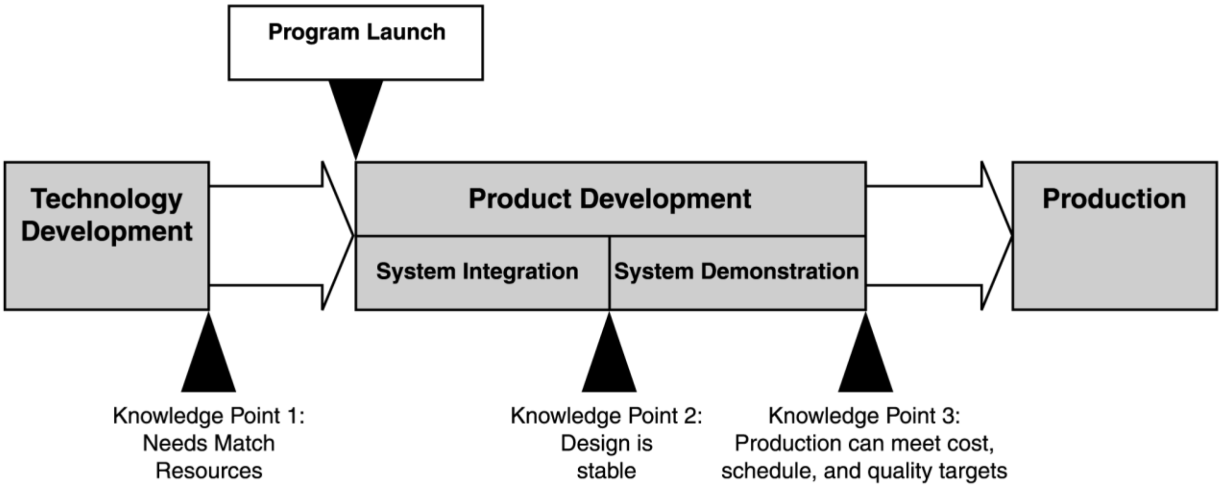

Figure 27. Knowledge-based development schedule[1]

GAO recommends three principal knowledge-based decision points within an acquisitions program, depicted by Figure 27:

1. At the technology development to system integration step, knowledge should meet the requirements and resources for a project.
2. At the system integration to system demonstration step, a stable design should be optimized for the requirements of the system, reproducibility, maintainability, and reliability.

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[1] U.S. Government Accountability Office, *Missile Defense: Knowledge-Based Decision Making Needed to Reduce Risk in Developing Airborne Laser*, GAO-02-631, Washington, D.C., 2002.

3. From system demonstration to production, the product performs as required as verified by testing (GAO, 12-13, 2002).

Projects throughout the MDA development legacy display a lack of a knowledge-based process. In the Airborne Laser Program, the MDA acquisition strategy contained elements of knowledge-based practices, namely developing a system with some capability without tying system development to meet technologically infeasible requirements. Further, additional time was provisioned for technology maturation, and facilities were constructed for testing. However, the agency did not establish knowledge-based decision points to determine when the program should move forward, leaving risk for reworking activities (GAO, 2, 2002). Part of the shortcomings of the program are rooted in its origins. The Air Force originally launched the ABL acquisition program when it realized the science and technology community did not have the resources necessary to mature the required technology on the desired time scale (GAO, 4, 2002). In many respects, the Air Force committed to a program prior to a sufficient maturation of technology to provide a capability. Further, cost-growth and schedule slippage occurred within the program because estimates were made before the level of effort required on the system was understood (GAO, 2, 2002). Namely, the Air Force underestimated the complexity of (1) designing laser components, (2) system engineering analysis and design effort, and (3) engineering the system to fit onboard an aircraft. Upon assuming control of the program, MDA chose to pursue spiral development, incrementally developing and fielding ABL capabilities as they emerged. However, this strategy did not sufficiently separate technology development, system integration, system development, and production with decision points utilizing knowledge-based criteria (GAO, 6, 2002). Again, the degree of concurrency hampered the ability to properly scope and design the system to meet a desired threat.

Similar behaviors existed across the KV development efforts within GMD, the principal vice being a propensity to fielding KVs prior to actually testing these systems, i.e. “buy before you fly.” In 2004, MDA undertook a high risk, highly concurrent technology maturation, system design, test, and fielding for the CE-I interceptors. MDA also prematurely delivered CE-II interceptors that required expensive retrofits (GAO, 9, 2013). The problems eventually found in the CE-I KVs after deployment significantly affect confidence in the system. Namely, CE-I retrofits did not address all known issues nor were the effect of instituted fixes demonstrated via flight tests. Concurrent development, fielding, and required retrofits negatively affected the ability to assess CE-I interceptor reliability as well (GAO, 3, 2014). In addition, the CE-II retrofits led to a rise in the cost of demonstration and fixes from $236 million to $1.309 billion in April 2014. However, despite the consistent need for retrofits of untested systems, the pressure to rapidly increase capability to keep pace with an apparent threat remains. The 2014 Defense Department plan submitted to Congress for homeland missile defense detailed intentions to deploy 11 additional interceptors by 2017 with CE-II Block I KVs for 44 total interceptors deployed. Reaching this figure by 2017 and an even more audacious robust capability by 2019 will require a highly concurrent, high-risk acquisition strategy (GAO, 4, 2014).

Tests demonstrated some of the difficulties and effects of concurrency. Test failures forced a shift in resources and a restructuring of test schedules towards return-to-flight activities, namely performing necessary retrofits and verifying those retrofits (GAO, 4, 2013). The effect is a cascade that effects the entire test agenda and decreases the ability to assess new capabilities as they deploy. MDA has been unable to complete its entire test plan since 2010 because the plan is ambitious and success-oriented whose structure makes changes difficult resulting in frequent disruptions from test results. Specifically, "MDA officials have told [GAO] that they do not plan for target failures, test failures, or potential retests when developing the test schedule, and that there is not flexibility to absorb these issues" (GAO, 12, 2015). Such delays and cancellations can have consequences for the performance of fielded systems, particularly as the concurrent approach fields these systems prior to the conduct of delayed tests. Delays in the tests of PAA assets creates the risk of performance shortfalls being found in fielded systems. In an effort to recoup for delays, tests are cancelled, reducing the knowledge collected for analysis and decision-making. For example, Aegis Ashore (PAA Phase 2) has had five of seven flight tests cancelled (GAO, 13-14, 2015).

Despite these identified issues, MDA continues to field systems prior to the completion of testing. MDA met some delivery goals in 2015 but continued to deliver untested element. Due to significant system interdependence, this can significantly degrade performance and necessitate major refits later (GAO, 15, 2015). For example, MDA redesigned a third-stage rocket motor component of the SM-3 Block IB but had no planned flight-tests prior to integration, in part to support the required European missile defense deployments. The contractors and the MDA believe that the fix was straightforward, low risk, and did not require a flight test (GAO, 18, 2015). Similarly, CE-II Block I deployments were planned two-years before any flight tests despite production before testing causing delays and cost increases in the BMDS in the past (GAO, 22, 2015).

However, MDA has made progress in these areas. In April 2013, MDA conducted the largest integrated air and missile defense test, intercepting three ballistic and two cruise missile targets with multiple systems. Individual systems demonstrated capability in tests, with the Army verifying operationally realistic tests upon accepting its first two THAAD batteries in 2011 (GAO, 6-7, 2013). Reducing concurrency would improve the ability to assess systems moving forward.

