

JUNE 2022

Boost-Phase Missile Defense

Interrogating the Assumptions

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A Report of the CSIS Missile Defense Project

CSIS

CENTER FOR STRATEGIC &
INTERNATIONAL STUDIES

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Introduction

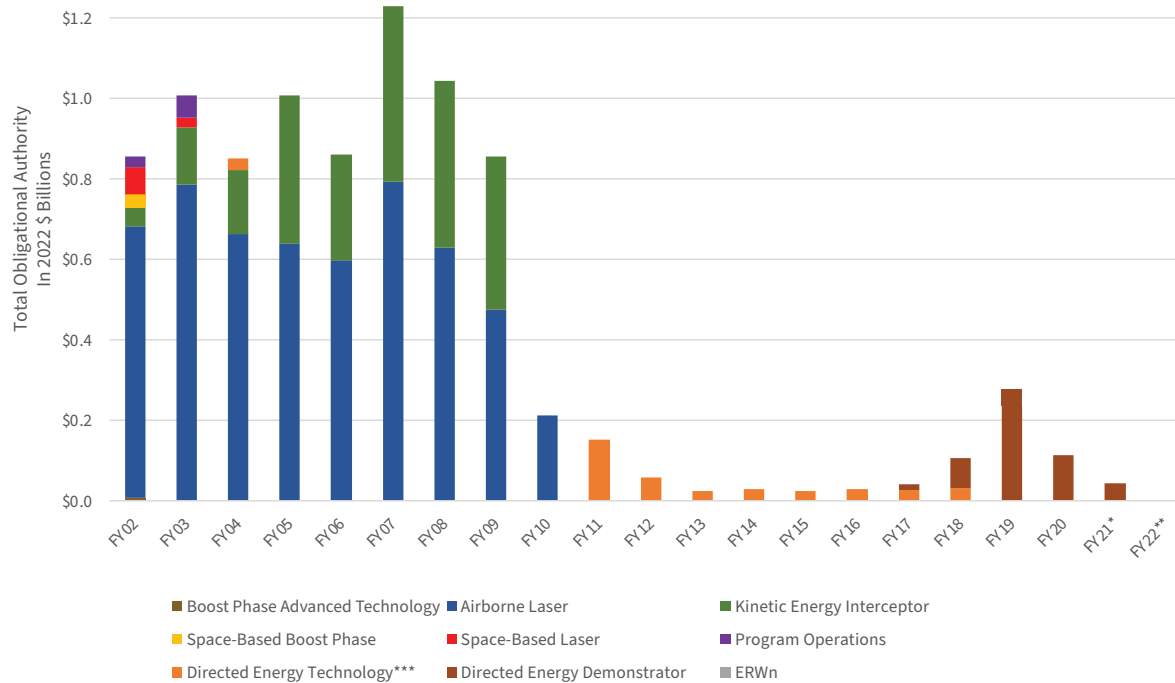
Despite its charter mandate to develop systems for defeating missile threats in all phases of flight, the Missile Defense Agency's (MDA) program efforts focus almost exclusively on intercepting ballistic missiles in their midcourse and terminal phases. Numerous technical, operational, and historical reasons inform this focus. Analysts have scrutinized prior boost-phase defense concepts and programs for being costly, strategically destabilizing, technologically unfeasible, or operationally impractical. While the United States has attempted to realize several boost-phase defense systems, none have made it past the developmental stage.

Nevertheless, the post-2017 demonstrations of North Korean intercontinental ballistic missile (ICBM) capability have reinvigorated questions about how the United States can improve its homeland missile defense. Likewise, the growing complexity of North Korean and Iranian missile threats—which might include post-boost maneuvering reentry vehicles and countermeasures—has prompted a renewed interest in ways to engage missile threats in their boost and ascent phases.

The utility of intercepting a missile early in its flight has long been recognized. Boost- or ascent-phase defense can mitigate many of the technical challenges associated with intercept in later phases of flight, where targets can deploy countermeasures and execute evasive maneuvers. Even well-known critics of the current missile defense programs of record have advocated for boost-phase intercept in some form.

The National Defense Authorization Act for Fiscal Year (FY) 2019 required MDA to begin a development program for either an air-launched or ship-based kinetic boost-phase interceptor and investigate a regionally focused space-based kinetic or directed-energy interceptor.¹ The subsequent 2019 Missile Defense Review (MDR) identified several options, including space-based interceptors

Figure 1: Selected Boost-Phase Missile Defense Program Funding, 2002–2022



Source: CSIS Missile Defense Project.

and adapting the F-35 for boost-phase defense. The MDR stated that “the F-35 . . . [might] be equipped with a new or modified interceptor capable of shooting down adversary ballistic missiles in their boost-phase.”² The 2019 MDR referred to boost-phase defenses 17 times, while the 2010 Ballistic Missile Defense Review only referred to boost-phase systems in the context of canceling the Kinetic Energy Interceptor.³

Despite its advantages, there remains a contentious debate over the viability and desirability of deploying boost-phase defenses. These disagreements stem from differing assumptions about threat characteristics, political and operational constraints, and the maturity of related technologies. A 2012 National Academy of Sciences study, for instance, assessed that the complexities and cost of a boost-phase layer were not worth the benefits and recommended instead focusing on midcourse intercept, emphasizing improvements to missile tracking and discrimination abilities.⁴

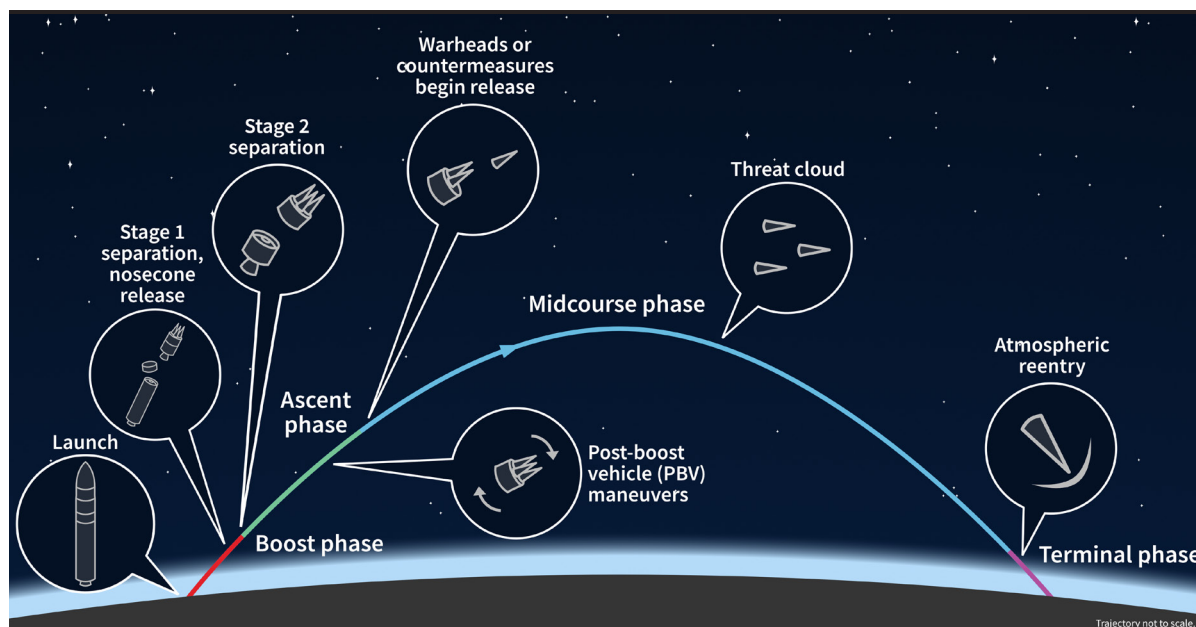
New Tailwinds Meet Old Headwinds

Ten years later, the assumptions underlying these past assessments are worth reexamining. The current effort to outpace North Korean and Iranian missile developments, the Next Generation Interceptor, is scheduled to enter service by 2028. Given the rate of change in these states’ ballistic missile programs, it is worth considering how boost-phase defenses might contribute to a layered defense.

Several technological changes over the past decade may have enhanced the viability of boost-phase defenses. The maturation of high-altitude, long-endurance remotely piloted aircraft (RPAs), for

example, has led some analysts to advocate for an air-based defensive architecture. Similarly, declining costs in satellite manufacturing and launch might impact the potential for a space-based architecture. Advances in remote sensing and image processing might improve early missile detection and tracking, potentially lengthening engagement timelines associated with boost-phase defense. And promising advances in laser scaling might revive the potential for a non-kinetic system in the longer term. The appendices of this study describe several such technological enablers and their relevance to the boost-phase mission.

Figure 2: Phases of Ballistic Missile Flight



Source: CSIS Missile Defense Project.

Despite these technological tailwinds, significant operational, budgetary, and political headwinds remain. The efficacy of missile defense deployments is especially sensitive to geography, particularly in the boost phase. Even considering potential technology enablers, surface- or air-based boost-phase defenses would still need to be located near a hostile missile's launch site, posing operational hazards. This challenge could be more manageable against geographically smaller adversaries such as North Korea.

Given the relative maturity of the related technologies and platforms, this study finds that an RPA-based kinetic interceptor solution remains a promising option for adding a boost-phase layer to the U.S. homeland missile defense. This study concurs with others in assessing that an RPA equipped with an adequately fast interceptor (4–5 km/s) could intercept a boosting liquid-propellant North Korean ICBM while operating in international airspace. ICBM trajectories from Iran are more challenging for air-based interceptors but may be possible in certain contingencies, thereby serving to supplement midcourse defenses or left-of-launch missile defeat operations.⁵ Nevertheless, engineering challenges remain to realizing an RPA-based boost-phase solution, and additional investment in technology development and systems integration would likely be required to realize such a system.

Developing a boost-phase defense against Russian or Chinese ICBMs is another matter. Kinetic interceptors—air or surface based—would need to operate deep within these countries’ territory to intercept a boosting missile, an activity conceivable only during wartime. Even then, their survivability would be questionable. Hence, an RPA-based boost-phase solution against near-peer adversaries would require a different operational concept, including coordination with actions to suppress enemy air defenses.

Though the policy environment may favor a boost-phase layer, fiscal constraints cannot be ignored. The U.S. missile defense budget has become crowded, with numerous priorities competing within MDA’s topline. Such priorities include a major update to the Ground-based Midcourse Defense system, a space-based sensor layer, and the emerging hypersonic defense program. Closing gaps in lower-tier defenses against cruise missiles and drones has also assumed a new priority, including homeland cruise missile defense.⁶ In this environment, U.S. policymakers should consider the relative costs and benefits of adding a boost-phase layer alongside other prospective augments to homeland missile defense, such as an interceptor underlay or an East Coast Ground-Based Interceptor site.

The addition of a new North Korea-centric missile defense layer could receive scrutiny when the United States is shifting its strategic focus from rogue states and counterterrorism toward great power competition. Even as attention shifts, the threats that prompted the United States to invest in the Ground-based Midcourse Defense system are still present and growing. Nevertheless, maintaining advantageous positions against adversaries such as North Korea remains important. As Russia’s invasion of Ukraine has made clear, U.S. vulnerability to nuclear blackmail can embolden authoritarian governments and constrain U.S. options in dealing with the ensuing consequences.

Study Goals and Methodology

This study seeks to provide a fresh assessment of key issues related to boost-phase defense. These issues include the ways missile threats are evolving and broader technological trends. It examines prior boost-phase programs for lessons learned and reviews prior studies, with particular attention to the assumptions underlying their conclusions.

The study identifies four areas of technological development and assesses to what extent, if any, such advancements impact the assumptions that have informed views on the viability and strategic benefit of boost-phase defense. The technological enablers discussed here are advances in RPAs, advanced sensors, space launch, and directed energy. The appendices of this report include four technical white papers exploring each of these areas. Based on this analysis, the researchers extracted a set of key findings and recommendations for U.S. policymakers.

In support of this review, CSIS held five workshops and other consultations between late 2020 and early 2021. These workshops explored each of the technological “enablers” mentioned above and served to review the technical white papers. These workshops were attended by members of the science and engineering community, missile defense subject matter experts, and former military and government officials.

To illustrate aspects of the boost-phase defense challenge, the study team has incorporated the results of computer-based modeling and simulations. The study team conducted these simulations using SMARTset, a software program for conducting air and missile defense simulations.⁷

SCOPE

While some of the systems discussed in this report could have regional defense applications, this study primarily evaluates the value of boost-phase approaches for defending the United States homeland against limited long-range ballistic missile threats from North Korea and Iran. This scope largely aligns with current U.S. homeland missile defense policy, which calls for a “comprehensive approach to missile defense against rogue state and regional missile threats.”

DEFINITIONS

The term “boost-phase” typically refers to the period when a ballistic missile’s motor is burning and ends after burnout. Defenders can exploit many of the benefits of boost-phase intercept even after burnout, as there will be a period between burnout and when the missile can deploy countermeasures and separate any reentry vehicles. As such, this report uses the term “boost-phase intercept” to refer to the time from launch up until burnout. The term “early intercept” refers to the engagement of a missile during the period after burnout until the separation of warheads and countermeasures. While this duration varies between missile types, this study considers early intercept to encompass the period from launch to 100 seconds after burnout.⁸ Engaging a missile becomes more complicated as more time passes after burnout, as countermeasures and reentry vehicles will separate throughout this period.

Findings

GENERAL FINDINGS

- Missile threats are growing more complex, including those employed by smaller adversaries such as North Korea and Iran. These states have demonstrated technologies such as maneuvering reentry vehicles and could soon employ multiple reentry vehicles, decoys, and other post-boost countermeasures. Advances in the ballistic missile threat may make boost-phase defenses more relevant.
- Previous U.S. boost-phase efforts have been unsuccessful due to technological and conceptual hurdles, inconsistent budgets, treaty restrictions, and fundamental disagreements over strategic goals.
- Physical and operational limitations present challenges, but advances in enabling technologies are increasing the viability of boost-phase defense.
- The efficacy of boost-phase missile defense is highly sensitive to the geographic characteristics of an adversary—more so than for other missile defense architectures.
- Advancements in long-endurance RPAs alter the feasibility calculus of airborne boost-phase defenses by offering a persistent platform for both sensors and interceptors.
- Advances in sensing technologies, such as lightweight gallium nitride-based radar, could enable greater availability of airborne radar platforms, thereby decreasing detection and track acquisition delays for a potential boost-phase architecture. Advances in infrared sensor resolution and image processing might further compress future satellite detection timelines.
- Persistent (“birth-to-death”) tracking of missile threats is essential to any boost-phase defense

system. A boost-phase sensor architecture should include a mix of sensor platforms and types to ensure prompt detection and tracking. Prompt kill assessment is also important for targeting the boost phase within a layered defense to avoid wasting midcourse interceptors or to enable multiple boost-phase engagement opportunities in favorable conditions.

SURFACE-BASED INTERCEPT

- There are few practical options for land basing interceptors for boost-phase defense against ICBM trajectories from North Korea or Iran. Geographical constraints drive very high interceptor performance requirements.
- Sea basing offers more favorable positioning options for a North Korea boost-phase intercept, but the operational availability of Navy surface combatants could be low during a military crisis.
- Adding a new ballistic missile defense demand on surface combatants could meet significant resistance from the Navy due to the scarcity of onboard launcher capacity and a desire among Navy leadership to lessen the role of surface ships in territorial ballistic missile defense missions.

AIRBORNE KINETIC INTERCEPT

- High-altitude, long-endurance RPAs equipped with kinetic interceptor missiles have the performance and affordability to be a promising near-term option for adding a limited, boost-phase/early-intercept layer to the U.S. missile defense system.
- The F-35's distributed aperture sensor suite and combat system make it a promising platform for boost-phase defense operations, but it lacks the persistence, relative affordability, and attritability of an RPA. The F-35 is a multimission platform and may lack operational availability during a crisis to conduct ballistic missile patrol.
- North Korea's lack of geographic depth makes its ICBMs relatively more vulnerable to airborne boost-phase defenses compared to other U.S. adversaries with greater landmass.
- ICBM trajectories from Iran to North America are more challenging, but early intercepts may be possible from allied airspace with fast interceptors.

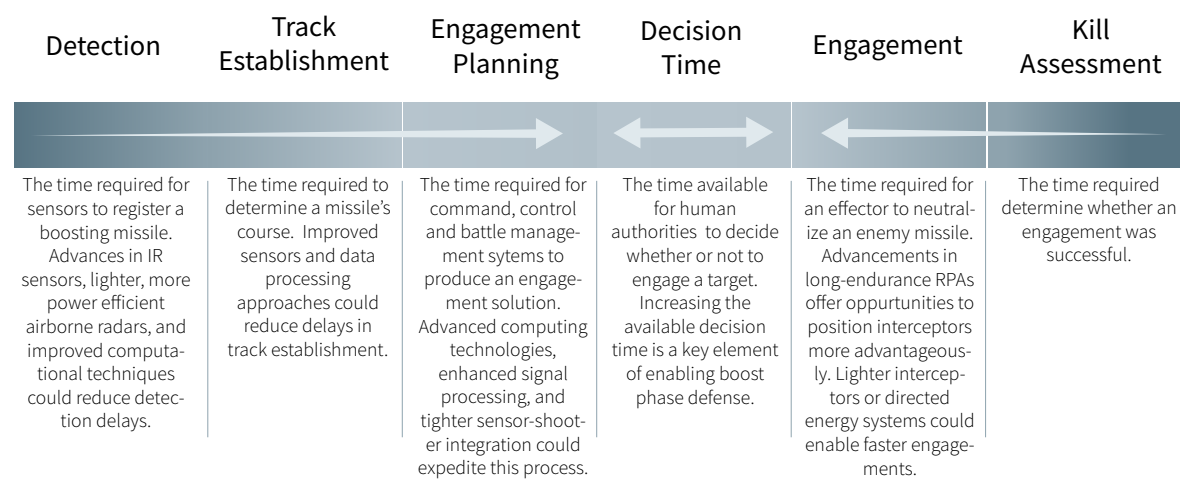
SPACE-BASED INTERCEPT

- A space-based system is the only option for getting interceptors close enough for a boost-phase layer against Chinese and Russian intercontinental missiles.
- Even a limited space-based interceptor constellation would be a considerable engineering and financial undertaking. However, reductions in space launch costs from reusable launch vehicles could make it more affordable than prior estimates.
- Advancements in miniaturized sensors, avionics, and turbopumps can reduce kill vehicle mass, which disproportionately impacts assumptions such as total interceptor weight. Such developments could also feed into reduced costs from prior estimates.
- The survivability of space-based interceptors to various forms of anti-satellite attack would be a primary concern, especially against near-peer competitors.

Defining the Challenge

Engaging a missile as it boosts—a phase of flight not longer than five minutes—is a daunting technical challenge. The compressed timeframe for detecting, tracking, processing, and intercepting a missile complicates requirements for a boost-phase missile defense system. The boost-phase engagement window is often understood as a function of a threat missile’s propulsion burn time and a defender’s delays in computing a fire control solution (i.e., predicting and refining the predicted impact point). The nature of this engagement window, coupled with assumptions about basing and engagement geometry, drives sensor and interceptor performance requirements.

Figure 3: Boost-Phase Engagement Cycle



Source: CSIS Missile Defense Project.

Prior assessments have differed on the length of this engagement window. Different assumptions about threat missiles, sensing and tracking delays, and other parameters have resulted in varying conclusions over the viability of a boost-phase engagement. In the past 20 years, these assessments have found possible engagement windows lasting from 175 to 235 seconds for slower-accelerating, liquid-fueled ICBMs and 125 to 151 seconds for quicker, solid-fueled ICBMs. With their correspondingly shorter boost phases, shorter-range ballistic missiles present an even greater challenge. Small variances in these assessments—driven by different assumptions about ICBM staging and other technical characteristics—have outsized effects on the requirements for a boost-phase missile defense system.⁹

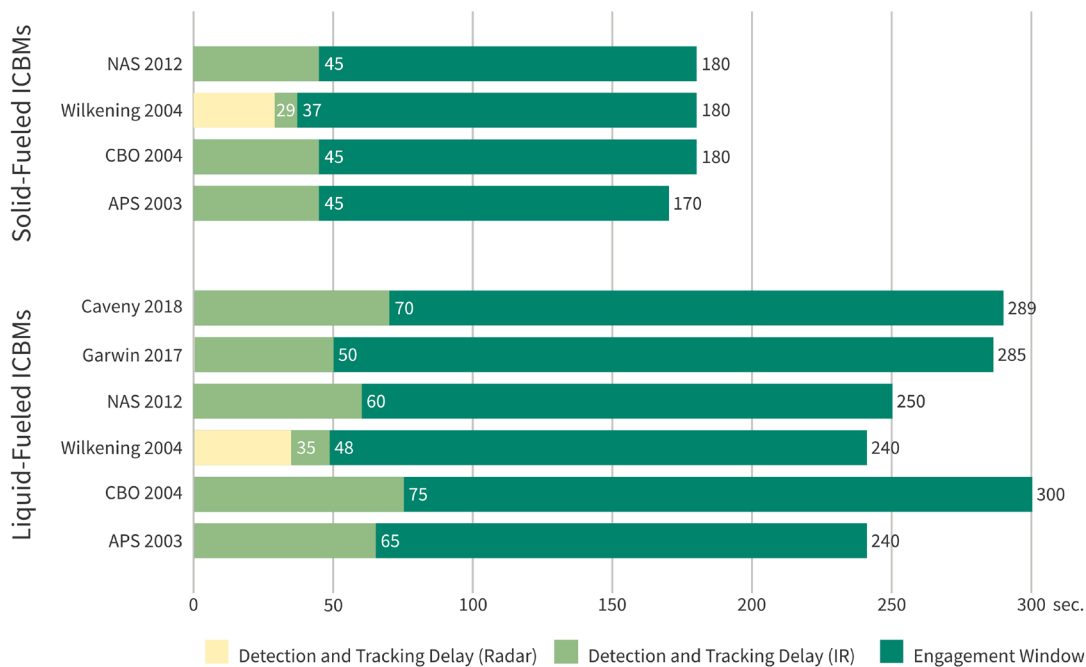
Table 1: Notional Burn Times

Authors	Liquid-Fueled ICBMs	Solid-Fueled ICBMs
IDA 1985	240 seconds	N/A
Postol 2001	250 seconds	N/A
APS 2003	240 seconds	170 seconds
Marshall 2004	300 seconds	180 seconds
CBO 2004	300 seconds	180 seconds
Garwin 2004	250 seconds	N/A
Wilkening 2004	240 seconds	180 seconds
NAS 2012	250 seconds	180 seconds
Garwin 2017	285 seconds	N/A
Caveny 2018	289 seconds	N/A
Goodby and Postol 2018	250 seconds	N/A

Source: CSIS Missile Defense Project.

Additionally, the cutoff point for a boost-phase engagement may be earlier or later than a missile’s projected burn time. In their respective assessments, the American Physical Society (APS) and National Research Council (NRC) noted that differences in a threat missile’s azimuth and thrust could create variances of up to 30 seconds in burn time, potentially shortening the engagement window.¹⁰ By contrast, studies by the RAND Corporation and Defense Science Board suggested that, even after its main motor burn, a threat ICBM would take a short period to deploy countermeasures and perform maneuvers that stress missile defenses. These studies noted that “early” or “ascent-phase” intercepts might effectively happen up to 100 seconds after an ICBM’s burnout.¹¹ However, the benefits of intercepting during this early intercept period diminish as time passes and the threat picture becomes more complex.

Figure 4: Boost-Phase Engagement Windows



Source: CSIS Missile Defense Project.

The Value of Time

With very short engagement windows, the addition of even a few tens of seconds of effective engagement time can significantly improve the performance of a boost-phase defense system. Delays associated with detecting and tracking a boosting missile increase demands on other system attributes such as interceptor speed and range. Figures 5A, 5B, and 5C show the defended area for North America from a notional North Korean ICBM. Each figure shows the variations in defensive coverage realized by an air-launched interceptor, with different time increments between the launch of the ICBM and the launch of the interceptor. The notional interceptor possesses an average speed of 4 kilometers per second (km/s) and launches at an altitude of 15,000 meters. The evaluation assumes full sensor coverage and a 15-second delay for kill assessment.

The red shading indicates an area where the notional boost-phase architecture could not defend. Yellow shading indicates areas where the interceptor platform would have enough time and space for a single engagement opportunity, adding a layer to the homeland missile defense system. Green areas show where the notional platform would have two shot opportunities, providing two additional layers of defensive coverage.¹²

Many variables can affect the defensive coverage of a missile defense system, including in the boost phase, such as the launch location, speed of the interceptor, and the threat's launch location. Yet the above figures illustrate that, holding these variables equal, reductions in engagement delay times can increase the performance of a hypothetical boost-phase defense layer. Reductions in engagement delays are one approach to making boost-phase defenses feasible. To understand solutions for reducing these delays, it is necessary to break down their contributing factors.

Figure 5A: Notional Defensive Coverage of North America from North Korean ICBM (4 km/s interceptor, 75-second engagement delay)



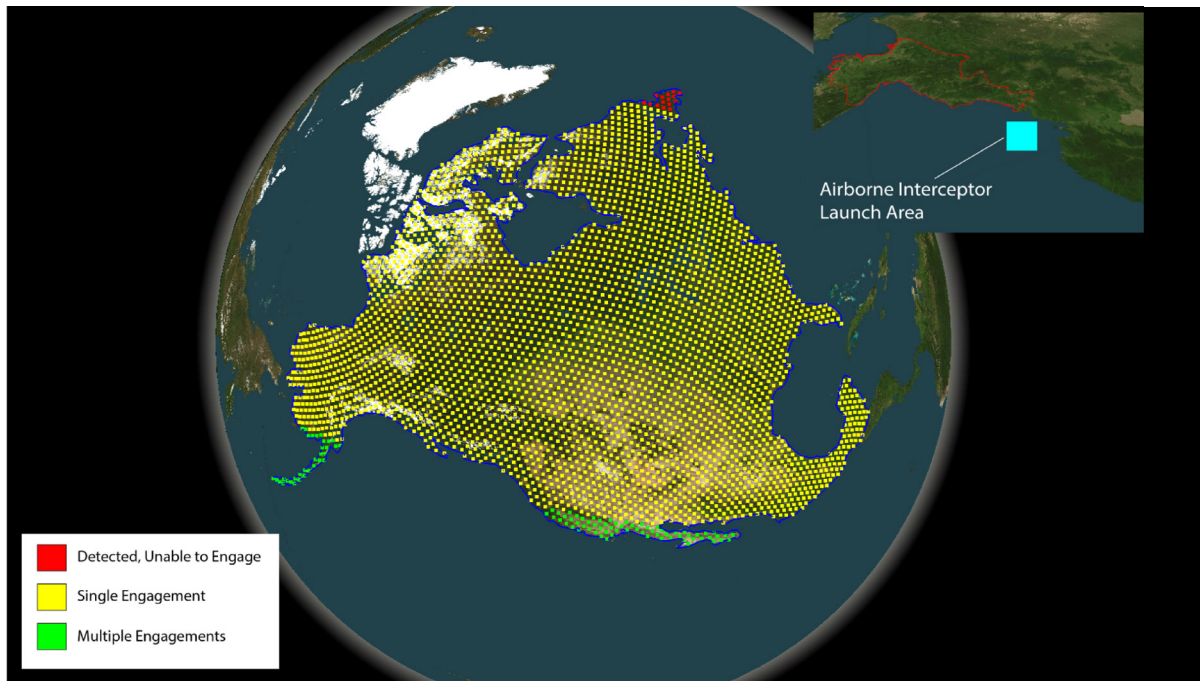
Source: CSIS Missile Defense Project.

Figure 5B: Notional Defensive Coverage of North America from North Korean ICBM (4 km/s interceptor, 50-second engagement delay)



Source: CSIS Missile Defense Project.

Figure 5C: Notional Defensive Coverage of North America from North Korean ICBM (4 km/s interceptor, 30-second engagement delay)



Source: CSIS Missile Defense Project.

Engagement Delay Contributors

The delay in detecting a boosting missile is the first contributor to such engagement delays. Space-based infrared sensors similar to Space Based Infrared Systems High (SBIRS High) may take up to 45 seconds to detect a target after launch.¹³ Prior studies assert that weather conditions would significantly limit space-based sensors' ability to detect ICBM threats earlier. Assuming worst-case cloud cover, these assessments conclude that a space-based sensor could only detect an ICBM after reaching an altitude of 7 km.¹⁴ Counterintuitively, solid-fueled ICBMs could be detected sooner than their liquid-fueled counterparts, as they would accelerate more quickly and pass through this cloud layer.¹⁵ With broadly similar assumptions about sensor capabilities, the studies' divergent estimates of detection delay flow from different assumptions about the threat ICBM's acceleration.¹⁶

Space-based infrared sensors are not the only approach to early detection. Several authors have proposed deploying airborne radar to detect boosting ICBMs, which could operate in adverse weather conditions and detect a moving target below an altitude of 7 km. Unlike space sensors, however, an airborne radar's range is limited by the earth's curvature; ICBMs only become detectable after climbing high enough to be within a radar's line of sight. As Wilkening and Garwin describe, an airborne X-band radar could have detection ranges of as much as 655 to 980 km for solid- and liquid-fueled ICBMs, respectively, with detection times roughly 10 to 15 seconds faster than space-based sensors.¹⁷

Table 2: Detection Delay

Authors	Liquid-Fueled ICBMs	Solid-Fueled ICBMs
APS 2003 (Space-based IR)	45 seconds	30 seconds
CBO 2004 (Space-based IR)	45 seconds	30 seconds
Garwin 2004 (Airborne radar) ¹⁸	“tens of seconds” lower than APS projections	“tens of seconds” lower than APS projections
Wilkening 2004 (Space-based IR)	39 seconds	32 seconds
Wilkening 2004 (Airborne radar) ¹⁹	30–45 seconds	24–37 seconds
NAS 2012 (Space-based IR)	45 seconds	30 seconds
Caveny 2018 (Airborne IR) ²⁰	15 seconds	Unspecified

Source: CSIS Missile Defense Project.

After initial detection, a sensor platform must track the ICBM’s flight downrange and provide tracking data to the fire control system to calculate a predicted intercept point (PIP)—the estimated position where the interceptor and ICBM’s trajectories would intersect.²¹ These tracking delays remain a source of considerable disagreement among analysts.

Varying estimates of these delays stem from varying assumptions about ICBM performance, sensor resolution, and PIP accuracy requirements, ranging between about 5 and 30 seconds. One source of this variance is different assumptions regarding the time required for an ICBM to settle on its final azimuth heading (for example, after conducting dogleg maneuvers). Assumptions about sensor resolution are another critical variable. Sensors that can more finely resolve differences in an ICBM’s position can more quickly establish a predicted intercept point. In its assessment, the Congressional Budget Office concluded its notional ICBM would travel only 0.6 km downrange after 30 seconds of vertical flight. Under these conditions, satellites would not be able to establish a successful track within 30 seconds if their spatial resolution is larger than 0.6 km.

Finally, different requirements for PIP accuracy will affect the necessary delay for tracking boosting ICBMs. While less accurate PIP requirements may reduce the time needed to compute a tracking solution, they would require interceptors with more divert capacity—the ability of the interceptor to correct its trajectory in flight. Higher requirements for agility—for divert capacity—would increase interceptor weight, cost, and complexity. Alternatively, lower PIP requirements might drive alternate interceptor firing doctrines, with defenders firing multiple interceptors to “bracket the range of possible offensive trajectories.” In other words, defenders must weigh trade-offs between PIP accuracy and interceptor characteristics in assessing the requirements for a boost-phase tracking system.²²

Table 3: Tracking Delay

Authors	Liquid-Fueled ICBMs	Solid-Fueled ICBMs
APS 2003 (Space-based IR)	20 seconds	15 seconds
CBO 2004 (Space-based IR)	~30 seconds	15 seconds
Levi 2004 (Space-based IR)	Far shorter than APS	Far shorter than APS
Wilkening 2004 (Space-based IR)	9 seconds	5 seconds
Wilkening 2004 (Airborne radar)	5 seconds	5 seconds
DSB 2011	60–100 seconds after burnout	60–100 seconds after burnout
NAS 2012	15 seconds	15 seconds
Caveny 2018	55 seconds	N/A

Source: CSIS Missile Defense Project.

Conclusion

Ballistic missiles' short boost times, coupled with detection and tracking delays, make boost-phase missile defense a challenging problem. Different assessments of threat characteristics, including boost times, penetration aid release rates, and the time it takes an ICBM to settle on its final ballistic trajectory, can dramatically alter the trade space for contemplating a boost-phase defense.