4.1.1.2 A Shortage of Consideration of Alternatives

The other principal effect of the compressed timelines created by political pressure is a paucity of Analysis of Alternatives (AOA), with the originally selected method usually locking-in as additional resources are committed to its development. The GAO reported, “We also found that MDA did not conduct AOAs for its new programs, which placed its programs at risk for cost, schedule, and technical problems as a result of pursuing potentially less than optimal solutions” (GAO, 23, 2015). Avoiding such analyses can lead to the alteration or cancellation of programs after false starts, contributing to a waste of funds (Grego, 13, 2016). Two programs illustrate the cost inefficiencies of failing to properly analyze a system and its alternatives relative to the desired effect. In response to stressing Presidential timelines, PTSS (Precision Tracking Space System) proceeded without a robust analysis of alternatives typically demanded by Defense Department acquisition guidelines. In the words of the National Research Council, “PTSS appears to be a solution looking for a problem” (National Research Council, 119, 2012) The system was eventually slated for cancellation in the FY2014 President’s Budget Submission after it was found it did not provide a capability to counter the desired threat. SM-3 Block IIB suffered a similar fate in the same budget decision (GAO, 15-16, 2013; GAO, 10, 2015). Further, while MDA put significant engineering effort internally into the Redesigned Kill Vehicle (RKV), it proceeded prior to considering alternative strategies beyond a new midcourse kill vehicle, proceeding based on interim alternative analysis results and design alternatives provided by industry (GAO, 23-24, 2015). In addition to a shortage of time, insufficient resources may also drive the tendency to not consider alternatives. Such assessments would take time, labor, and funds to complete, and may reduce the likelihood of the program remaining funded. As Sapolsky notes, “It is easier to get the funds to fix [a program] than it is to get the money to start production on the wrong side of the budget cycle” (Sapolsky, 71, 2009). Of particular concern to BPI, the lack of assessing alternatives makes the consideration of innovative strategies more difficult, as these techniques are less likely to rise to the level necessary for decision makers to select such approaches and can result in the lock-in of suboptimal systems.

4.1.2 The Opaque Nature of MDA Decisions

Though highly sensitive to the time demands of civilian decision makers, MDA’s process is largely internally focused and opaque to outside observers and potential contributors. To a certain extent, isolation was by design in the formation of MDA, namely its exemption from many of the standard Department of Defense oversighting and reporting requirements upon its inception. The resultant procedures developed reflect the resultant inward disposition. The original MDA acquisitions strategy, in force from 2002 to 2007, developed capability in two-year blocks. The blocks had little visibility into baseline costs, schedules, and how they addressed specific threats, making assessing progress difficult. In December 2007, MDA transitioned to capability based blocks, resulting in multiple boxes operating concurrently. The blocks committed to establish total acquisition cost and only include planned capabilities in that block. However, this approach was short lived, as it was cancelled in June 2009 as MDA transitioned to an integrated approach for BMDS (GAO, 9, 2011). The shifting paradigms made establishing progress within a program and the BMDS as a whole difficult.

Further, MDA did not regularly report on the projected costs and expected timelines for programs in its portfolio. In the 2008 National Defense Authorization Act (NDAA), Congress required MDA to report cost and schedule baselines for its efforts. MDA submitted the June 2010 BMDS Accountability Report (BAR), the first such reporting of its baselines and two years after the mandate (GAO, 6-7, 2015). However, these estimates were lacking, as the cost estimates were not comprehensive and did not contain lifecycle estimates from the services, and frequent adjustments to baselines made assessing progress difficult (GAO, 11, 2013). Subsequent MDA reports regarding its efforts were neither forthcoming nor fully enlightening on its efforts. Despite a requirement in the FY 2013 NDAA for the Secretary of Defense to submit a report to Congress on efforts to improve homeland defense by July 2, 2013, the report was not furnished until February 7, 2014. The report, titled *Status of Efforts to Improve the Homeland Ballistic Missile Defense Capability of the United States*, described actions taken but not effects. For example, MDA upgraded the EKV software but no statement was given on the effectiveness of the upgrade. Plans to improve GMD reliability also lacked detail with respect to implementation. Again, frequent changes also prevented a comparison of the effectiveness of various methodologies over time. Plans were also presented without expected time until completion. For example, the report did not contain a finalized interceptor acquisition plan, despite the planned acquisition occurring in 2018. The report also did not explain that CE-I retrofits did not fix all the issues identified in that configuration of the KVs nor did it address that the effect of these fixes was not demonstrated through flight tests (GAO, 1-3, 2014). The Defense Department also did not provide insight to Congress as to why the flight test FTG-06b was delayed, nor did it contextualize the success of the non-intercept test CTV-01 with the fact additional ground testing required further fixes to the CE-II (GAO, 5, 2014).

The periodic MDA reports remain the principal mechanism to obtain information on the status of missile defense efforts, as the BMDS still remains exempt from standard Defense Department acquisition guidelines. BMDS was planned to move to standard oversight mechanisms when a fielded capability was transferred to the services. However, this transfer has been deferred, effectively deferring normal oversight mechanisms. These policies include:

1. Documenting parameters in an acquisition program baseline that have been approved by a higher-level DoD official before moving into engineering or manufacturing development
2. Measuring the program against the baseline and obtaining approval from the reviewing official prior to making changes
3. Reporting increases in unit cost from the baseline
4. Obtaining independent lifecycle cost estimates prior to engineering and manufacturing development, production, and/or deployment
5. Regularly providing detailed program status information to Congress (GAO, 6-7, 2015).

Finally, MDA does not systematically report integrated capabilities, reducing the insight available for decision makers and preventing the assessment of MDA's progress and schedule. Reporting integrated capabilities is essential for performance reviews, as the highly and increasingly integrated nature of the system and the expanded ability of integration provides decision makers with better knowledge to make policy determinations. Such information is available in the form of detailed internal engineering reports, which could provide needed insight to decision makers if high-level information was extracted from these reports (GAO, 25, 2015).

Overall, the opaque nature of MDA acquisition efforts, though improving, makes it difficult for outside entities to understand the nature of decisions made by the agency and to assess the progress of its chosen strategy.

4.1.3 Summary and Implication and for Boost-Phase Intercept

The rapid pace of MDA acquisition efforts combined with its internal focus make adaption of innovative ideas, particularly ones proposed by external organizations, difficult. This hurried pace is the result of the pressures applied by civilian leaders to field a capability to meet the perceived emergence of threats and has resulted in significant concurrency in development. As a result, alternatives are often not considered and significant lock-in of possibly suboptimal systems occurs once resources are committed. As a result, the development of a BPI capability may require the pursuit of a system outside of the typical missile defense acquisition structure.

4.2 Building a Political Coalition around Airborne Boost-Phase Intercept

With the historical MDA environment potentially less willing to consider the development of a BPI capability, particularly one suggested from external analysis, a new coalition is necessary to build the political support to carry such a system to fruition.

4.2.1 The Combatant Commands as a Source of Advocacy

Engendering the support of the commanders in the relevant theaters would be a powerful means to generate support. Previous acquisition programs were sensitive to the needs of warfighters as articulated by the Combatant Commanders (CCDR), the four-star admiral or general responsible for a specific area of the world.