Several elements of this problem also are ripe for reassessment. Leaps in infrared sensor resolution and image processing since 2012 might compress future satellite detection timelines.²³ Likewise, smaller, lighter radars made possible by new semiconductor technologies (e.g., gallium nitride) and enhanced backend processing might allow for more numerous and operationally feasible airborne sensors.

Examination of Architectures

Several defense designs are possible for attacking the boost-phase problem. These approaches can be roughly classified by their effectors' operating domain: surface-based, air-based, and space-based. The requirements for each change with different assumptions about mission set, basing locations, and other operational factors.

In a terrestrial concept of operations, a defender would field effectors on ship- or ground-based platforms. Terrestrial approaches benefit from potentially reduced logistical complexity and fewer size and weight constraints on interceptor design. Unlike airborne or space-based architectures, however, surface platforms are unsuited for supporting directed-energy approaches, which depend on long lines of sight and more favorable optical conditions at higher altitudes.

Meanwhile, an airborne boost-phase intercept approach might incorporate boost-phase effectors and sensors onto patrolling aircraft, potentially offering simpler sensor-effector integration and simplifying operations. Furthermore, by not having to accelerate from a static position through the dense lower atmosphere, airborne interceptors could be made smaller and lighter while attaining similar performance.²⁴

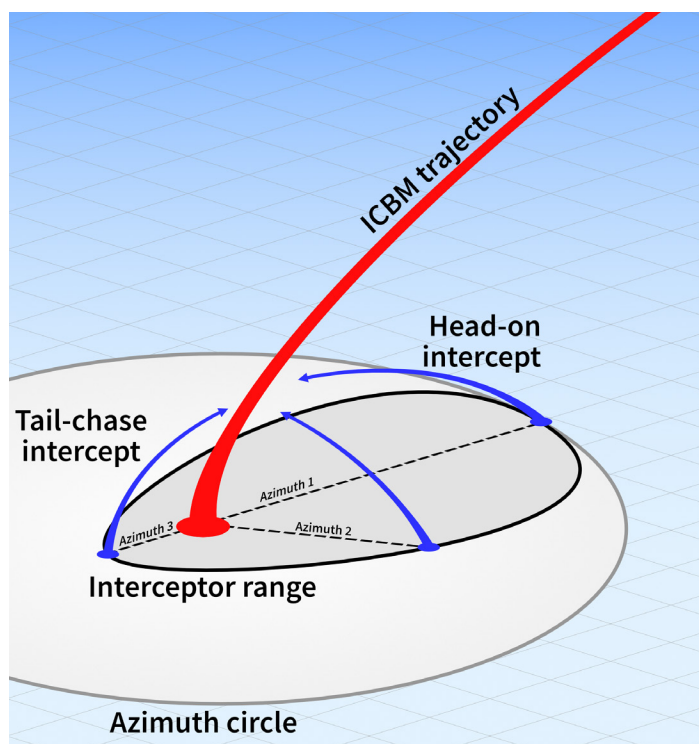
Finally, space-based approaches would employ a constellation of orbiting sensors or interceptors to maintain coverage over a threat area. While this mitigates some of the geographic challenges encountered by other architectures, space-based measures require a larger quantity of interceptors since most effectors will be out of range at any given time. A space-based interceptor must inhabit lower orbits to be close enough to the earth to intercept a boosting ballistic missile, thereby spending only a limited time each day above a threat's launch area. Many satellites become necessary to cover a fixed area on the earth's surface. Given these challenges, the problem of space-based intercept is fundamentally one of satellite production cost and space launch capacity.

One commonality of terrestrial, airborne, and space-based architectures is that they all would require air- or space-based sensors to operate. Considering the earth's curvature and the compressed timeframes involved, no surface-based sensor architecture could detect or track a threat missile soon enough to support a boost-phase intercept.

Terrestrial

A terrestrial boost-phase defense architecture would integrate an air- or space-based sensor network with surface-launched effectors to achieve early intercepts. Basing interceptors on surface platforms—ships, siloes, or mobile launchers—may impose less stringent design constraints than designing interceptors for space or air basing. Conversely, the limited geographic options for basing surface-based interceptors tend to drive up interceptor performance requirements (i.e., farther away requires faster interceptors).

Figure 6: Boost-Phase Intercept Azimuths



Source: CSIS Missile Defense Project.

different requirements for canonical scenarios focused on North Korea and Iran. Against a North Korean threat, these analyses suggest that a fast-accelerating interceptor capable of travelling 5 km/s or faster would be necessary for limited coverage of the continental United States.²⁵ Such an interceptor would be substantially larger than the Navy Aegis system's existing Standard Missile-3 (SM-3) ballistic missile interceptor and would need to be based in the Sea of Japan northeast of North Korean waters.

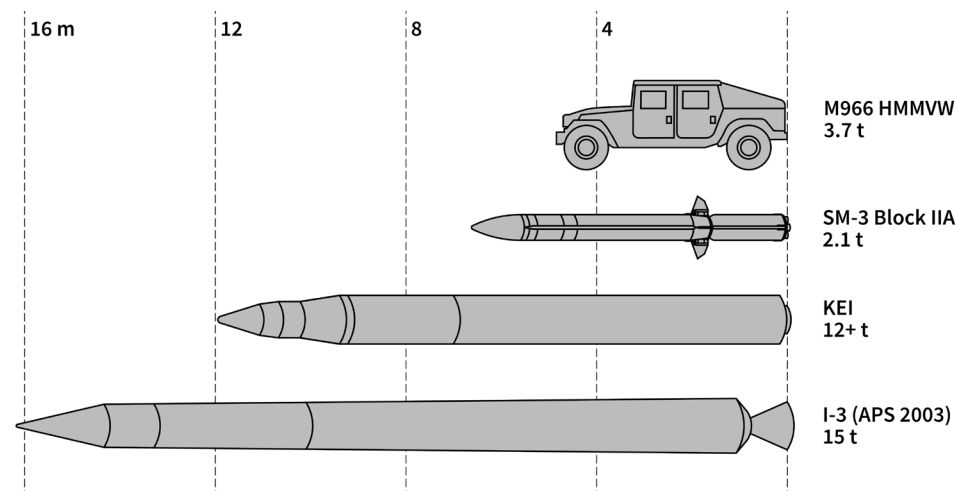
Intercepting an Iranian missile would be considerably more difficult. According to the American Physical Society (APS), such a system would require 8 km/s interceptors or faster to intercept Iranian liquid-fueled ICBMs from eastern Turkey and western Afghanistan.²⁶ Meanwhile, due to its

The viability of surface basing is especially sensitive to the geography of the threat. The size of the threat state's landmass and the positions available for basing interceptors dictate boost-phase defense requirements. Boost-phase interception becomes more difficult as a launcher is offset from the incoming missile's flight path; a "tail-chase" scenario presents significantly higher kinematic requirements than a head-on approach. Larger states such as Iran offer few locations for basing interceptors and, against threats aimed at the United States, do not always present favorable engagement geometries. To compensate, a defender must employ substantially faster interceptors to reach the boosting target before burnout.

Prior analyses have thus assessed

more optimistic assumptions on basing locations near the Caspian Sea, the National Academy of Sciences (NAS) asserts that a 6 km/s interceptor could sufficiently engage liquid-fueled ICBM threats.²⁷

Figure 7: Interceptor Size Comparison



Source: CSIS Missile Defense Project.

These requirements become more challenging when considering solid-fueled ICBMs, which have shorter engagement windows. In its 2012 assessment, the NAS concluded that, when accounting for particulars in ICBM staging and earth rotation effects, a 6 km/s interceptor would be inadequate for defeating a North Korean solid-fueled ICBM.²⁸ Against an Iranian solid-fueled ICBM, a 2004 Congressional Budget Office (CBO) analysis concluded the United States would need 8 km/s interceptors or faster based in Afghanistan and Iraq to provide minimal boost-phase coverage. The APS notes that, short of basing a 10 km/s interceptor in the Caspian Sea, boost-phase engagements of Iranian solid-fueled ICBMs were unfeasible.²⁹

Table 4: Coverage of Liquid-Fueled ICBMs

Study	Interceptor Speed	North Korea Coverage	Iran Coverage
APS 2003	5 km/s (I-2)	Yes	No
APS 2003	6.5 km/s (I-4)	Yes	No
APS 2003	10 km/s (I-5)	Yes	Yes
CBO 2004	6 km/s (Opt. 1)	Yes	No
CBO 2004	8 km/s (Opt. 2)	Yes	Yes
CBO 2004	10 km/s (Opt. 3)	Yes	Yes
NAS 2012	4.5 km/s (Opt. 2)	No	Yes
NAS 2012	6 km/s (Opt.1)	Yes	Yes

Source: CSIS Missile Defense Project.

Table 5: Coverage of Solid-Fueled ICBMs

Study	Interceptor Speed	North Korea Coverage	Iran Coverage
APS 2003	5 km/s (I-2)	No	No
APS 2003	6.5 km/s (I-4)	Yes	No
APS 2003	10 km/s (I-5)	Yes	No
CBO 2004	6 km/s (Opt. 1)	Yes	No
CBO 2004	8 km/s (Opt. 2)	Yes	Yes
CBO 2004	10 km/s (Opt. 3)	Yes	Yes
NAS 2012	4.5 km/s (Opt. 2)	No	No
NAS 2012	6 km/s (Opt.1)	No	No

Source: CSIS Missile Defense Project.

Table 6: Interceptor Characteristics

Study	Interceptor Speed	Interceptor mass	KV mass
APS 2003	5 km/s (I-2)	2,300 kg	94 kg
APS 2003	6.5 km/s (I-4)	16,900 kg	94 kg
APS 2003	6.7 km/s (I-3)	14,600 kg	91 kg
APS 2003	10 km/s (I-5)	65,600 kg	94 kg
CBO 2004	6 km/s (Opt. 1)	3,088 kg	140 kg
CBO 2004	8 km/s (Opt. 2)	3,469 kg	30 kg
CBO 2004	10 km/s (Opt. 3)	17,160 kg	30 kg
NAS 2012	4.5 km/s (Opt. 2)	Not specified	Not specified
NAS 2012	6 km/s (Opt.1)	Not specified	Not specified

Source: CSIS Missile Defense Project.

Such surface-based interceptors would likely be much larger than those used on current mobile missile defense systems. The canceled Kinetic Energy Interceptor (KEI) was roughly twice the length of the SM-3 interceptor. In its 2003 analysis, the APS estimated that a comparable 6 km/s interceptor would likely weigh over 10 times more than the SM-3. Attaining 10 km/s burnout velocities, it assessed, would “push the limits” of technical feasibility and require an interceptor weighing over double the mass of a Minuteman III ICBM.³⁰

These assumptions for interceptor mass are highly sensitive to assumptions regarding the weight of their payloads. Marginal increases in the weight of a kinetic kill vehicle translate to exponential

increases in the fuel needed to accelerate them. Given varying assumptions over potential kill vehicle mass, the APS and CBO diverge on their assessments of a feasible boost-phase interceptor. Assuming a payload two-thirds lighter than the APS estimate, the CBO estimates that a 10 km/s interceptor would weigh 17,000 kg—75 percent lighter than the APS assessment of a comparable system.³¹ In either case, such a missile would be substantially larger and heavier than most midcourse interceptors currently in service.

If broadening the acceptable engagement window to include boost phase and early intercept (time until burnout plus about 100 seconds), these requirements may become less stressing. Several prior studies limited their consideration of boost-phase architectures to those engaging before the threat motor's burnout before the release of penetration aids. The requirements for an operable system may be significantly more feasible if one considers early intercept during the ascent phase.

Nevertheless, terrestrially basing interceptors has drawbacks that make them less desirable for boost-phase engagements. The ability to forward deploy land-based interceptors may induce political sensitivities, which shift unpredictably. The 2004 CBO study, for example, analyzed the potential of land-based sites in Iraq, Afghanistan, and Turkmenistan. These options were not inconceivable, given the presence of U.S. forces in the region at the time and optimism about greater regional stability in the coming years. Yet such options would be implausible under current circumstances.

Sea basing interceptors, such as those envisioned for KEI, may provide greater operational flexibility, but they remain limited to small areas where favorable intercept geometries are possible. One must also consider the operational availability of sea-based platforms. U.S. Navy destroyers and cruisers are among the most in-demand military assets, even in peacetime. Some members of Navy leadership have publicly complained about the geographic constraints on ships conducting ballistic missile defense missions.³² With the greater kinematic demands of boost-phase defense, these constraints would likely be even more severe. More recently, Navy leaders have urged the divestment of Navy ships from strategic missile defense operations altogether.³³ As such, a sea-based boost-phase approach could encounter resistance, making it difficult to operationalize.

Airborne

Another boost-phase concept is to base interceptors on aircraft, such as fighters or remotely piloted aircraft (RPAs). An airborne approach mitigates several of the geographic challenges of surface basing. Aircraft could patrol in areas with favorable intercept geometries and quickly surge closer to enemy launch sites in a crisis. Air basing could also relax requirements for interceptor performance when compared to surface basing. To attain similar performance levels, air-launched interceptors may be smaller and lighter, as surface-based interceptors must be designed with more propellant to accelerate from a dead stop to intercept altitude.³⁴

An airborne architecture might also integrate boost-phase sensors and weapons on a single platform. Such an approach might offer a simpler concept of operations and decreased latencies associated with passing data between separate offboard sensors, ground-based processing stations, and interceptors. Advances in cheaper, lightweight optics, radars, and edge computing could make this kind of integration more conceivable than some previous boost-phase studies may have considered.³⁵

Airborne architectures, however, are also subject to several limitations. Unlike with land- or sea-based platforms, which can stay on station for months, it can be costly to maintain constant airborne patrol near adversaries. However, there is little practical reason why airborne boost-phase platforms would need to maintain a constant presence. Rather, a more cost-effective approach would be to employ defensive airborne assets as a surge capability during heightened geopolitical tensions.

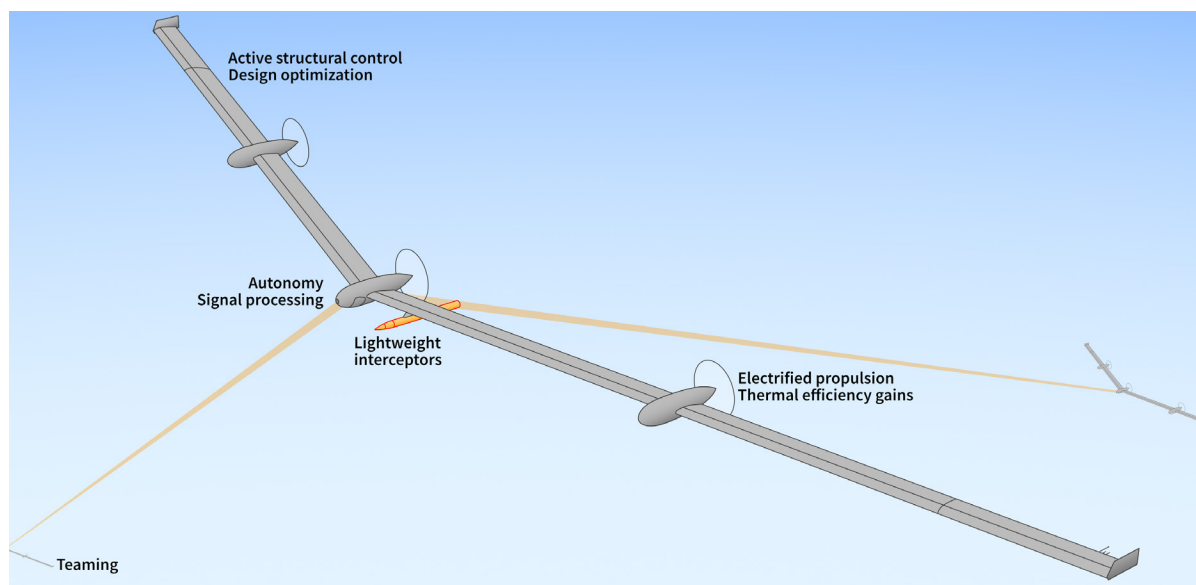
Several contemporary assessments have proposed airborne boost-phase architectures based around existing fighter aircraft with low endurance and high operating costs. In 2021, the CBO assessed the 2019 Missile Defense Review's suggestion to equip the F-35 aircraft with a boost-phase interceptor, concluding that the operating cost of a North Korea-focused architecture would cost \$20 billion per year. To achieve its stated metric of defeating 20 or more ICBMs, the study assessed a requirement for 30 to 60 F-35s carrying 120 to 240 interceptors to remain on continuous patrol.