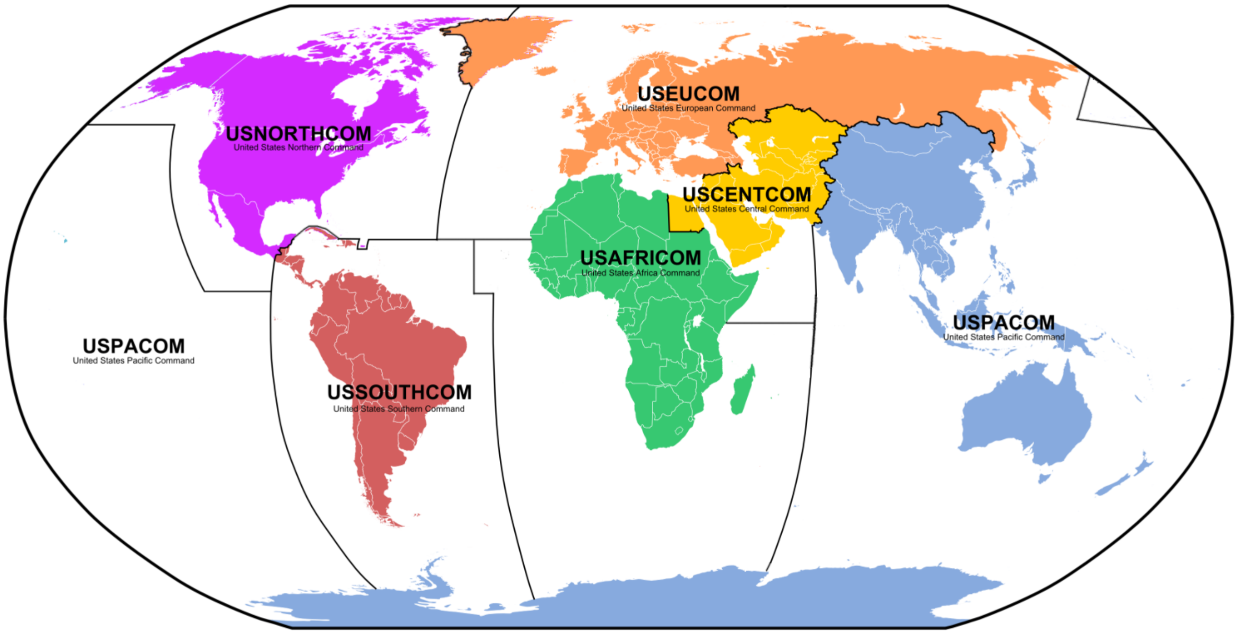

Figure 28. Geographic combatant command areas of responsibility[1]

Specifically, the Pacific Command CCDR, as the officer responsible for the forces countering North Korea, would likely have the greatest interest in such a system. Generating interest from the relevant CCDRs could create the basis for a political coalition. The capability demonstrated above against IRBM-class weapons would provide the CCDR with an improved ability to defend assets in theater while simultaneously providing a defense of the homeland capability against ICBMs. Providing an additional capability against IRBMs, and therefore an extra layer in TMD systems, is an attractive capability particularly for the Pacific Command (PACOM) CCDR, as it would provide an additional means of defending fixed assets on Guam beyond Aegis midcourse and THAAD and Patriot batteries.

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[1] "Unified Combatant Command," Wikipedia.org (accessed March 3, 2017).

While examples from active theaters of war abound, developing a new missile defense system does not present the political force that a pressing need in an active theater creates. However, the retrofit of the USS *Ponce* to support "peacetime" activities outside of the active theater in Iraq serves as an example of CCDRs ability to influence acquisition activities rapidly. Responding to a request in late 2011 from Central Command, at the time headed by Marine General James R. Mattis, the Navy slated the USS *Ponce*, an aging amphibious landing transport dock, for conversion into an interim Afloat Forward Staging Base (AFSB). The platform allows for the stationing of helicopters, small-boats, and possibly special operations forces. The AFSB concept was developed to support sea basing for special operations forces, mine countermeasure personnel and helicopters, and amphibious capabilities by providing enhanced flight deck, berthing, fuel and equipment storage, and repair spaces at lower cost over other platforms. The ship class aims to provide logistic movement from sea to shore supporting a broad range of military operations ("Afloat Forward Staging Base," 2015). The Navy conducted a rush retrofit of the *Ponce* in order to rapidly field the capability to Central Command in the interim while awaiting purpose constructed vessels (Whitlock, 2012).

After a retrofit and reclassification from amphibious landing transport dock to an interim AFSB, USS *Ponce* arrived to its new Bahrain homeport in July 2012. The ship provided the first permanently based and dedicated platform for humanitarian relief, special operations, mine countermeasures, and other mission sets (Simoes, 2013). To test and demonstrate the new capabilities offered by the platform, the *Ponce* participated, as the centerpiece, in a countermine exercise in the Persian Gulf, deploying MH-53 helicopters and divers abroad small boats and demonstrated multiple new weapon capabilities. The *Ponce* served as a "close-to-the-action support hub for mine-clearing ships, coastal patrol vessels, and helicopters," allowing these platforms to have less downtime by not needing to return to ports to resupply and allows for offshore staging of a variety of assets. In commenting on the new capabilities of the *Ponce*, General Mattis remarked, "Any extremist group, any country that puts mines in the water should be cautioned. We do have the means to take mines out of the water if they go in. We will open the waterways to freedom of navigation" ("US Navy's New Floating Base," 2012).

In addition to its initial demonstrated capability, the retrofitted *Ponce* offers a variety of capabilities to the CCDR. While the initial assignment for the *Ponce* was as a logistics and operations hub for mine-clearing, its medical suite, helicopter deck, and combat troop berthings could be used for special forces to conduct counterterrorism, reconnaissance, and other operations from international waters. The deployment of the retrofitted ship to meet Central Command's request also reinforced the diplomatic and political objectives of the American government at large, increasing pressure on Iran amidst nuclear arms negotiations and reassuring American-allied Israel (Shanker, 2012). The ship also continued to evolve as the demands of the

COCOM and the development community shifted. The *Ponce* demonstrated further utility, and the responsiveness of acquisitions to articulated warfighter interests, by integrating and demonstrating the Laser Weapons System as a roll-on system, now fully certified as a defensive weapon for the ship while operating ("Navy Expanding NIFC-CA," 2017).

The example of the *Ponce* demonstrates the ability for COCOMs to rapidly influence the acquisition process to field a desired capability, even without the constant pressure of active hostilities. Further, the alignment with the broader diplomatic interests in the region likely increased the effectiveness of such a request. A BPI capability could prove to be a similar type of interest, given the emerging threat to forces in theater and the political interest in containing that threat. Specifically, the UAV-based BPI capability would provide PACOM with an enhanced capability against theater ballistic missile threats and allow for improved contributions to homeland defense. As demonstrated, a combination of available, mature systems and near-term technology could provide this capability, making an acquisitions program in the vein of the *Ponce* a legitimate possibility.

4.2.2 The United States Navy: A Potential Champion

While a request or pressure from a combatant command could create the demand for a given system, the development, acquisition, and deployment of that system also requires the support of a service. Similar to the USS *Ponce* case, the Navy is uniquely positioned to champion a UAV-based BPI capability as such a system would complement existing Navy efforts and provide complimentary and dual-purpose contributions to emerging capabilities.

4.2.2.1 Navy Efforts in Integrated Warfare and Unmanned Systems

Beyond providing a useful capability to defend the homeland and a more theater specific capability to support defense of deployed naval assets and fixed installations from intermediate-range missile attack, the BPI system would provide another sensor link useful for the integrated and network warfare capabilities currently under development. Due to several recent efforts, unmanned capabilities are providing a greater amount of the capability in Navy systems to expand the capability of more traditional manned platforms. One such system, the MQ-8C Fire Scout, an unmanned helicopter, forms a critical part of the LCS concept of operations, offering increased endurance and the possibility of integrating additional ships and platforms into an integrated combat system ("MQ-8C Makes First Flight," 2014). In addition, the Office of Naval Research continues to invest in improving the ability of platforms to integrate engagements, awarding a contract to Raytheon to enhance data exchange through multiple data links, enhancing Cooperative Engagement Capability (CEC). CEC exchanges fire-control-quality data between platforms to allow different systems to engage targets utilizing another system's targeting information, allowing for the maximization of weapons effectiveness and range (Warwick, 2017).

An increasing number of examples illustrate the utility of CEC. The emerging Navy architecture for providing CEC across multiple platforms, Naval Integrated Fire Control – Counter Air (NIFC-CA), links multiple platforms together, allowing for the exchange of information over multiple data links. Such a capability allows different platforms to make use of others' sensors to fire weapons at targets they cannot necessarily see and leverage information gained from different sensor types. DDG-53, the USS *John Paul Jones*, used the NIFC-CA architecture to perform the longest naval surface-to-air engagement in history during a test in June 2014. The ship launched multiple SM-6 and an SM-3 missile at various classes of targets over multiple days of testing ("Test Stretches Aegis," 2014). In addition, integrated unmanned platforms provide capability against surface targets as well. Navy engineers demonstrated the ability to guide naval gunfire onto a target with data from unmanned platforms provided to Aegis ships. A ScanEagle UAV was used to stream video to the gun operators. CDR Mike Williams, Military Deputy for the Naval Surface Warfare Center Dahlgren Division Engagement Systems Department, stated, "ScanEagle has been deployed on guided missile destroyers for years to provide persistent electro-optical and infrared surveillance" ("U.S. Navy Demonstrated Integrated Unmanned-Aegis Ops," 2014).

Increasing the number of assets and associated sensors linked to NIFC-CA increases the amount of information available for engaging targets. Navy engineers are working to integrate new aircraft sensors and weapons into NIFC-CA, focusing recently on the F-35 Radio Frequency (RF) sensor and the SM-6 missile. A January 2016 test demonstrated the ability of NIFC-CA to engage slower moving targets and transmit data through different links, demonstrating an SM-6 Block I for use against surface threats. The principal focus presently is integrating the F-35 into NIFC-CA. A subsequent test, conducted on September 12, 2016, demonstrated the further integration of the F-35 into NIFC-CA, launching an SM-6 and destroying a target aircraft on a track generated by a Marine Corps F-35B. The test demonstrated an expansion of NIFC-CA from the E-2D and carrier-centric paradigm to allow for information across a variety of platforms, utilizing the F-35 Multifunction Advanced Data Link (MADL) vice data-links reliant on the E-2D for transmission.[1] Anant Patel, the major program manager for future combat

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[1] The E-2D Hawkeye is the latest carrier-based airborne early warning aircraft. The F-35B, by contrast, is capable of operating of smaller amphibious assault ships. Its ability to act as a node in NIFC-CA reduces the dependence on aircraft launched from an aircraft carrier for linking platforms together.

systems in the Program Executive Office for Integrated Warfare Systems, remarked, “This was a demonstration to show within the NIFC-CA architecture we can add another sensor. As long as it meets quality of service, we can engage the threat” (“Successful F-35, SM-6,” 2016). The shift away from the carrier allows for the integration of additional platforms and sensor to provide a distributed CEC. As Patel stated, “The more sensors, the better off we are” (“Successful F-35, SM-6,” 2016). Patel further added that while the F-35 offers significant capability, his office is funded only to investigate and integrated the RF sensor, while many additional sensors could be integrated if funds were appropriated (“Navy Expanding NIFC-CA,” 2016).

4.2.2.2 The Utility of a Navy Boost-Phase Intercept Platform and Possible Candidates

The addition of a BPI-capable UAV could further enhance the NIFC-CA system by providing an additional sensor and weapons node. First, the system would provide an additional layer within the missile defense system by providing the ability to engage missiles during the boost segment of flight. The Navy recently began to express interest in adding a boost-phase kill capability, studying a high-power, shipboard laser concept (“Navy, MDA Experimenting,” 2017). In addition, a forward UAV-based sensor could expand the reach of the SM-3 to allow earlier engagements (Stevenson, 2016). Further, the sensor suite onboard the platform could provide additional capability to provide firing cues to other platforms against other types of targets. For example, the tracking ability demonstrated against boosting missiles could also be leveraged against aircraft or possibly surface contacts, depending on the ultimate sensor suite onboard the aircraft, especially with the multi-spectral capabilities of the MTS-C.

While the Navy does not currently operate the MQ-9, the Navy could acquire Reapers in the interim or pursue a joint effort with the Air Force to provide capability while Navy specific platforms are utilized in the midterm. Two UAV programs currently in the Navy portfolio could provide platforms for the BPI mission, the MQ-4C Triton and the MQ-25A Stingray programs. The MQ-4C represents the more mature of the two options, with the first squadron standing up in October 2016. The Triton is the successor to the Broad Area Maritime Surveillance Demonstrator (BAM-S) following BAM-S successful utilization in the Middle East for several years. The aircraft is designed to provide persistent surveillance in support of the manned P-8A Poseidon (“Navy’s First Operational MQ-4C,” 2016). The aircraft carries the MTS-B EO/IR sensor, also carried by the Reaper, as well as the AN/ZPY-3 Multi-Function Active Sensor Maritime Radar (Rogoway, 2014). The sensor suite abroad the P-8A or the MQ-4C Triton would “be ideally suited for the job” of tracking slow moving targets at long range, indicating a future ability for the platform to eventually contribute as a part of the NIFC-CA architecture (“Navy Expanding NIFC-CA,” 2016). This sensor suite could also provide BPI support as is.

The mission of broad area surveillance could and BPI also are mutually supporting, as the aircraft stationing to perform both roles may prove similar.

In many respects, the Triton presents an ideal platform for airborne BPI. The MTS-B already integrated into the aircraft would provide the necessary tracks for supporting the engagement of a boosting missile as previously shown if properly configured. Further, while not specifically assessed as a part of this work, the radar system may provide mono-tracking capability, particularly when fused with the highly accurate angular measurements provided by the MTS-B. Replacing the MTS-B with the C variant would place a demonstrated sensor for tracking ballistic missiles onboard the aircraft. Such a capability would increase the ability of the system to track multiple targets or decrease the number of required aircraft. The high cruising altitude of 55,000 feet would also provide speed advantages to interceptors by reducing the drag the missile encounters and by launching the interceptor closer to the eventual intercept altitude. Finally, the aircraft has the payload necessary to support carriage of multiple interceptors of the size considered in this work, although the airframe would require modification in order to do so.

The developing MQ-25A Stingray program offers another option for a possible BPI platform, although on a longer-time horizon. The MQ-25A is the latest evolution of the Navy's pursuit of a carrier-based, unmanned aircraft. While its primary stated role at this time is as an airborne tanker, the platform is planned to grow into additional capability in the future ("It's Offical: 'MQ-25A Stingray'," 2016). In addition, the Navy request-for-information at the inception of the program calls for a small, lightweight EO/IR sensor for tracking small boats and combatants through the maritime atmosphere, with a sensor turret diameter of 19-23 inches and weighing 68.5-113 kilograms. Further, the request detailed the system to come from the existing inventory. Such a system has a similar profile to the MTS-B in use onboard in the Triton and Reaper and would provide the Stingray with the same sensor capability as the Reaper for supporting BPI engagements (Giangreco, 2016). As such, the sensor requirements for the system would not need to be modified if the BPI role were included in its mission set. Further, the carriage of interceptors should be possible from a mass standpoint, given the platforms desired ability to carry sufficient fuel to refuel other platforms, although carriage of the interceptors would require a specific design effort.

4.2.3 Summary

In order for a BPI system to reach maturation, a political coalition outside of the historic missile defense acquisition structure is likely necessary. The pairing of interest from the combatant commands, particularly PACOM, coupled with the support of the Navy could provide such a winning coalition. As the example of the USS *Ponce* illustrated, such a combination was able to produce a capability in a short amount of time. Further, systems currently fielded or in development within the Navy provided possible candidates for improved BPI capability in the future while also providing dual capability as a part of the NIFC-CA architecture or other mission sets.

4.3 Case Studies in Missile Defense and Developing a Good Product

Missile defense systems are highly complex technical feats, comprising nets of platforms, sensors, and interceptors spread around the globe. Developing such systems is a challenging endeavor and requires the highest competency in managing technical systems from agencies. As previously demonstrated, the structuring of incentives for a bureaucracy often drives the results obtained. Learning from the previously highlighted challenges and the reasons for those challenges in missile defense development is essential to the development of enhanced capabilities. In referring to the Airborne Laser program, Frank Kendall, the Pentagon procurement chief, stated,

> I was in the Pentagon when the Airborne Laser was proposed, and I asked questions about how many we would have to buy, how we'd know to put them in the air, and how we'd keep them alive. We didn't have good answers to those questions, but we went ahead with the Airborne Laser anyways (Freedberg, 2015).

The question then becomes, how can missile defense acquisition processes be improved to prevent such outcomes in the future? The first, and arguably most important step, is to remove strong incentives from political decision makers that produced the sense of urgency in MDA. First, the Rumsfeld Commission report, then 9/11, then a constant stream of threats and developments from third-world actors have created a continued sense of defensive systems "chasing the threat." This constant sense of defense capability gaps over the course of missile defense development continues the perceived need for rapid, concurrent fielding of systems. However, the GAO warned against such an approach in 2003, stating,

> Because the ballistic missile threat is rapidly increasing, MDA could always believe it is operating in an emergency environment. Yet, it has never proven that it takes longer to acquire a weapon system if a knowledge-based acquisition plan is followed. Instead, the opposite should be true, because such a plan decreases the likelihood that deadlines will be missed because critical elements do not work as intended (Grego, 15, 2016).