Nevertheless, the United States could likely achieve a useful boost-phase capability at a lower cost than assumed in the CBO's assessment with different assumptions about persistence. As previously noted, a boost-phase architecture would exist to supplement the Ground-based Midcourse Defense system's existing capability. Airborne interceptor platforms, for instance, might deploy only when there are indications and warning to justify a raised posture. Any boost-phase defense system should be considered one element of a layered system rather than the entire system itself.

The CBO study rightly notes that the F-35's high operating costs make it a questionable candidate for dedicated missile defense operations, although its capability may be available on a less persistent basis or during wartime. Other analysts have proposed architectures based on long-endurance uncrewed aircraft, which would lessen operating costs. In prior tests, MDA has demonstrated boost-phase infrared tracking using medium-altitude long-endurance RPAs.

In 2019, several analysts suggested that, for a North Korea-focused scenario, the United States could realize an RPA-based boost-phase architecture with long-endurance RPAs for substantially reduced cost.³⁶

Figure 8: RPA Technology Enablers



Source: CSIS Missile Defense Project.

An MQ-9 Reaper’s operating cost, for example, is just over 15 percent of that of the F-35.³⁷ An RPA-based system may be less likely to face the operational availability crunch that an exquisite, multirole fighter such as the F-35 would experience during a military crisis. The world has witnessed tremendous innovation in the field of RPAs over the past decade, and the field continues to evolve in ways that make them an attractive option as an interceptor platform. Appendix 4 of this report discusses some of these innovations and how they might lend themselves to a boost-phase system (Figure 8).

To be sure, none of this is to say that multi-role fighters should not play a role in missile defense, during the boost phase or otherwise. Advanced sensors such as the F-35 sensor suite would provide a powerful tool to achieve early detection and tracking of ballistic missiles. Likewise, boost-phase interceptors designed for RPA platforms could be interoperable for carriage on tactical aircraft, to permit deployment on a more intermittent or opportunistic basis. This approach could open new avenues for offense-defense integration and novel operational concepts for missile defeat.

Interceptor Performance

Several prior studies of airborne boost-phase architectures have postulated interceptors with speeds between 3 and 6 km/s. Studies based on more optimistic assumptions about feasible interceptor velocities and threat models suggest a single airborne platform armed with a 1,500 kg, 5.3 km/s interceptor could provide robust capability against North Korean ICBMs.³⁸ Assuming the implementation of certain innovations reductions in kill vehicle and motor mass, studies by Garwin, Caveny, Goodby, and Postol have proposed that 5 km/s interceptors could be far lighter. Goodby and Postol propose as light as 490 kg and Caveny as light as 230 kg.³⁹

Table 7: Interceptor Velocity and Mass Trade-Offs

Author	Interceptor Speed	Interceptor Mass	Mission Set
Wilkening 2004	5.3 km/s	1,500 kg (90 kg KV)	Liquid ICBM
Wilkening 2004	6.1 km/s	1,500 kg (50 kg KV)	Solid ICBM
NAS 2012	4.1 km/s	713 kg	Not specified
NAS 2012	3.5 km/s	754 kg	Not specified
Schaffer 2016	AMRAAM-like	AMRAAM-like	Not specified
Garwin 2017	4 km/s	660 kg	Liquid ICBM
Caveny 2018	3.5 km/s	214 kg	Liquid ICBM
Garwin 2018	5 km/s	490 kg	Liquid ICBM
Goodby 2018	5 km/s	500–544 kg	Liquid ICBM
Caveny 2021	4 km/s	230 kg	Liquid ICBM

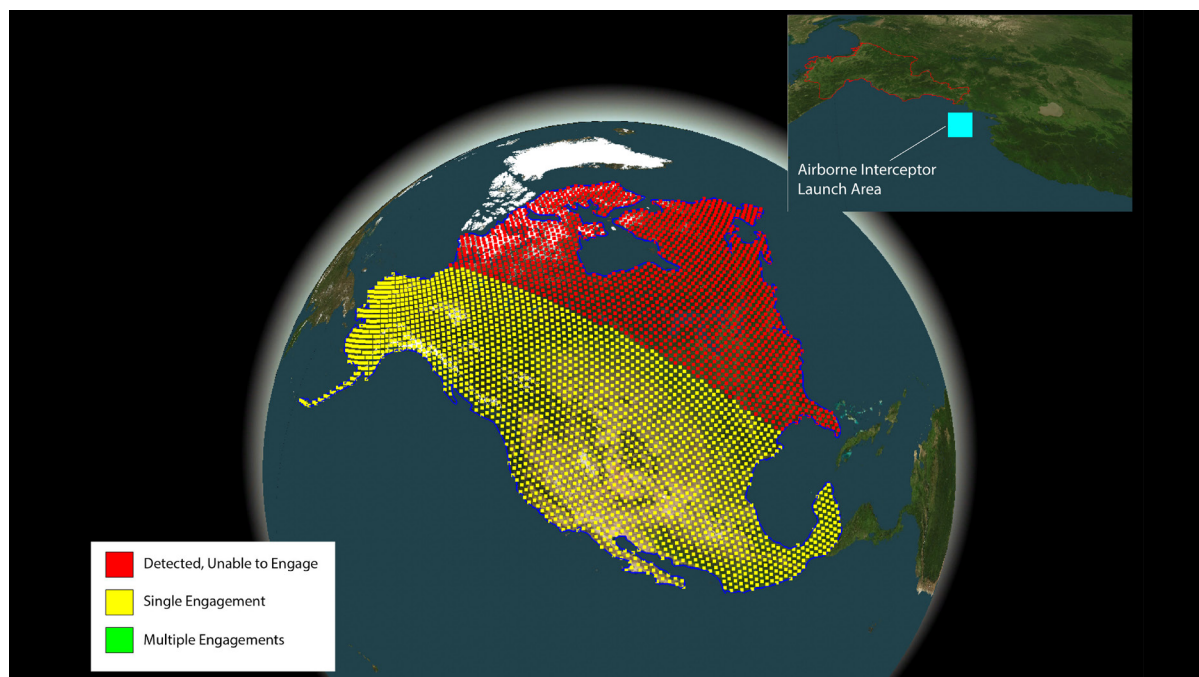
Source: CSIS Missile Defense Project.

Table 8: Kill Vehicle Mass and Performance

Author	KV Divert	KV Mass
Wilkening 2004	2 km/s	90 kg, 50 kg, 25 kg
Garwin 2017	2 km/s	75 kg
Garwin 2017	1.5 km/s ⁴⁰	55 kg
Caveny 2018	-	24 kg
Garwin 2018	2 km/s	43 kg

Source: CSIS Missile Defense Project.

Figure 9A: Notional Defensive Coverage of North America from North Korean ICBM (3 km/s interceptor, 50-second engagement delay)



Source: CSIS Missile Defense Project.

North Korea

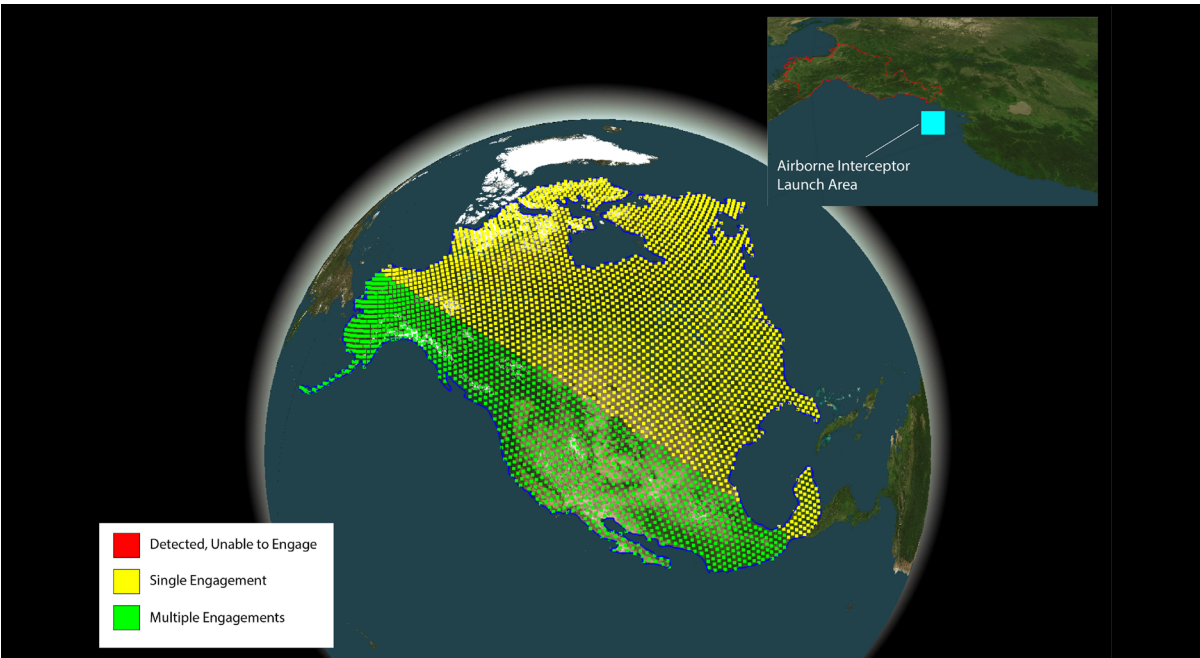
Most prior studies have found that an air-based system could provide homeland defense against North Korean ICBMs with interceptors with speeds between 3 and 5 km/s (Table 9). Such an architecture's defended area shrinks considerably with interceptors on the slower end of this range. Figures 9A, 9B, and 9C depict notional defended area coverage from interceptors with different speeds launched from a single point in the Sea of Japan. Simulations assume a 15-second kill assessment time.

Figure 9B: Notional Defensive Coverage of North America from North Korean ICBM (4 km/s interceptor, 50-second engagement delay)



Source: CSIS Missile Defense Project.

Figure 9C: Notional Defensive Coverage of North America from North Korean ICBM (5 km/s interceptor, 50-second engagement delay)



Source: CSIS Missile Defense Project.

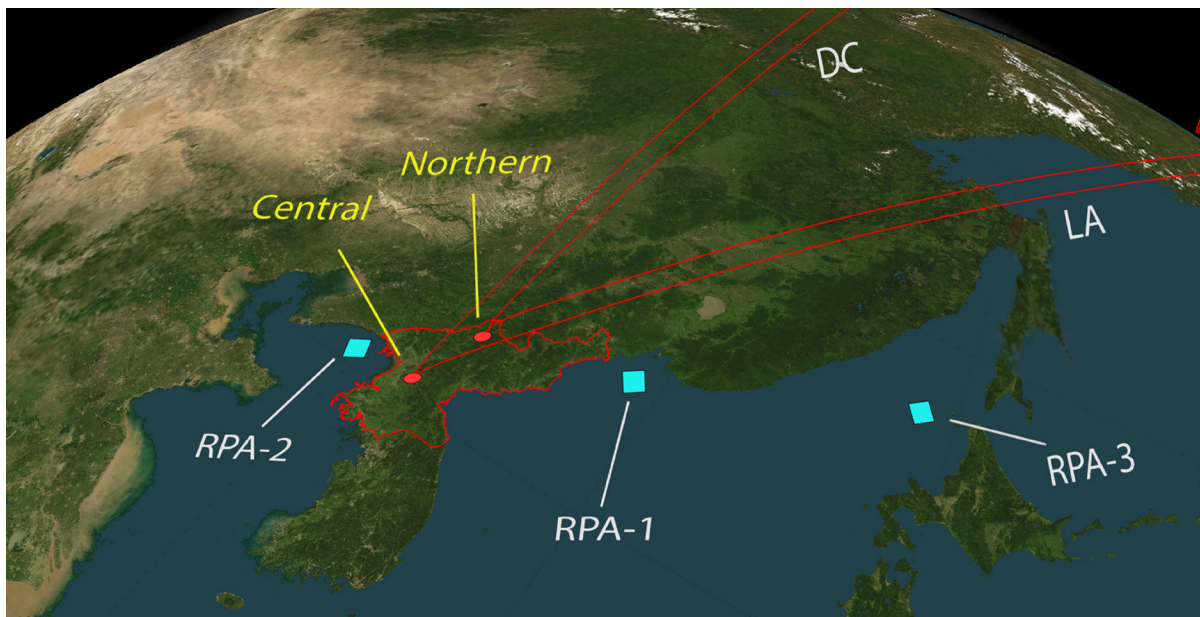
An aspect of defense quality not captured by Figures 9A, 9B, and 9C is how soon an interceptor could strike an ICBM after its launch. To be sure, all simulated engagements depicted in these figures fell within the defined boost phase/early intercept window of burnout plus 100 seconds for canonical solid- or liquid-fueled ICBMs. Even within this window, however, intercepting a missile earlier carries advantages, including a reduced likelihood of debris or partially damaged warheads falling into a third country's territory. Earlier intercepts also hedge against the development of ICBMs with shorter burn times.

Table 9 below shows intercept times from RPA-based interceptors against notional ICBMs launched from two locations within North Korea (Figure 10). The figure shows that RPA-1, based 100 km northeast of North Korea and armed with interceptors capable of 4–5 km/s, could engage a boosting ICBM quite early in flight. Based off North Korea's west coast, RPA-2 struggled to engage most threats due to its more challenging engagement azimuth, which puts the interceptor into a tail chase with both the northern and central trajectories. RPA-2 provided some protection for the United States' eastern seaboard using faster interceptors. RPA-3, in a notional standoff position near northern Japan, showed some ability to protect the West Coast but was unable to cover threats to the eastern United States.

Iran

Iranian ICBM launches are more challenging to defeat in the boost phase in all assessments. In prior studies, defeating an Iranian threat would require multiple orbits north of the country and interceptors with significantly increased speeds—from 4 to 6 km/s. As a practical matter, however, flying U.S. military aircraft north of Iran would be politically challenging and strategically risky in circumstances short of wartime. Indeed, some authors omit Iran from their analyses entirely. Nevertheless, if higher speeds (5+ km/s) can be achieved from air-launched interceptors, some coverage might be had from airborne patrols in eastern Turkey (Figures 11A and 11B). This study's simulations showed no protection for the contiguous United States for 3 km/s interceptors.

Figure 10: Notional RPA Positions and ICBM Launch Points



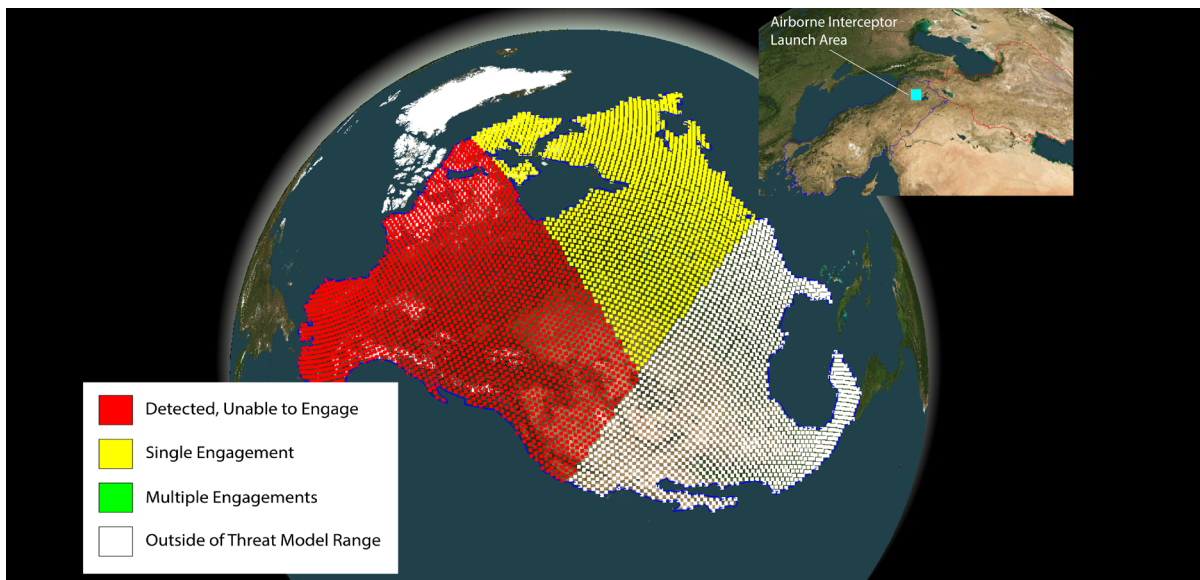
Source: CSIS Missile Defense Project.

Table 9: Notional Intercept Times (North Korea)

Target	Launch Area	Engagement Delay	Interceptor Average Speed	Earliest Time of Intercept (seconds after threat launch)
RPA-1 (East Sea)				
42.22°N, 131.79°E /15,000 m ASL				
Los Angeles	Central	50 seconds	3 km/s	155 seconds
			4 km/s	142 seconds
			5 km/s	131 seconds
	Northern	50 seconds	3 km/s	140 seconds
			4 km/s	125 seconds
			5 km/s	114 seconds
Washington, D.C.	Central	50 seconds	3 km/s	X
			4 km/s	158 seconds
			5 km/s	140 seconds
	Northern	50 seconds	3 km/s	X
			4 km/s	154 seconds
			5 km/s	128 seconds
RPA-2 (Yellow Sea)				
39.13°N, 123.95°E / 15,000m ASL				
Los Angeles	Central	50 seconds	3 km/s	X
			4 km/s	X
			5 km/s	111 seconds
	Northern	50 seconds	3 km/s	X
			4 km/s	X
			5 km/s	X
Washington, D.C.	Central	50 seconds	3 km/s	X
			4 km/s	123 seconds
			5 km/s	97 seconds
	Northern	50 seconds	3 km/s	X
			4 km/s	X
			5 km/s	X
RPA-3 (Off Hokkaido – Standoff Posture)				
45.01°N, 140.05°E / 15,000m ASL				
Los Angeles	Central	50 seconds	3 km/s	247 seconds
			4 km/s	224 seconds
			5 km/s	206 seconds
	Northern	50 seconds	3 km/s	237 seconds
			4 km/s	210 seconds
			5 km/s	193 seconds
Washington, D.C.	Central	50 seconds	3 km/s	X
			4 km/s	X
			5 km/s	253 seconds
	Northern	50 seconds	3 km/s	X
			4 km/s	X
			5 km/s	255 seconds
X = Unable to Intercept		Central ICBM Launch Location: 39.358994°N, 126.175153°E		Northern ICBM Launch Location: 41.375410°N, 126.904358°E

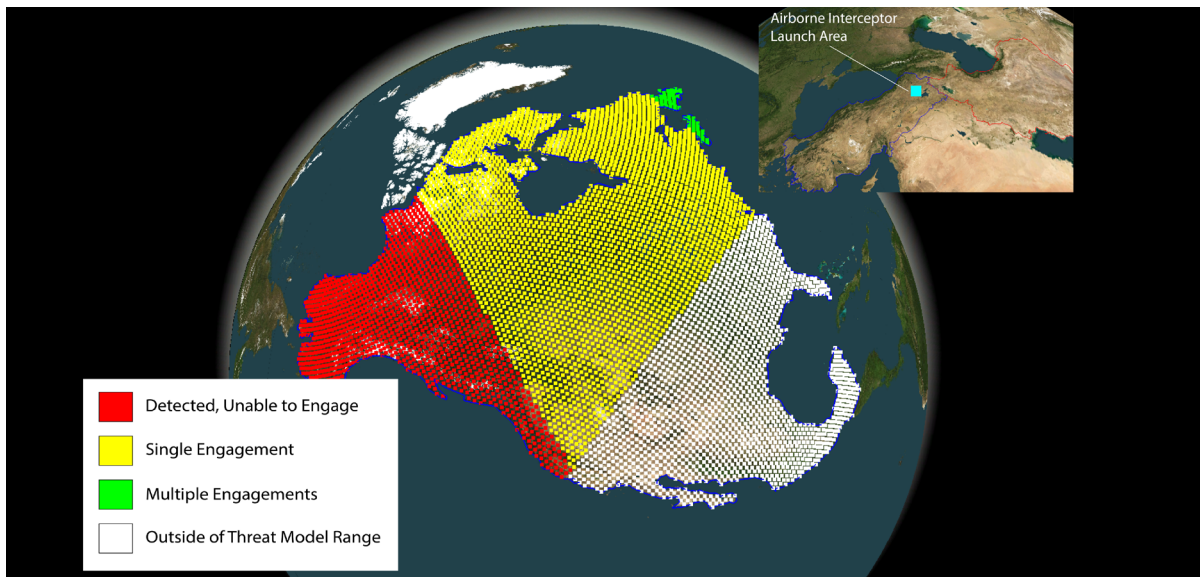
Source: CSIS Missile Defense Project.

Figure 11A: Notional Defensive Coverage of North America from Iranian ICBM (4 km/s interceptor, 50-second engagement delay)



Source: CSIS Missile Defense Project.

Figure 11B: Notional Defensive Coverage of North America from Iranian ICBM (5 km/s interceptor, 50-second engagement delay)

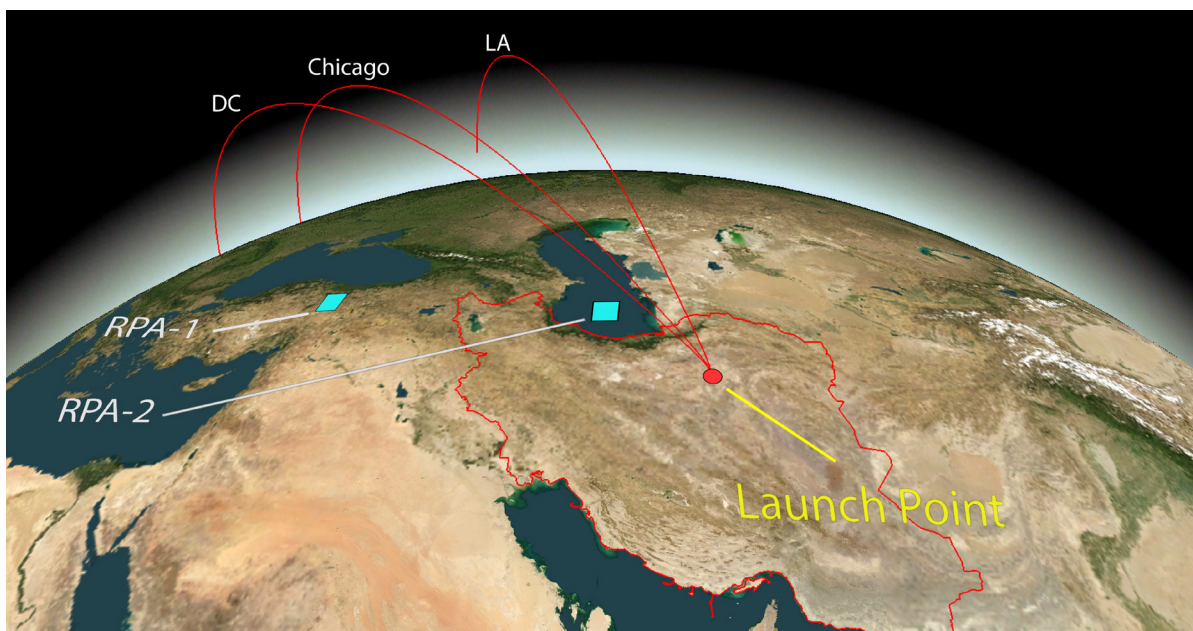


Source: CSIS Missile Defense Project.

Boost-phase intercepts in an Iran-based context continue to look challenging when considering times of intercept. In simulations, intercept times from a 5 km/s interceptor over Turkey (RPA-1) were approximately 100 seconds later than in the North Korea-based scenarios (Table 10 and Figure 12). This difference is meaningful. If defending against a solid-fuel ICBM, the intercept would occur after

burnout and possibly after the separations of penetration aids or warheads, reducing the benefit of a boost-phase defense. Such a system would likely be more effective against slower-burning liquid-fuel ICBMs, however. In sum, this architecture could likely provide some defense against Iranian ICBMs, but that defense would be highly conditional on threat characteristics.

Figure 12: Notional RPA Positions and ICBM Launch Points (Accompanying Table 10)



Source: CSIS Missile Defense Project.

Airborne Directed Energy

Airborne platforms also remain the most likely basing mode for a directed-energy architecture. Unlike kinetic interceptors, a directed-energy weapon—specifically a high-powered laser—engages an ICBM immediately after targeting, allowing for multiple engagements in a single timeframe.⁴¹ Given the near-instant speed of lasers, laser weapons are less sensitive to changes in engagement geometry. For example, laser systems behind a missile's launch azimuth do not contend with the kinematic challenge of tail-chase intercept, thus increasing the battlespace. Directed-energy weapons could also have significantly deeper magazines, although chemically powered lasers, such as the Airborne Laser (ABL), remain limited by their stores of reactants for powering their laser systems.⁴² This limitation is one reason that contemporary directed-energy programs have focused on solid-state lasers.

Despite considerable advancements in solid-state laser technologies, few studies have assessed directed-energy approaches to the boost-phase problem in the past 10 years. Although several aspects of a boost-phase engagement would remain similar—particularly detection and tracking—laser engagements present different challenges to consider. Unlike kinetic interceptors, laser range is limited by a platform's line of sight and atmospheric conditions that dissipate energy at longer distances. Although lasers reach their targets nearly instantly, engagements themselves may take several seconds to complete, including the short time necessary to slew the laser and the longer time needed for the beam to heat, weaken, and destroy the target.

Table 10: Notional Intercept Times (Iran)

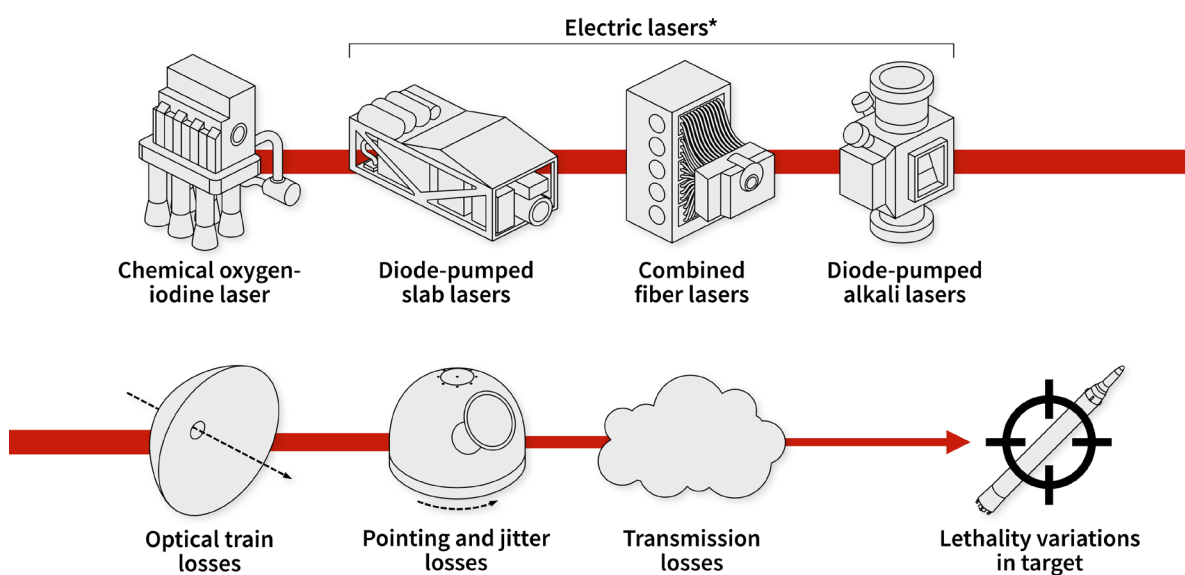
Target	Engagement Delay	Interceptor Average Speed	Earliest Time of Intercept (seconds after threat launch)
RPA-1 (Eastern Turkey) 42.19°N, 39.26°E / 15,000m ASL			
Los Angeles	50 seconds	3 km/s	X
Los Angeles	50 seconds	4 km/s	351 seconds
Los Angeles	50 seconds	5 km/s	276 seconds
Chicago	50 seconds	3 km/s	X
Chicago	50 seconds	4 km/s	266 seconds
Chicago	50 seconds	5 km/s	242 seconds
Washington, D.C.	50 seconds	3 km/s	X
Washington, D.C.	50 seconds	4 km/s	257 seconds
Washington, D.C.	50 seconds	5 km/s	236 seconds
RPA-2 (Caspian Sea – “Aggressive” Posture) 38.60°N, 51.46°E / 15,000m ASL			
Los Angeles	50 seconds	3 km/s	162 seconds
Los Angeles	50 seconds	4 km/s	146 seconds
Los Angeles	50 seconds	5 km/s	134 seconds
Chicago	50 seconds	3 km/s	154 seconds
Chicago	50 seconds	4 km/s	141 seconds
Chicago	50 seconds	5 km/s	131 seconds
Washington, D.C.	50 seconds	3 km/s	297 seconds
Washington, D.C.	50 seconds	4 km/s	142 seconds
Washington, D.C.	50 seconds	5 km/s	132 seconds
Within Liquid-Fuel Intercept Window Only		X = Unable to Intercept	ICBM Launch Point: 34.561642 °N, 55.741438 °E

Source: CSIS Missile Defense Project.

Laser weapons may take considerably longer to defeat solid-fueled ICBMs than their liquid-fueled counterparts, mirroring the challenges presented in kinetic architectures. As solid-fueled ICBMs burn their propellant in a hollow cavity spanning the missile's axis, their casings are insulated and reinforced to contain the combustion inside. By contrast, liquid-fueled ICBMs burn propellant within a dedicated combustion chamber at the base of the missile; the missile body itself—including the fuel tanks—is typically constructed with minimal reinforcement to reduce weight. The more robust structure of solid-fueled ICBMs make them more difficult to compromise with laser beams, requiring up to eight times more fluence—the amount of energy deposited on a missile target—to disable.⁴³ Consequently, both the APS and Dean Wilkening suggest that, against solid-fueled targets, a notional 3-megawatt (MW), ABL-like system would possess substantially degraded effective range.

The main limitation to deploying an airborne laser system is the technical challenge of basing a sufficiently accurate and powerful laser on a weight, space, and power-constrained airborne platform. The prior ABL—an expensive, vulnerable, and complex system—never achieved the 3-MW-class beam powers postulated in architectural studies. A potential directed-energy architecture will require substantial advancements in laser technology to base on higher-endurance, lower-cost airborne platforms. These weight and power constraints become even more acute for space-based systems, though fewer subsystems may be necessary for attenuating airflow-induced vibration and other concerns peculiar to aircraft. Though technological trends offer some room for optimism, no laser system appears close to meeting requirements for long-range boost-phase intercept in the near term.

Figure 13: Laser Types and Sources of Loss



Source: CSIS Missile Defense Project.

A future directed-energy-based system would likely leverage recent advancements in electrically powered lasing. Unlike the toxic, complex subsystems employed in ABL's chemical laser, an electrically powered system could draw on the onboard power supplies of its host aircraft to generate a beam. In addition to their logistical advantages, solid-state systems offer significantly improved beam qualities over chemical lasers, requiring lower beam powers to achieve equivalent fluence. The efficacy of a

laser weapons system is not merely a function of beam power; it is determined by a combination of variables, including beam power, beam quality, spot size, and pointing accuracy. Nonetheless, the power levels of current solid-state lasers (several hundred kilowatts) and heavier power-to-weight ratios fall short of the performance necessary to achieve boost-phase intercept at range.

Orbital Systems

Space-based architectures are among the earliest approaches investigated for boost-phase defense.⁴⁴ Space-based kinetic interceptors could be optimally placed to intercept a boosting ICBM without the geographic constraints of surface or airborne deployments.⁴⁵

Analysts diverge on the viability and cost of a space-based defensive layer. Due to the constant motion required to stay in orbit, a single space-based interceptor cannot dwell within range of a launch site for a significant length of time. Therefore, many interceptors are needed to maintain a continuous presence over a given point, with a constellation of multiple interceptors necessary for covering a given area.⁴⁶ The size of this constellation hinges upon several variables: (1) the location and density of coverage, (2) the ICBM's burn time, (3) the interceptor's flyout velocity, and (4) the interceptor's lifespan and average rate of failure. Many studies assume that a constellation would require replenishment with new satellites to account for natural mechanical breakdowns over their lifespan. And while several solid- and liquid-fueled motors have remained functional after several years in space, unknowns remain over the long-term lifespan of a space-based interceptor. With some estimates of global coverage ranging far over 3,000 interceptors, most studies opted to analyze a limited mission set: defeating boost-phase intercepts originating from Iran and North Korea.⁴⁷ Such a mission would encompass orbits between 25 and 45 degrees latitude, with roughly two interceptors within range at any point in time.