Congressional and executive branch officials transfer such pressures to the MDA, which responds to their requests by attempting to rapidly field systems, leading to the continuation of the concurrency cycle. Congress further contributes in two-ways: first through neither skepticism of nor a requirement for analysis of alternatives of missile defense systems, and second by adding programs either through the politicization of the acquisition process or via weakened oversight (Grego, 16, 2016). Such Congressional action stems both from their analysis of the security environment and an associated desire for rapidly fielding capabilities, and through political pressures (Cho, 289, 2009). As an example, from 1999 to March 2014, Boeing, the prime contractor for GMD, spent $261.6 million on lobbying, and Raytheon, the EKV manufacturer, spent an additional $144.4 million. Further, thousands of jobs depend on GMD, particularly in Arizona and Alabama. Senator Jeff Sessions', of Alabama, repeated support of GMD fits a response to political interests (Willman, 2014).

While threats continue to evolve, reducing the political pressure from decision makers to rapidly field systems would likely improve outcomes. Some more immediate steps could aid in reducing such pressures. Currently, the MDA director has concurrent and conflicting responsibilities for developing missile defense systems and certifying that the program is achieving desired milestones. While such a structure can improve coordination, it also creates conflicting incentives. Separating these responsibilities for development and oversight would likely result in qualitative improvements by reducing urgency demands on the officials in charge of oversight. Further, GMD, despite being a highly complex system-of-systems with any one element constituting a major defense program, is regarded as a single system and remains exempted from traditional oversight until the entire system is deemed ready for "initial production" (Grego, 13, 2016). Such an arrangement, again while reducing coordination problems, can stress the management capabilities of a program office (Sapolsky, 87, 2009). While the unified approach is necessary due to the extreme coordination required for such a large system, bringing GMD under the standard DoD 5000 acquisition regulations would improve oversight and reduce concurrency pressures.

Reducing concurrency pressures would also allow for a focus on qualitative improvements in capabilities vice quantitative increases in deployed interceptors. Such a shift in focus would help develop robust capabilities that can then be scaled as necessary. The 2008 Welch report, heading by retired Air Force Chief of Staff General Larry Welch, stated,

> For midcourse intercept systems, the balance between qualitative improvements and deploying more of existing capabilities should be strongly in favor of qualitative improvements. Without such a focus, the current system capabilities will become obsolete regardless of the numbers of interceptors deployed (Grego, 25, 2016).

In contrast, pressure to deploy additional interceptors adversely affected the 2010 KV redesign, leading to a scaling back of goals deemed the CE-II Block I. The GAO assessed the Pentagon did not head their suggestion to delay production until a successful intercept test because delays "would unacceptably increase the risk to reaching the Secretary of Defense mandate to achieve 44 emplaced interceptors by the end of 2017" (Grego, 25, 2016).

Related to reallocating resources to focus on qualitative improvements, increasing the amount of testing would also aid in assessing and improving missile defense capabilities. Testing is vital to understanding the mission set a system a system can fulfill and how to operational employ that system. The accelerated deployment schedule requires devoting resources to production at the expense of testing. As the MDA reported, "in order to meet fielding obligations of 44 interceptors by the end of 2017, all current interceptor production resources are devoted to manufacturing operational interceptors" (Grego, 29, 2016). In most systems, "fly, then buy" is a standard acquisition maxim that the DoD 5000 requirements codify. GMD, however, throughout its history has followed a course of "buy, then fly." Secretary of Defense Rumsfeld's decision to exempt the MDA from standard practices and to allow research and development money to fund fielding system enabled such practices (Willman, 2014). Further, constantly changing components has complicated efforts to assess the capability of GMD. Establishing baselines with increased testing would also aid in assessing the effects of changes to the system (Grego, 28, 2016). Finally, a further commitment to the study of alternative approaches to proposed or existing systems could help provide improved capability. Exemptions from alternatives studies as stipulated in the DoD 5000 "allowed the MDA to start expensive, poorly vetted initiatives, only to cancel them a few years later after having spent millions of dollars" (Grego, 16, 2016). ABL, KEI, PTSS, and others serve as examples.

The study of these recent trends in missile defense acquisitions leads to several recommendations that could improve the acquisition process and deliver improved capabilities at lower cost. Sufficiently analyzing alternatives before major investments, stabilizing baselines, and ensuring comprehensive testing would likely deliver improved, more reliable capability (GAO, 19, 2013). Implementing a knowledge-based approach demonstrating capability at key points, similar to successful commercial firms, would also improve the process. As the GAO noted, "Successful programs that deliver promised capabilities for the estimated cost and on schedule use a disciplined, knowledge-based approach where knowledge supplants risk over time" (GAO, 8, 2015). MDA has made progress in risk reduction through such mechanisms recently. For example, the SM-3 Block IIA had 100 percent of design drawings complete at its critical design review, indicating design stability prior to moving to production. Further, its schedules were relaxed to allow the review of subsystems and associated risk reduction (GAO, 8, 2015). The MDA Director, Vice Admiral James Syring, indicated his agency's movement towards an incremental and knowledge-based approach, stating, “It is a very different approach than we did in the past of just leaping to something and investing everything we had” (Freedberg, 2015).

4.4 Summary

This chapter surveyed the historical pressures and ensuing process that drove previous MDA decisions. Drawing from this dynamic, this chapter suggested an alternative mechanism to advocate for an AHTK system, recognizing the power of combatant commanders to influence acquisitions, and suggesting the PACOM commander as the most likely interested party. This chapter also identified the Navy as a potential champion givens its interest in integrated warfare and unmanned systems. Finally, this chapter reviewed previous missile defense acquisition efforts and made suggestions on how to avoid challenges associated with concurrency in future programs.

Chapter 5. Conclusions and Broader Applications

This thesis traced the history of modern missile defense to highlight the broad patterns that resulted in the systems of today and the lack of a boost-phase kill capability within a layered defense. It then assessed the rise of the North Korean missile threat and suggested boost-phase intercept as a means of addressing such a threat. Technical analysis of such an airborne hit-to-kill system showed the ability to provide intercept capability against ICBMs and IRBMs during their boost. Finally, this thesis studied the decision making process of MDA, showed a new means to advocate for such a system, and made suggestions on how to improve the missile defense acquisition process.

The lessons drawn from this specific case study may have broader applicability than the material and process improvement of missile defense acquisitions. Perhaps most prominently, the challenges of missile defense stemming from its unique procurement environment may suggest the utility of the standard set of acquisition requirements. Though such a process may be perceived as clunky, unwieldly, or slow, missile defense acquisition troubles point to the value of such a process. The codified, consistent standards in many ways alleviate the pressures that strategic environments and political realities can place on a program and enable the success of such a program in a difficult environment.

Dedicating resources at the outset of a program to studying alternatives and testing as a part of a knowledge-based process should also have the ability to improve programs that do not make use of such practices. Robust analysis of alternatives, though perhaps time and resource intensive, can improve results, either by identifying other more cost-effective approaches or simply by generating knowledge about the issue domain and allowing the incorporation of that knowledge in future development efforts. Further, the increased utilization and reliance on engineering modeling presents the risk of decreasing the perceived need for more standard physical tests. The lesson from missile defense that tests are necessary probably extends to most other domains, where models can only model what is known. Tests, however, can show what is unknown. The coupling of analysis of alternatives and testing increases the knowledge available to make informed decisions, and informed decisions generally produce better outcomes across domains. Finally, reducing or eliminating concurrency, particularly in the development of highly complex systems, should improve results across fields. Recognizing and explicitly defining prototypes as merely steps towards the final solution to a problem could help reduce the pressure to field immature systems.

More challenging, however, is reducing the incentives that produce concurrency. This study of missile defense displayed the extent to which bureaucracies respond to the incentives placed upon them. MDA rapidly moved to field systems because it was incentivized to do so. Creating political systems that do not create such incentives is difficult. The visual of lowering an interceptor into a silo creates a powerful political narrative of action in the face of an emerging threat. Technical analysis of the shortcomings of that interceptor to addressing the threat, less so. However, some mechanisms exist to allow for at least the partial separation of high-stakes defense acquisitions and political pressures and were highlighted in this thesis. Some have already been implemented, much to the credit of the political and bureaucratic bodies responsible for their implementation. Other complex sociotechnical systems have faced similar pressures and managed to produce stunning outcomes. There is no reason that missile defense, and defense acquisitions in general, with a continued dedicated pursuit of technical and process improvements, cannot do the same.

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Appendix A – Generating Ballistic Missile Trajectories

Generating the trajectories of a missile in boost, either a threat or an interceptor, required numerically integrating the equations of motion for the missile through the duration of boosting flight. Equations (3) and (4) give the equations of motion.

$$\dot{\boldsymbol{r}}(t) = \boldsymbol{v}(t) \tag{3}$$

$$\dot{\boldsymbol{v}}(t) = -\frac{\mu}{\|\boldsymbol{r}(t)\|^3}\boldsymbol{r}(t) + \frac{T}{m(t)}\boldsymbol{u}(t) + \frac{\boldsymbol{D}(t)}{m(t)} \tag{4}$$

Bold characters denote a vector quantity, with all vectors given in the Earth Centered Inertial (ECI) frame. In the above, ***r(t)*** the inertial position at time *t*, **v**(t) is the inertial velocity, ***u(t)*** is the thrust command vector, ***D(t)*** is the drag vector, *m(t)* is the mass of the missile, *T* is the thrust, and μ is Earth's gravitational parameter. Thrust was constant for a given stage, specified by the average thrust. Propellant burned at a constant rate over the burn time of a stage. Equation (5) expresses the drag vector.

$$\boldsymbol{D}(t) = -\frac{1}{2}\rho S C_D \|\boldsymbol{v}_{rel}(t)\| \boldsymbol{v}_{rel}(t) \tag{5}$$

ρ is the atmospheric density at the current altitude, given by the 1976 Standard Atmosphere. *S* is the aerodynamic reference area taken as the cross-sectional area of the current stage, C_D is the drag coefficient of 0.25 for all threat stages and 0.5 for the interceptor I-1, and $\boldsymbol{v}_{rel}(t)$ is the relative velocity vector of the missile with respect to the atmosphere, given by Equation (6).

$$\boldsymbol{v}_{rel}(t) = \boldsymbol{v}(t) - \omega_e \text{ x } \boldsymbol{r}(t) \tag{6}$$

ω_e is Earth's angular velocity (Coskun, 42-48, 2014).

The thrust command vector depended on the guidance law the missile was using at time *t*. For the initial stages of flight, the thrust vector is aligned with the position of the missile to produce purely vertical acceleration relative to the surface of the earth. After the initial vertical flight, the missile first performed a gravity turn then shifted to Lambert guidance. At all times, the missile set the thrust vector to achieve a heading measured from true north, β, on a great circle route to the target at all times. β is found by solving Equations (7) through (10), where τ_t and λ_t are the latitude and longitude of the target, τ_k and λ_k are the current latitude and longitude of the missile, and t_{ff} is the time of flight of the missile in ballistic flight and t_b is the time of flight remaining in boost (Jang, 7, 2008).

$$\tan(\beta) = \frac{\cos(\tau_t)\cos(\tau_k) * \sin(\lambda_t - \lambda_c + \omega_e(t_{ff} + t_b)}{\sin(\tau_t) - \cos(a)\sin(\tau_k)} \quad (7)$$

$$\cos(a) = \cos(b)\cos(c) + \sin(b)\sin(c)\cos(\lambda_t - \lambda_c + \omega_e t_{ff}) \quad (8)$$

$$b = \frac{\pi}{2} - \tau_k \quad (9)$$

$$c = \frac{\pi}{2} - \tau_t \quad (10)$$

Time of flight and the heading necessary are both dependent on the range of the missile. Further, the range is dependent on the time of flight due to the rotation of the Earth. To find t_{ff}, Equations (11) through (18) are solved iteratively until t_{ff} converges to a stable answer (Bate, 280-310, 1971).

$$\cos(\varphi) = \sin(\tau_c)\sin(\tau_t) + \cos(\tau_c)\cos(\tau_t)\cos(\lambda_t - \lambda_c + \omega_e t_{ff}) \quad (11)$$

$$Q_{bo} = \frac{{v_{bo}}^2 r_{bo}}{\mu} \quad (12)$$

$$a = \frac{r_{bo}}{2 - Q_{bo}} \quad (13)$$

$$\sin\left(\frac{\varphi}{2}\right) = \frac{Q_{bo}}{2 - Q_{bo}} \quad (14)$$

$$\sin\left(2\gamma_{bo} + \frac{\varphi}{2}\right) = \frac{2 - Q_{bo}}{Q_{bo}}\sin\left(\frac{\varphi}{2}\right) \quad (15)$$

$$\mathrm{e} = \sqrt{1 + Q_{bo}(Q_{bo} - 2)\cos(\gamma_{bo})^2} \quad (16)$$

$$\cos(E_1) = \frac{e - cos\left(\frac{\varphi}{2}\right)}{1 - e\ cos\left(\frac{\varphi}{2}\right)} \tag{17}$$

$$\mathrm{t}_{ff} = 2\sqrt{\frac{a^3}{\mu}}(\pi - E_1 + e\sin(E_1)) \tag{18}$$

In the proceeding equations, φ is the central angle between the burnout location and the target, v_{bo} and r_{bo} are the velocity and radius magnitude at missile burnout, Q_{bo} is a nondimensional parameter at burnout, a is the semimjaor axis of the missile orbit, γ_{bo} is the flight-path angle at burnout, e is the eccentricity of the missile orbit, and E_1 is the eccentric anomaly at burnout.

During the gravity turn, after an initial "kick," in which the thrust vector is pointed to turn the nose of the missile from purely vertical towards the desired direction of flight, the thrust vector is aligned with the velocity of the vehicle. Gravity then gradually pulls the nose of the missile down, creating a "gravity turn." Such a turn prevents aerodynamic loading on the missile while within the atmosphere (Barton, S270, 2004). The gravity turn continued until dynamic pressure fell below 23 Pa, within loading tolerance of the vehicle to allow maneuvers (Barton, S264, 2004).

The missile then utilized Lambert guidance to achieve the necessary velocity to reach the target. Lambert guidance require solving for the necessary flight-path angle to achieve a desired ballistic time of flight from a starting position to a final position. With the desired t_{ff} given from Equation (18), the flight-path angle is iterated until the time of flight matches within tolerance the desired time of flight. By restricting cases that would result in the missile achieving escape velocity, Equations (19) and (20) give the bounds of the possible flight-path angles.

$$\gamma_{min} = \tan^{-1}\left\{\frac{\sin(\varphi) - \sqrt{\frac{2r_0}{r_f}(1 - \cos(\varphi))}}{1 - \cos(\varphi)}\right\} \tag{19}$$

$$\gamma_{max} = \tan^{-1}\left\{\frac{\sin(\varphi) + \sqrt{\frac{2r_0}{r_f}(1-\cos(\varphi))}}{1-\cos(\varphi)}\right\} \tag{20}$$

To efficiently perform the search across the range, a secant method is utilized, given by Equation (21). The next flight-path angle, γ_{n+1}, is calculated from the current and previous flight-path angle, γ_n and γ_{n-1}, and the current, previous, and desired times of flight, $t_{ff,n}$, $t_{ff,n-1}$, and $t_{ff,des}$.

$$\gamma_{n+1} = \gamma_n + \frac{(\gamma_n - \gamma_{n-1})(t_{ff,des} - t_{ff,n})}{t_{ff,n} - t_{ff,n-1}} \tag{21}$$