Like ground- and surface-based approaches, interceptor speed and performance remain significant determinants of constellation size. Interceptors with higher flyout velocities could strike targets within the boost-phase engagement window at greater distances, reducing the number needed to maintain coverage. Trade-offs in interceptor kill vehicle agility—between higher agilities and kill probabilities and lower weights—also drive estimates over constellation sizing and performance. Ultimately, increasing an interceptor's range and agility will increase its launch mass.

In other words, assumptions about boost-phase constellation sizing vary significantly based on assumptions about space-based interceptor launch and unit costs. Heavier, higher-performing interceptors may increase the costs of launch, but fewer interceptors may be necessary and each may offer greater value. Lighter, less capable systems might be significantly less costly to launch and marginally less costly to manufacture but may need to be purchased and launched in substantially greater numbers.

Nevertheless, technological developments are upending many prior assumptions about constellation sizing. With launch costs declining nearly tenfold since 2000, such an architecture may be ripe for reassessment. At the time of their writing, most major studies assumed that launch costs would be “the dominant design criterion” for minimizing total system cost—between \$8,000 and \$15,000 per kilogram lifted into orbit.⁴⁸ Despite this, the number of independent variables resulted in significant variance in projected constellation size. Estimates have ranged from as low as 240 to as high as 700

interceptors for systems designed to defeat Iranian and North Korean liquid-fueled ICBMs. While, for example, the APS and CBO assume roughly identical flyout velocities, divert velocities, kill vehicle mass, and interceptor mass, they respectively estimate constellation sizes of 700, 368, and 240.⁴⁹ Meanwhile, the NAS and Roberts—who assume interceptor speeds of 5 and 6 km/s—assess constellation sizes from 450 to 496, respectively, upsetting intuitions about the inverse relationship between interceptor speed and quantity.⁵⁰

Table 11: Constellation Size and Mission

Author	Constellation Size (liquid)	Constellation Size (solid)	Mission Set
IDA 1986	N/A	286	Global coverage against massive USSR attack
LANL 1991	N/A	4,000	Global coverage against massive USSR attack; assuming other defenses will “mop up” the 800 reentry vehicles which penetrate
CACNP 2003	N/A	1,000	Global coverage against “sophisticated attack of up to 60 warheads”
APS 2003	700	1,600	Coverage of North Korea, Iran with 2 space-based interceptors (SBIs) overhead, intercept 5 seconds before burnout
CBO 2004	368 (156 with faster interceptors)	1,308	Coverage of North Korea, Iran with 1–2 SBIs overhead
Marshall 2004	240	Unspecified	Coverage of North Korea, Iran with 1–2 SBIs overhead
IDA 2011	N/A	24–960	“Limited” coverage for carrier defense or “global” coverage; each unit carries ~4 interceptors
NAS 2012	450 (700 with 30-second decision delay)	1,100 (2,200 with 30-second decision delay)	Coverage of North Korea, Iran with 2 SBIs overhead (5 km/s)
Schaffer 2016		3,000	Global coverage of 1,000 ICBM salvo
Roberts 2018	496	Unspecified	Coverage of North Korea, Iran with 1–2 SBIs overhead (6 km/s)
Wright 2018	300–400	Unspecified	“Limited” coverage of North Korea

Source: CSIS Missile Defense Project.

Many of these conclusions flow from different assessments of threat characteristics. With its “more conservative assumptions” regarding the threat missile’s burn time—240 seconds versus the 300 claimed by the CBO and Marshall—the APS study estimates a significantly larger constellation than the latter two.⁵¹ Others diverge over the mission set: while Canavan’s constellation only covers likely fixed silo locations, the CBO assumes that Iran and North Korea would develop mobile missiles, necessitating coverage of the countries’ entire landmasses. And as Roberts and Wright note, the Institute for Defense Assessment’s estimate of a “limited” 24-satellite defense derives from assumptions that the mission is limited to defending U.S. carriers from missiles in midcourse, allowing more time to engage.⁵²

Table 12: Interceptor Characteristics

Author	Flyout Velocity	Divert Velocity	Interceptor Mass
LANL 1991	6 km/s	6 km/s	-
APS 2003	4 km/s (“baseline”)	2.5 km/s	820 kg, including 136 kg KV
CBO 2004	4 km/s	2.5 km/s	847 kg, including 136 kg KV
Marshall 2004	4 km/s	2.5 km/s	820 kg, including 136 kg KV
NAS 2012	5 km/s	2.5 km/s	1,978 kg, including 164 kg KV (extrapolated)
Schaffer 2016	6 km/s	-	3 kg, including 70 kg bus
Roberts 2018	6 km/s (“generous”)	2.5 km/s	-
Wright 2018	4 km/s	-	-

Source: CSIS Missile Defense Project.

Other variations are more puzzling. For its baseline 5 km/s interceptor, the NAS estimates a dry mass of 1,978 kg—much higher than the APS estimate of ~1,400 kg to attain the same velocity.⁵³ And while many major studies decline to produce cost estimates, lifecycle costs differ even between roughly similar constellation sizes, such as between the CBO’s \$221–304 billion estimate and the NAS’s \$329–556 billion estimate for a system designed to defeat solid-fueled ICBMs.⁵⁴ These studies can be difficult to accurately compare, as they draw on different models for assessing satellite weight and construction cost.⁵⁵ Without an assessment of launch, satellite manufacturing, and research costs, it is difficult to understand how—as one commentator contends—high cost estimates “should be understood to represent a ceiling, rather than a floor.”⁵⁶

Here, it is important to note the vulnerability of space-based architectures to countermeasures. Adversaries could target space-based interceptors with anti-satellite weapons or develop ICBMs with reduced burn times, significantly degrading the constellation’s coverage. Several assessments also highlight how

adversaries could fire a salvo of missiles to punch through a space-based defensive layer. Given the few space-based interceptors on station at any time, a determined adversary could concentrate its missile launches in one location to overwhelm a constellation.⁵⁷

It remains unclear how recent revolutions in space launch cost and satellite mass production might alter these considerations. As previously described, reusable space launch systems have reduced launch costs tenfold, potentially reducing some weight trade-offs constraining earlier constellation architectures.⁵⁸ Other advancements, particularly in the cost of satellite manufacturing, might also mitigate parts of this challenge.

Table 13: Interceptor Constellation Cost

Author	Unit Cost (2019)	Launch Cost (2019)	Total Cost (2019)
LANL 1991	\$1.9–2.8 million (acquisition), \$4.3 million (lifecycle)	6 km/s	-
CACNP 2003	-	-	\$93 billion
APS 2003	-	\$19,400–27,700/kg	-
CBO 2004	\$42–53 million (acquisition)	\$27,200/kg	\$221–304 billion (solid), \$77–108 billion (liquid)
Marshall 2004	\$14 million (acquisition)	\$27,200/kg	\$27–68 billion (liquid)
IDA 2011	-	-	\$30 billion (“limited”), \$322 billion (“global”)
NAS 2012	-	\$10,900–17,200/kg	-
Schaffer 2016	4 km/s	\$21,200/kg	\$43 billion

Source: CSIS Missile Defense Project.

Conclusion

With North Korea and Iran introducing more capable and maneuverable missile systems, the United States should reexamine boost-phase missile defense as an option for improving homeland missile defense. These missile threats strain existing homeland defenses just as their supporting assets become increasingly needed to counter peer competitors in regional contingencies. This reality drove the decision to pursue the Next Generation Interceptor, which will be able to counter more complex threats than the currently deployed Ground-Based Interceptors. Even with the more capable Next Generation Interceptor in place, it may be risky relying solely on a single solution for homeland defense. U.S. missile defense efforts have long envisioned a layered approach, for good reason. A boost-phase defense architecture based on appropriately mature technologies might usefully supplement homeland defense, lessening the burden on the Ground-based Midcourse Defense system.

Just as threat trends make boost-phase defense more desirable, ongoing technical trends may make this approach more viable. Advancements in sensors—in image processing and next-generation radar—might aid in lengthening engagement timelines, making the boost-phase problem more tractable. Advancements in long-endurance remotely-piloted aircraft likewise offer the promise of a persistent airborne platform that can overcome some of the challenges of terrestrial basing and the cost, availability, and persistency shortcomings of crewed aircraft.

By harnessing and integrating advances in the military and commercial sectors, a kinetic boost-phase defense against North Korean ICBMs may be possible in the near term as Pyongyang continues to advance its ballistic missile program. Such a goal would, of course, require renewed policy prioritization and budgetary commitment. Advancements in space launch, high-powered

lasers, and satellite manufacturing might promise more significant performance in the longer term. The appendices explore the state and potential of these technologies and industries in more detail.

The world has not stood still since the last comprehensive boost-phase assessments took place nearly 10 years ago. Many of the assumptions that drove past assessments may no longer be valid. A combination of new threats, enablers, and strategic priorities warrants renewed attention to boost-phase missile defense.

Appendix 1

Implications of Low-Cost Launch

BY THOMAS G. ROBERTS

In the six decades since the Soviet Union and United States successfully launched their Sputnik and Vanguard rockets and placed satellites into orbit for the first time, the global space launch landscape has become more competitive and less expensive.⁵⁹ Space launch is cheaper today than ever before.⁶⁰ If launch costs continue to fall, many space missions previously deemed too costly could become affordable. This appendix interrogates the observed trend toward lower-cost space launch and evaluates its implications for the viability of using space-based interceptors for boost-phase missile defense. It finds that reductions in space launch costs would make a space-based interceptor layer less costly. Nevertheless, other cost mitigations could still be necessary to make such a system fiscally feasible in the current budgetary environment.

THE FALLING COST OF SPACE LAUNCH

Space launch vehicles (SLVs) can have vastly different characteristics from one another, including the orbital regimes into which they can place payloads, the spaceports from which they can launch, and their reliability.⁶¹ Despite these differences, all SLVs share the same core mission: to place payloads into orbit around the earth. To compare the cost at which different vehicles achieve this mission, analysts often combine several vehicle characteristics into a single figure of merit: the cost to launch 1 kilogram of payload mass to low earth orbit (LEO) as part of a dedicated launch.⁶²

ESTIMATING THE COST OF LAUNCH

Despite the simplicity of the cost-per-kilogram metric, the process of estimating it is rarely straightforward. In many cases, space launches are arranged through private or classified contracts, which can obscure the true costs associated with individual launches.⁶³ In other cases, launch providers may provide a cost estimate for a single configuration of a launch vehicle while also

offering a wide range of other variants for which they do not provide corresponding cost estimates.⁶⁴ Most critically, the very definition of “cost of launch” is subject to interpretation. This analysis cites launch cost estimates from U.S. government resources, academic studies, and publicly available documentation from commercial launch providers, which often use the cost-per-kilogram figure to describe vehicles’ “unit flyaway cost,” a term borrowed from the aviation industry. According to the RAND Corporation, the unit flyaway cost “includes all direct and indirect manufacturing costs and their associated overhead plus recurring engineering, sustaining tooling, and quality control.”⁶⁵ Notably, this definition does not include the costs associated with researching and developing the vehicle design before manufacturing individual, launch-ready vehicles. For older SILVs, which were often developed with direct funding by civil space agencies and military services, unit flyaway costs are not always available. In those cases, non-recurring costs, including research and development, may be factored into the figure. Due to these discrepancies, the data sources in this analysis and the accompanying data repository are cited on a vehicle-by-vehicle basis.⁶⁶

Figure 14: Comparing Costs for Space Launch Vehicles



Note: Each bubble represents a launch vehicle. A bubble’s size corresponds to the number of successful orbital launches achieved by that vehicle as of December 31, 2019. A bubble’s vertical position corresponds to that vehicle’s estimated flyaway cost per kilogram of payload mass to LEO in FY 2021 dollars, adjusted using the GDP Chained Price Index published by the Office of Management and Budget in Historical Table 10.1. A bubble’s horizontal position indicates the year of that vehicle’s first successful orbital launch. Learn more about these figures at cs.is/launchcosts.

Source: CSIS Aerospace Security.

EMERGING TRENDS

One way to reveal the trends in the cost of space launch over time is to plot the relationship between the cost-per-kilogram figure described in the previous subsections against the years in which each vehicle achieved its first successful orbital launch (see Figure 14).

In aggregate, the data points in Figure 14 display a distinct trend: newer launch vehicles tend to offer lower launch costs than older launch vehicles, with a gradual decline from 1957 to 2005 and a steeper decline between 2005 and 2020. This trend is less clear, however, when the data is filtered by certain critical vehicle characteristics such as country of origin or payload mass capacity.

For example, filtering launch vehicles by country of origin, as shown in Figure 15, reveals different trends for different countries. For the United States, which has the greatest number of launch vehicles for which cost estimates are available, the downward trend visible in Figure 14 remains. The claim that newer U.S. space launch vehicles are more cost-effective than older ones is underscored by the positions of SpaceX's Falcon 9 and Falcon Heavy, the two lowest-cost launch vehicles according to the cost-per-kilogram figure. For Russia, which has a pattern of continuing to use new variants of Soviet-era launch vehicles, the downward trend is present but less noticeable than that of the United States.⁶⁷ For China, an emerging space power that first reached orbit in 1970, no clear upwards or downwards trend can be observed without also accounting for other SLV characteristics, such as payload mass class.⁶⁸

Figure 16 shows vehicle launch costs over time for each of three payload mass classes.⁶⁹ The SLVs in the small-lift payload mass class shown at the top of Figure 16 first exhibit a gradual upward trend during the first space age (from 1957 to 1990), followed by a downward trend in the second space age (from 1990 until today). During the second space age, small-lift launch vehicle designs have become more popular, but each vehicle is launched less frequently on average. The medium-lift payload mass class, the most represented of the three classes in the data set, exhibits the clearest downward trend of all three classes. The heavy-lift class, the rarest of the three principal payload classes, exhibits the steepest downward trend of any mass class from the early 1980s until 2018.

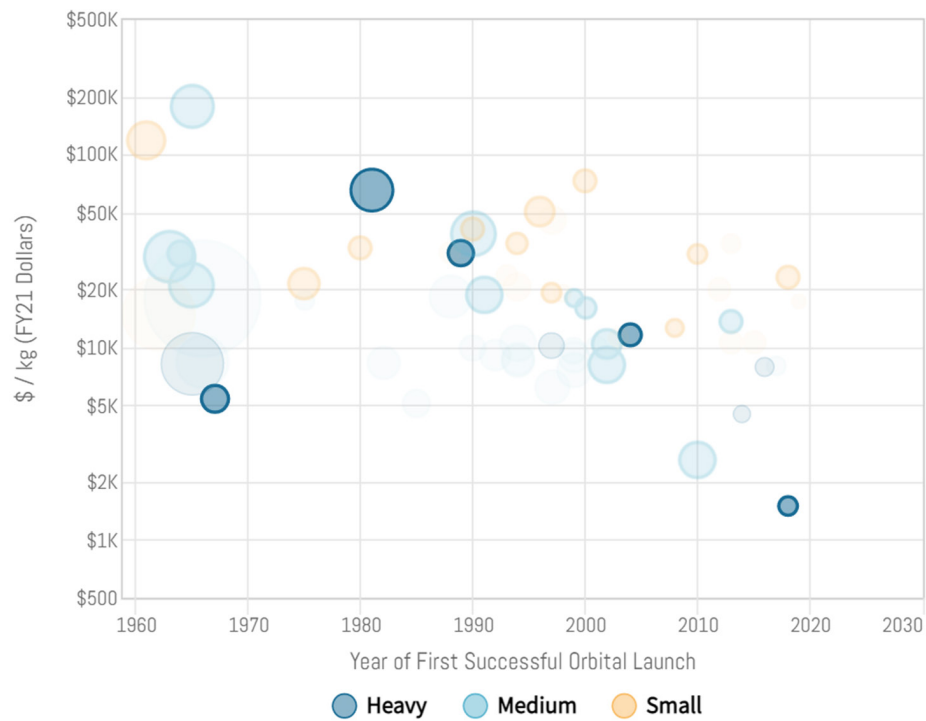
REDUCING THE COST OF ACCESS TO SPACE

How do newer launch vehicles reach orbit at lower costs than their predecessors? Could those same principles lead to further cost reductions in the coming years?