The necessary velocity vector from the Lambert routine, $\mathbf{v}_{Lambert}$, is calculated from the heading and flight-path angle by converting the polar angles into the ECI coordinate frame. Equations (22) and (23) then give the thrust command vector at time *t*, where $\boldsymbol{\Delta v}$ is the vector difference between the missiles current velocity and the Lambert velocity as shown in Figure 29.

$$\Delta\mathbf{v} = \boldsymbol{v}_{Lambert} - \boldsymbol{v} \tag{22}$$

$$\mathbf{u}(\mathrm{t}) = \frac{\Delta\mathbf{v}}{||\Delta\mathbf{v}||} \tag{23}$$

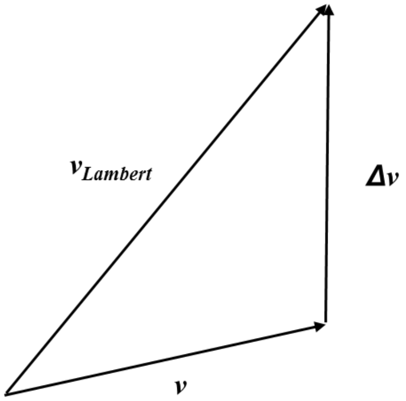

Figure 29. Geometric relationship between current velocity and Lambert velocity

Appendix B – Modeling Missile Exhaust Plume Detection during Boost

Simulating the detection and tracking of a ballistic missile by an electro-optics/infrared sensor requires characterizing the signature of that ballistic missile. The region of interest for launching a boost-phase interceptor is while the missile is still at low altitude, from sea level to around 50 kilometers. In this region, the exhaust plume takes a long, slender shape resembling a cigar. Sensors typically can only resolve the longer dimension of the plume, vice the width of the plume. Further, effects from the standing shock wave within the plume are generally negligible. As a result, the dominant effects within the plume structure occur on the downstream axis of the plume, while effects on the cross-stream such as mixing and reaction effects, occur rapidly enough to generally be negligible. Assuming these cross-stream effects are in fact negligible, the properties at any station within the plume depend only on the downstream distance from the rocket nozzle exit plane. The governing continuity equations then reduce to their one-dimensional forms. Equations (24) through (28) give the mass flow, mass continuity, momentum continuity, energy conservation, and species conservation at any given downstream station, *z*, respectively.

$$\dot{m} = \pi r^2 \rho u \tag{24}$$

$$\frac{d\dot{m}}{dz} = 2\pi r(\rho\rho_\infty)^{\frac{1}{2}}(u - u_\infty) \propto \tag{25}$$

$$\frac{d(\dot{m}u)}{dz} = u_\infty \frac{d\dot{m}}{dz} \tag{26}$$

$$\frac{d(\dot{m}h)}{dz} = (h_\infty + \sum_{i,j} q_i x_i \varphi_{i,j}) \frac{d\dot{m}}{dz} \tag{27}$$

$$\frac{d(\dot{m}x_i)}{dz} = (x_{i,\infty} + \varphi_{i,j} x_j) \frac{d\dot{m}}{dz} \tag{28}$$

The equation of state, (29), gives the final equation that govern the plume flow.

$$p = \rho R T \tag{29}$$

In the proceeding equations, $\dot{m}$ is the mass flow rate, r is the radius of the plume, ρ is the density of the flow, u is the flow velocity at that station, u_∞ is the velocity of the rocket, h is the total enthalpy, q_i is the heat of formation of the ith species in the mixing reaction, and $\varphi_{i,I}$ is the mass ratio of the ith and jth species in the mixing reaction, p is the pressure, R is the specific gas constant of the plume, and T is the temperature (Simmons, 113-115, 2000). The above equations are numerically integrated to generate the plume profile, given the initial conditions at the nozzle exit. The properties of the stage such as thrust and nozzle exit area and the composition of the exhaust define the initial conditions. All the threat models used the exhaust composition of the N_2O_4/A-50 liquid-fueled Titan IIIB first stage, scaled to the thrust and size of the threat model (Simmons, 86, 2000). This work selected the Titan IIIB for the availability of sound data that is reflective of possible threat fuels. Further, using a liquid-propellant baseline is likely a conservative estimate of the brightness of solid-propellant missiles as metal oxides in solid fuel exhaust typically increase the radiation of the plume (Wilkening, 5, 2004). Table 7 contains the species and the mole fraction of those species at the nozzle-exit.

Table 7. Nozzle-Exit Properties, Titan IIIB, Stage 1[1]

Species	Mole Fraction
CO_2	0.0901
H_2O	0.4670
H_2	0.0377
N2	0.3555
CO	0.0335
NO	0.0087
H	0.0030
OH	0.0033
Σ(O2, O, N)	0.0012

Equation (30) then gives the spectral radiance at any station for a given frequency, I_{st}, where I_v^* is the Planck function, r' is the transverse distance measured from the plume axis.

$$I_{st}(z) = \int I_v^*[T(z)]\varepsilon_v(r',z)dr'(z) \tag{30}$$

---

[1] Simmons, 87.

Equation (31) defines the emissivity, ε_v, where *k* is an emission constant and *s* is the path chordal length linearly varying from twice the plume radius *r* when *r'* = 0 to 0 at the plume boundary (Simmons, 115, 2000).

$$\varepsilon_v(r', z) = 1 - e^{-k(T)\rho(z)s(r')} \tag{31}$$

Integrating the spectral station radiance profile over the entire plume yields the total spectral radiance of the plume for a given frequency. Integrating over the spectrum of observed frequencies then gives the total radiance of the plume.

Appendix C – Two Passive Sensor Extended Kalman Filter

To rapidly generate tracks utilizing two-passive sensors and reduce the influence of noise, the AHTK system utilized an extended Kalman filter. The tracking coordinate system is centered at the location of the first sensor, S_1. Figure 30 shows the coordinate frame, where φ_1 and λ_1 are the angles from the x- and y-axis, as shown from S_1 and φ_2 and λ_2 are the similar angles from S_2 to the target. d is the distance separating the sensors.

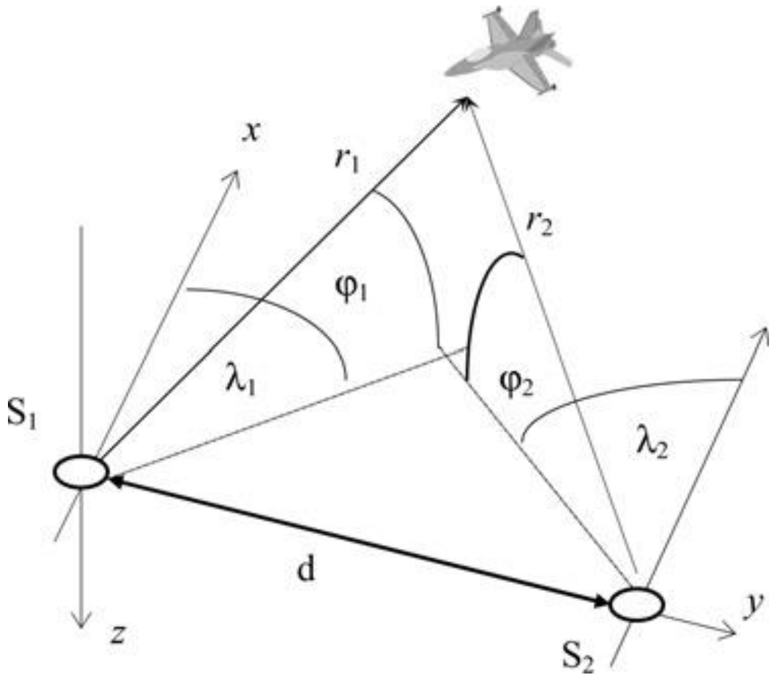

Figure 30. Tracking coordinate frame and measures of interest

The target dynamics are given by the model in Equation (32), where $\boldsymbol{X}$ is the target state vector defined as $[x\ \dot{x}\ \ddot{x}\ y\ \dot{y}\ \ddot{y}\ z\ \dot{z}\ \ddot{z}]^T$.

$$\boldsymbol{X}(k) = \boldsymbol{FX}(k-1) + v(k-1) \tag{32}$$

Equation (33) define the matrix $\boldsymbol{F}$ for a given sampling interval of T, where $\boldsymbol{O_3}$ is 3x3 matrix of zeros.

$$\boldsymbol{F} = \begin{bmatrix} \boldsymbol{G} & \boldsymbol{O_3} & \boldsymbol{O_3} \\ \boldsymbol{O_3} & \boldsymbol{G} & \boldsymbol{O_3} \\ \boldsymbol{O_3} & \boldsymbol{O_3} & \boldsymbol{G} \end{bmatrix}, \boldsymbol{G} = \begin{bmatrix} 1 & T & T^2/2 \\ 0 & 1 & T \\ 0 & 0 & 1 \end{bmatrix} \tag{33}$$

v(k-1) is a zero-mean white Gaussian process noise with known covariance given by Equation (34), where *q* is the variance of the process and *δ(k,j)* is the Kronecker delta symbol.

$$\boldsymbol{E}[v(k)v(j)^T] = \boldsymbol{Q}\delta(k,j) \tag{34}$$

$$\boldsymbol{Q} = \begin{bmatrix} \boldsymbol{U} & \boldsymbol{O_3} & \boldsymbol{O_3} \\ \boldsymbol{O_3} & \boldsymbol{U} & \boldsymbol{O_3} \\ \boldsymbol{O_3} & \boldsymbol{O_3} & \boldsymbol{U} \end{bmatrix}, \boldsymbol{U} = \begin{bmatrix} T^4/4 & T^3/2 & T^2/2 \\ T^3/2 & T^2 & T \\ T^2/2 & T & 1 \end{bmatrix} q \tag{35}$$

Equation (36) givens the model for measurements taken by the sensor at any discrete time, where ***Z****(k)* is the measurement vector [$\lambda_1\ \varphi_1\ \lambda_2\ \varphi_2$]^T.

$$\boldsymbol{Z}(k) = h[\boldsymbol{X}(k)] + w(k), k = 0, 1, 2, \ldots \tag{36}$$

*h[**X**(k)]* is the transformation from Cartesian to polar states, given by Equations (37) to (40).

$$\lambda_1 = \tan^{-1}\left(\frac{y}{x}\right) \tag{37}$$

$$\varphi_1 = \tan^{-1}\left(\frac{-z}{(x^2 + y^2)^{1/2}}\right) \tag{38}$$

$$\lambda_2 = \tan^{-1}\left(\frac{y - d}{x}\right) \tag{39}$$

$$\varphi_2 = \tan^{-1}\left(\frac{-z}{(x^2 + (y - d)^2)^{1/2}}\right) \tag{40}$$

w(k) is the white Gaussian process noise with known covariance as expressed by Equations (41) and (42), where σ_λ^2 and σ_φ^2 are the angle measurement variances of the sensor.

$$\boldsymbol{E}[w(k)w(j)^T] = \boldsymbol{R}\delta(k,j) \tag{41}$$

$$\boldsymbol{R} = diag[\sigma_\lambda^2\ \sigma_\varphi^2\ \sigma_\lambda^2\ \sigma_\varphi^2] \tag{42}$$

Equations (43) to (46) then give the extended Kalman filter equations.

$$\overline{\boldsymbol{P}}(k) = \boldsymbol{F}\widehat{\boldsymbol{P}}(k-1)\boldsymbol{F}^{\boldsymbol{T}} + \boldsymbol{Q} \tag{43}$$

$$\boldsymbol{S}(k) = \boldsymbol{H}(k)\overline{\boldsymbol{P}}(k)\boldsymbol{H}^{\boldsymbol{T}}(k) + \boldsymbol{R} \tag{44}$$

$$\boldsymbol{K}(k) = \overline{\boldsymbol{P}}(k)\boldsymbol{H}^{\boldsymbol{T}}(k)\boldsymbol{S}^{-\boldsymbol{1}}(k) \tag{45}$$

$$\widehat{\boldsymbol{P}}(k) = \overline{\boldsymbol{P}}(k) - \boldsymbol{K}(k)\boldsymbol{H}(k)\overline{\boldsymbol{P}}(k) \tag{46}$$

H(k) is the Jacobian matrix given by Equation (47) with the elements in Equations (48) through (57).

$$\boldsymbol{H}(k) = \begin{bmatrix} \frac{\delta\lambda_1}{\delta x} & 0 & 0 & \frac{\delta\lambda_1}{\delta y} & 0 & 0 & 0 & 0 & 0 \\ \frac{\delta\varphi_1}{\delta x} & 0 & 0 & \frac{\delta\varphi_1}{\delta y} & 0 & 0 & \frac{\delta\varphi_1}{\delta z} & 0 & 0 \\ \frac{\delta\lambda_2}{\delta x} & 0 & 0 & \frac{\delta\lambda_2}{\delta y} & 0 & 0 & 0 & 0 & 0 \\ \frac{\delta\varphi_2}{\delta x} & 0 & 0 & \frac{\delta\varphi_2}{\delta y} & 0 & 0 & \frac{\delta\varphi_2}{\delta z} & 0 & 0 \end{bmatrix} \tag{47}$$

$$\frac{\delta\lambda_1}{\delta x} = \frac{-y}{x^2 + y^2} \tag{48}$$

$$\frac{\delta\lambda_1}{\delta y} = -\frac{\delta\lambda_1}{\delta x}\frac{x}{y} \tag{49}$$

$$\frac{\delta\varphi_1}{\delta x} = \frac{zx(x^2 + y^2)^{-1/2}}{x^2 + y^2 + z^2} \tag{50}$$

$$\frac{\delta\varphi_1}{\delta y} = \frac{\delta\varphi_1}{\delta x}\frac{y}{x} \tag{51}$$

$$\frac{\delta\varphi_1}{\delta z} = -\frac{\delta\varphi_1}{\delta x}\frac{x^2 + y^2}{zx} \tag{52}$$

$$\frac{\delta\lambda_2}{\delta x} = \frac{-(y-d)}{x^2 + (y-d)^2} \tag{53}$$

$$\frac{\delta\lambda_2}{\delta y} = -\frac{\delta\lambda_2}{\delta x}\frac{x}{y-d} \tag{54}$$

$$\frac{\delta\varphi_2}{\delta x} = \frac{zx(x^2 + (y-d)^2)^{-1/2}}{x^2 + (y-d)^2 + z^2} \tag{55}$$

$$\frac{\delta\varphi_2}{\delta y} = \frac{\delta\varphi_2}{\delta x}\frac{y-d}{x} \tag{56}$$

$$\frac{\delta\varphi_2}{\delta z} = -\frac{\delta\varphi_2}{\delta x}\frac{x^2 + (y-d)\_^{2}}{zx} \tag{57}$$

Since truth is not available, the above elements are calculate from the state predictions $\hat{x}(k|k-1)$, $\hat{y}(k|k-1)$, and $\hat{z}(k|k-1)$. With the last measurement ***Z(k)*** and its predicted value $\overline{\boldsymbol{Z}}(k)$ from Equations (37) to (40), Equation (58) gives the state update equation.

$$\widehat{\boldsymbol{X}}(k) = \overline{\boldsymbol{X}}(k) + \boldsymbol{K}(k)[\boldsymbol{Z}(\boldsymbol{k}) - \overline{\boldsymbol{Z}}(k)] \tag{58}$$

$\overline{\boldsymbol{X}}(k)$ is calculated from the state prediction matrix and previous predicted state vector as shown in Equation (59) (Djurovic, 178-179, 2008).

$$\overline{\boldsymbol{X}}(k) = \boldsymbol{F}\widehat{\boldsymbol{X}}(k-1) \tag{59}$$

The tracks were then converted from the tracking coordinate system into the ECI coordinate system (Cai, 23-34, 2011).