In 2016 and 2017, the CSIS Aerospace Security Project, the National Defense and Johns Hopkins Universities, and seven other think tanks each contributed reports as part of an Air University study on how drastic reductions in the cost of access to space could affect the future of U.S. space operations.⁷⁰ As part of its report, CSIS held a series of workshops with government space launch regulators, satellite manufacturers, space security analysts, and launch providers to better understand how developments in launch vehicle design, mission-extension technologies, and U.S. government regulations could allow for lower launch costs in the future.⁷¹

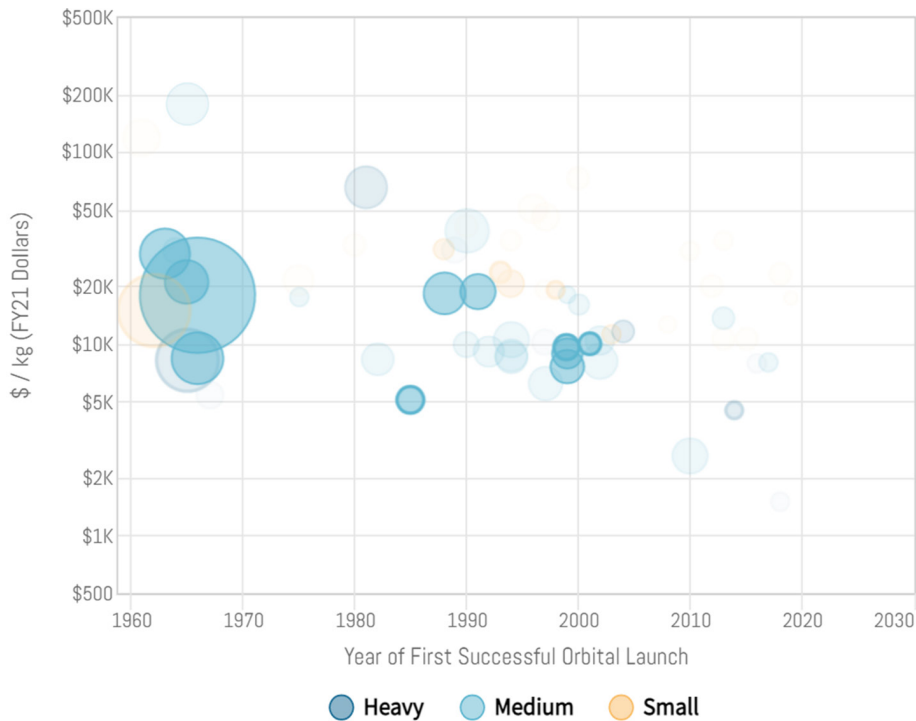
Although the U.S. space industry has yet to achieve the orders-of-magnitude reduction in launch costs described in the report, some space launch providers are employing several of the study's cost-lowering principles, with ample room to implement more strategies in the future.

Figure 15A: Comparing Costs for Space Launch Vehicles by Country – United States



Source: CSIS Aerospace Security.

Figure 15B: Comparing Costs for Space Launch Vehicles by Country – Russia



Source: CSIS Aerospace Security.

COST-EFFECTIVE LAUNCH VEHICLE DEVELOPMENT

Like manufacturers in any industry, space launch providers would likely benefit from the cost reductions associated with economies of scale and learning efficiencies, where increases in a manufacturer's production volume decrease unit cost. Although the total number of space launches are on the rise, the global space launch industry only supports about 100 launches per year.⁷² Until individual SLV manufacturers drastically increase their unit production, significant cost reductions from economies of scale and learning efficiencies are likely out of reach.⁷³

Although vehicle reusability did not lead to drastic cost reduction for SLVs in the first space age (some analysts argue that the Space Shuttle's partially reusable design actually led to cost increases for the program), there is strong evidence that partial reusability is more cost-effective.

Other cost-saving practices for space launch—such as avoiding the fixed costs associated with maintaining a ground-based spaceport by pursuing air- or sea-based launch instead—have been explored to a lesser degree than vehicle reusability. Although both air- and sea-based launches can benefit from better fuel efficiency than ground-based space launch, they only account for about 1 percent of all global space launches.⁷⁴

POTENTIAL IMPACT ON THE VIABILITY OF BOOST-PHASE SPACE-BASED MISSILE DEFENSE

Like all space-based systems, launch costs represent only a fraction of the costs associated with establishing and maintaining a space-based interceptor system for boost-phase defense. How could the launch cost reductions discussed in the previous sections affect the feasibility of such a system?

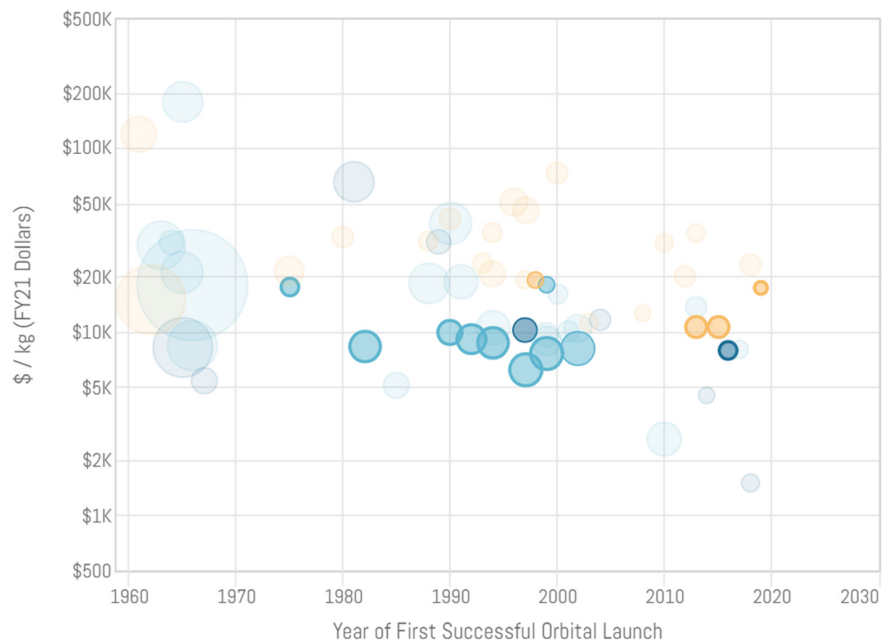
The 2019 National Defense Authorization Act was vague when it required the Department of Defense (DOD) to develop a “regionally focused” space-based interceptor system for boost-phase missile defense. Nonetheless, such a system would certainly require hundreds of individual interceptors in orbit.⁷⁵ The cost savings from launch cost reductions for any satellite constellation system corresponds to the number of launches the mission requires. That number, in turn, depends on the total mass of the interceptors within a constellation, the number of orbital planes in the constellation, and the number of launches required to maintain the system after its initial deployment. The launch cost approximations in the following section use the total mass of several proposed constellations of space-based missile interceptors and the cost-per-kilogram figure in FY 2021 dollars for various launch vehicles. This combination almost certainly underestimates the launch costs for each satellite constellation, since each proposed design would require both additional launches for full deployment and orbital placements at higher altitudes than those associated with the launch cost estimates used in this analysis. These are just two of many factors that could lead to significantly higher launch costs than those described in the following subsection.

REVISITING PREVIOUS SPACE-BASED INTERCEPTOR STUDIES

Although analysts have studied space-based interceptors for boost-phase missile defense for decades, several studies released within the past 15 years are particularly salient within the missile defense analysis community.⁷⁶ How might recent reductions in launch costs affect the price tag of the space-based interceptor systems described in these past studies?

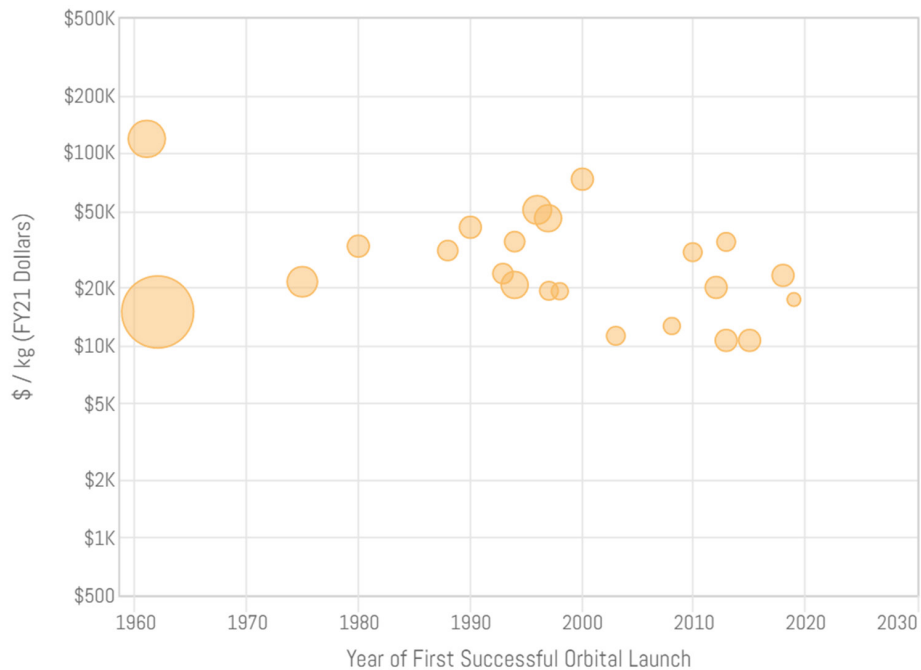
In 2004, the American Physical Society (APS) offered an in-depth analysis of the mission requirements for a partial-coverage constellation of space-based interceptors for boost-phase missile

Figure 15C: Comparing Costs for Space Launch Vehicles by Country – China



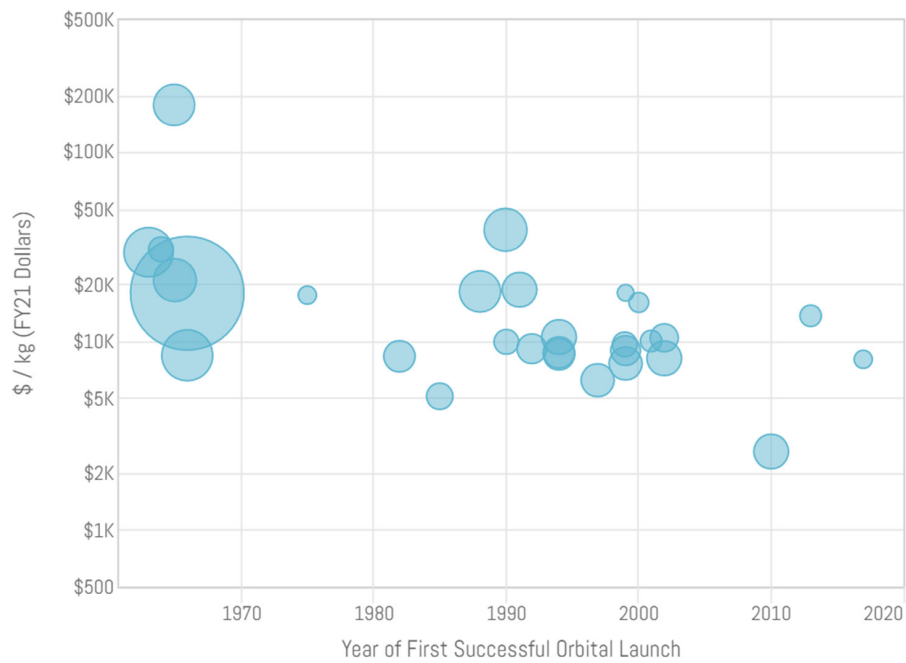
Note: The United States (top), Russia (center), and China (bottom) exhibit different launch cost trends over time. The full data set, available at cs.is/launchcosts, can highlight vehicles from any space-faring country, including those not listed here. Source: CSIS Aerospace Security.

Figure 16A: Comparing Costs for Space Launch Vehicles by Payload Mass Class – Small Payload



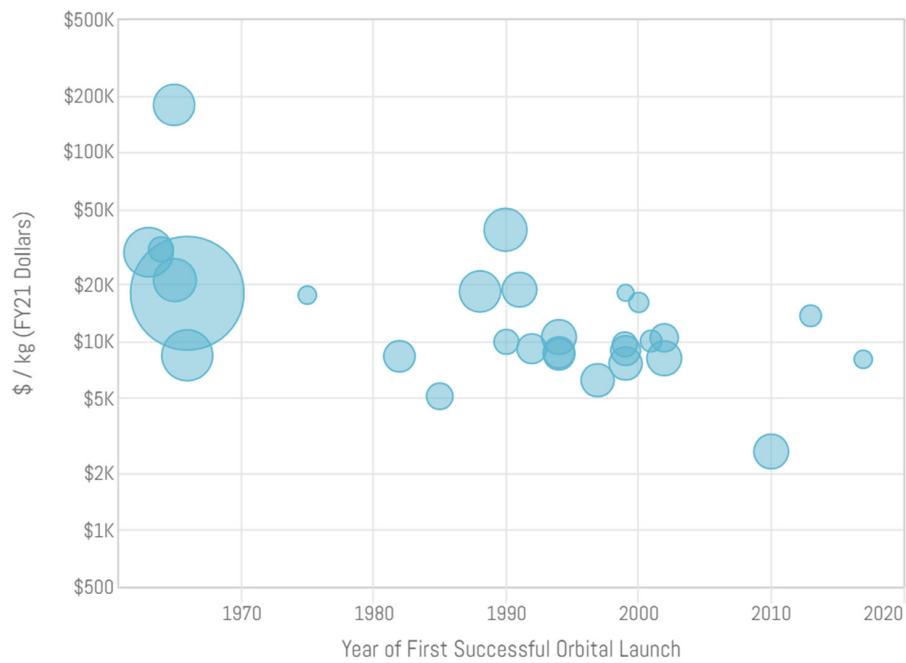
Source: CSIS Aerospace Security.

Figure 16B: Comparing Costs for Space Launch Vehicles by Payload Mass Class – Medium Payload



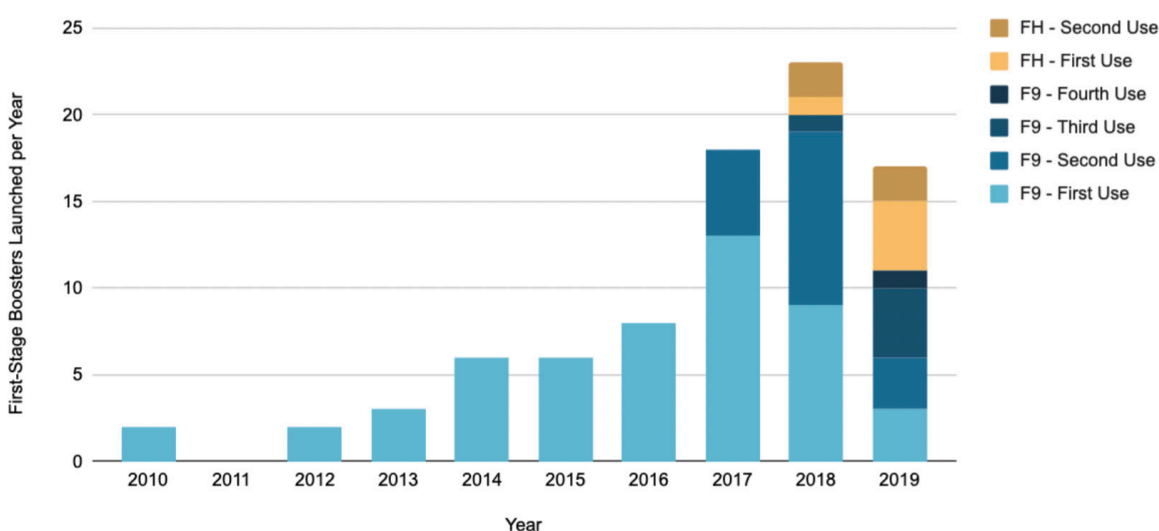
Source: CSIS Aerospace Security.

Figure 16C: Comparing Costs for Space Launch Vehicles by Payload Mass Class – Heavy Payload



Note: The small-, medium-, and heavy-lift payload mass classes exhibit different launch cost trends over time.
Source: CSIS Aerospace Security.

Figure 17: First-Stage Booster Use and Reuse on SpaceX Launch Vehicles



Note: Seven years after its first flight, the Falcon 9 completed its first successful orbital space launch using a reused first stage booster. Since then, boosters have been reused many times, including as part of Falcon Heavy launches, which use three first-stage boosters per flight.

Source: Jonathan McDowell, "Jonathan's Space Report," Jonathan's Space Report, planet4589.org.

defense.⁷⁷ One particular constellation endorsed by the APS was composed of 1,646 interceptors, each with a mass of 991 kilograms.⁷⁸ The report offered several launch vehicles that could launch the interceptors, such as the Delta II, Atlas V, Delta IV Heavy, and others.⁷⁹ Using the approximation methodology described in the previous subsection, a minimum launch cost can be estimated: \$13 billion (using all Atlas V vehicles, the most cost-efficient option available at the time of the report's publication) to \$63 billion (using all Delta II vehicles, the least cost-efficient option listed).⁸⁰ Using today's most cost-efficient vehicles (the Falcon 9 and Falcon Heavy), launching the APS constellation would cost at least \$2.5–4.3 billion.⁸¹

In 2006, the Congressional Budget Office published a study that featured 128 space-based interceptors, with each unit weighing 907 kilograms.⁸² If the interceptors were launched on Delta IV or Delta IV Heavy launch vehicles, as was suggested in the report, the total launch costs would be at least \$1.2–1.3 billion.⁸³ Employing Falcon 9 or Falcon Heavy to launch the same interceptors, the total launch costs would be only \$180–300 million.

Similarly, in 2012, the National Academies of Sciences released a committee report featuring a 650-interceptor constellation, with each interceptor weighing 1,796 kilograms.⁸⁴ Launching onboard the Delta IV Heavy, the vehicle referenced as part of the study, would cost at least \$14 billion, while using the Falcon Heavy would cost only \$1.8 billion.

Table 14: Estimated Launch Cost Reductions for Three Boost-Phase Interceptor Layer Designs

Source	Number of Interceptors	Mass per Interceptor	Proposed Launch Vehicle	Estimated Cost of Proposed Launch	Estimated Reduced Launch Cost
American Physical Society (2004) ⁸⁵	1,646	991 kg	Delta II, Atlas V, Delta IV Heavy, and others	\$13–63 billion	\$2.5–4.3 billion
Congressional Budget Office (2006) ⁸⁶	128	907 kg	Delta IV or Delta IV Heavy	\$1.2–1.3 billion	\$180–300 million
National Academies of Science (2012) ⁸⁷	650	1,796 kg	Delta IV Heavy	\$14 billion	\$1.8 billion

Note: The “Estimated Cost of Proposed Launch” refers to the approximate cost of using the proposed launch vehicles to launch the total mass of the interceptor system to a nominal low-altitude orbit. The “Estimated Reduced Launch Cost” refers to the approximate cost of launching the same mass to the same altitude instead using the Falcon 9 or Falcon Heavy launch vehicles.

Source: CSIS.

CONCLUSION

Despite the cost savings described in the previous section, reductions in launch costs alone may not make space-based missile interceptor systems affordable within foreseeable budgetary constraints. Launch costs typically account for only between 10 and 40 percent of the total procurement costs associated with space-based missile interceptors.⁸⁸ Therefore, launch cost reductions—both those observed over the history of global space launch and a continuation of that pattern into the years to come—can only do so much.

Further analysis is required to determine how an extrapolated reduction in launch costs in addition to other factors that reduce the cost of procuring space-based missile interceptors—such as innovative, lightweight propulsion systems, new satellite manufacturing techniques, or on-orbit servicing—could contribute to boost-phase missile defense in space.

Appendix 2

Implications of Advanced Sensing for Boost-Phase Missile Defense

INTRODUCTION

The principal challenge in developing a boost-phase missile defense system is the relatively short window of time available to engage a boosting ballistic missile. A critical variable in this timeline is how quickly a defense system can detect, track, and compute a fire control solution for the ballistic missile. Reducing detection and tracking delays could make a boost-phase defense more achievable by reducing time pressure on other system requirements, such as interceptor speed or proximity to enemy territory.

Most analyses of notional boost-phase defenses have evaluated space-based infrared (IR) and airborne radar sensors for missile detection and tracking. Their authors have assumed delays of up to 65 seconds before defenders can begin tracking a boosting missile.⁸⁹ With an ICBM's boost phase lasting between only 160 and 300 seconds, these delays can substantially impact a prospective boost-phase architecture's technical and operational feasibility. These conclusions—echoed by the Congressional Budget Office and others—continue to inform recent debates on boost-phase missile defense.⁹⁰ Many assumptions made in such prior studies are ripe for reexamination.

Rapidly maturing radar, IR, and computing technologies promise meaningful improvements in detection performance. Meanwhile, new developments in sensor platforms could allow for improved cost and survivability in the longer term. Though atmospheric and trajectory factors impose a hard limit on detection and tracking performance, small improvements to the sensing timeline may be achievable in the near term.

SOURCES OF DELAY

Such a conclusion merits a brief discussion of the factors responsible for detection and tracking

delays. Several factors responsible for delays are fixed; a defender cannot begin tracking a ballistic missile, for example, until it transitions from its initial vertical flight into its trajectory toward the target, including possible plane changes a booster might make to adjust its azimuth. Other delays depend on environmental factors. For space-based IR and air-based radar sensors—the two system configurations evaluated in prior studies—sources of delay include IR-attenuating atmospheric conditions and the earth’s curvature, which imposes a hard limit on when missiles become observable to airborne radar.

Prior studies have asserted that atmospheric conditions play a key role in delaying the detection of ballistic missiles. Boosting ballistic missiles tend to emit most energy at short- and mid-range IR wavelengths, which are easily attenuated by atmospheric water vapor.⁹¹ Sensors tuned to these bands, such as the legacy Defense Support Program satellites, are unable to detect threat missiles until they rise past 7 to 10 km in altitude, where atmospheric absorption is reduced.⁹² Consequently, studies have concluded that faster-accelerating missiles can be detected more quickly, with solid-fueled missiles breaking cloud cover within roughly 30 seconds of launch.

To detect a missile earlier in flight, defenders could employ IR sensors tuned to wavelengths that penetrate cloud cover, such as those found on the Space-based Infrared System (SBIRS). Though theoretically faster in detecting threat missiles, sensor systems tuned to these “window” wavelengths would need to identify missile plumes in the presence of cluttered signals from the ground. Prior studies have asserted that such clutter rejection could not be possible or would take tens of seconds to process.

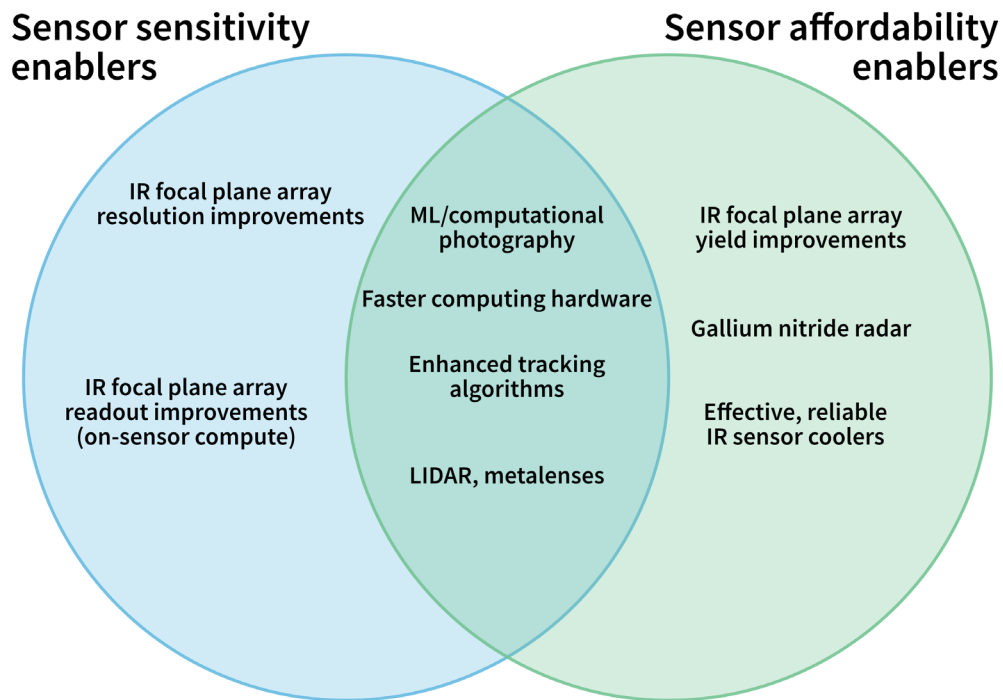
The timeline for missile tracking, however, remains fundamentally constrained by the time it takes for a vertically boosting missile to pitch over toward its trajectory. Following missile pitchover, a space-based IR sensor such as SBIRS could observe the horizontal movement of the missile to develop a tracking solution: a predicted envelope of the missile’s current and future location.

This process is constrained by a space-based sensor’s ability to resolve the missile’s position over time. In a 2004 assessment, Wilkening assumed that a notional SBIRS-like satellite would resolve IR signals within a 1 km-by-1 km footprint, with each pixel on the sensor’s focal plane array (FPA) corresponding to a kilometer-wide square on the earth’s surface. The resultant tracking delay, between 5 and 14 seconds, directly corresponds with the time taken for a missile to travel two pixels downrange, enough to form an adequate assessment of missile heading.⁹³

DELAYS TO AIRBORNE RADAR

Delays in radar detection and tracking are subject to a different set of limitations. Unlike IR sensors, surveillance radars do not require multiple units to triangulate a missile’s position, can rapidly integrate target heading, and are largely insensitive to poor weather conditions. Yet radar systems possess a significantly shorter detection range, restricted by the earth’s horizon and their own power output. The curvature of the earth poses a central limitation to radar-based detection and tracking. To maintain an unrestricted line of sight to the ground, an airborne radar would need to remain within 600 to 1,000 km of a missile’s launch site. When in range, a boosting missile would become detectable after reaching a speed that distinguishes it from surrounding objects. Depending on a radar’s position, scanning rate, and nearby terrain features, this can delay total detection by 14 to 60 seconds.⁹⁴

Figure 18: Sensor Technology Enablers



Source: CSIS Missile Defense Project.

After missile pitchover, studies have asserted that an airborne radar could integrate a track within five seconds. In order to obtain an accurate estimate of the missile's exact location, such a radar would need to use a higher frequency, such as the X-band, attaining a positional accuracy of roughly 1 km at a 600 km range.⁹⁵

NEW TECHNOLOGICAL ENABLERS

Several new or emerging technologies could make boost-phase defenses more tractable by shortening detection and tracking timelines. More prompt detection and track establishment can reduce challenging requirements in other parts of a boost-phase architecture, such as achieving adequate interceptor speed and acceleration. Improved manufacturing techniques are also reducing the costs of key sensor components, a trend that could also make boost-phase defense more feasible by reducing overall costs. Indeed, new optics, radars, and IR sensor production techniques are changing a number of assumptions that underpinned earlier cost estimates, opening a window for decisionmakers to contemplate different architectures for boost-phase defense.

DETECTION ENABLERS

Improvements in IR sensors, computational techniques, and satellite mapping could reduce detection delays for space-based IR sensors. By reducing ground clutter, such technologies could allow the employment of IR sensors that see to the ground, eliminating cloud-layer-induced detection delays.

New computational advancements could improve detection performance in the near term. Breakthroughs in machine learning software offer one pathway to improve ground clutter rejection.

Writing in 2012, the authors of a National Academies analysis reiterated the American Physical Society's 2003 assumption that see-to-ground detection would not be possible. That same year, researchers Krizhevsky, Sutskever, and Hinton developed an image-recognition algorithm that dramatically outperformed earlier systems, kickstarting the "AI revolution" observed today.⁹⁶ Hardware-accelerated convolutional neural networks now meet or exceed human performance in a variety of image recognition tasks.⁹⁷ Such advancements—leveraged for space-based missile detection—might enhance clutter rejection in ways unanticipated in earlier analyses.

A marked increase in available training data could enable such improvements. The wide proliferation of commercial satellite imaging capabilities—supplying high-resolution, on-demand imagery—offers a rich source of data for training clutter rejection algorithms.⁹⁸ Commercial providers are now capable of providing same-day imagery in multiple bands, offering the potential to rapidly document changing conditions. The confluence of these innovations—in machine learning software and large satellite imagery data sets—could promise near-term detection speed gains without fielding new satellites.

Advancements in IR sensor hardware might also enhance detection performance. The state of the art in IR sensors has advanced considerably since earlier assessments of boost-phase defense.⁹⁹ Today's short-wave infrared (SWIR) and mid-wave infrared (MWIR) FPAs eclipse past systems in sensitivity, easing the task of isolating useful signals from background noise.¹⁰⁰ Multiband FPAs, considered "very important in boost-phase for early missile typing and booster verification," have also matured, promising meaningful improvements in the probability of detection.¹⁰¹ Finally, improvements in FPA readout technologies—the circuitry located directly on the sensor—could allow for the rapid preprocessing of image data to reduce workloads for machine learning inference.¹⁰²

TRACKING ENABLERS

Such technologies will prove equally important for reducing the timeline between missile pitchover and successful tracking. These gains could be realized either by improving a system's spatial and time resolution or by reducing the time taken to compute a tracking solution.

Recent computational advancements widen both avenues for growth. A generalized improvement in computing power—orders of magnitude greater than when SBIRS entered service—might reduce the time needed to integrate a track. New computational photography techniques also promise improved resolution using existing IR sensors. Private sector researchers have demonstrated methods for extracting additional information from low-resolution sensors with novel demosaicing techniques.¹⁰³ These and other innovations might be leveraged to reduce the threshold for detecting changes in a missile's position.

Advancements in FPA technologies support these developments. Several varieties of multi-megapixel FPAs are now commercially available, allowing the fabrication of high-resolution or wide-field-of-view (WFOV) IR cameras.¹⁰⁴ In addition to increased pixel counts, current high-resolution sensors benefit from lower operating temperatures and improved, low-vibration cooling system designs, reducing jitter-induced limitations on resolving power.¹⁰⁵ Future early-warning satellites such as the Next-Generation Overhead Persistent Infrared (OPIR) are planned to have sensor resolutions greater than 64 megapixels, 10 times higher than assumed in the APS's 2003 assessment.¹⁰⁶ With diffraction-limited resolution for a geostationary, 30-cm-aperture SWIR sensor ranging as low as ~300 meters per pixel, future IR detection systems may be capable of resolving missile movements far sooner in flight.¹⁰⁷

COST ENABLERS

These and other technologies could also reduce the projected cost of a boost-phase defense system. Software and computational improvements, while intensive in human capital, are suited for extracting additional performance from existing investments. Many innovations in IR FPAs, moreover, have substantially reduced their acquisition cost.

High-performance IR sensors have notably declined in cost. Between 2001 and 2009, commercial producers made significant advancements in FPA manufacturing, with producers such as Raytheon, DRS, and Sofradir developing improved epitaxy techniques and scaling production by an average of 20 percent per year.¹⁰⁸ High-resolution mercury-cadmium telluride (HgCdTe) FPAs are now readily obtainable on commercial markets and have delivered a near-doubling of resolution since 2004.¹⁰⁹ At the same time, research in alternative FPA material systems has progressed rapidly, offering the potential for higher-yield production processes.¹¹⁰

Further developments in IR arrays promise enhanced resolution, detectivity, manufacturability, and high-temperature performance in the near to medium term.¹¹¹ The missile defense enterprise must update its assumptions given these cost and performance trends.

In addition, new technologies could allow for the fabrication of optical sensors—laser and lidar—at substantially lower cost. Commercial demand for autonomous driving and augmented-reality systems has driven substantial innovations in high-performance lidar systems.¹¹² Moreover, the recent commercialization of metalens technology—planar lenses made with nanostructured materials—could simplify the production of optics.¹¹³ Unlike traditional lenses, which require laborious polishing to manufacture, metalenses are thinner, require fewer exotic materials, and can be fabricated with processes similar to those used in semiconductor manufacturing.¹¹⁴

Finally, the maturation of gallium nitride (GaN) semiconductors promises an improved cost-performance ratio for radar systems. Compared to the preceding gallium arsenide (GaAs) materials used in radar amplifiers and switches, GaN supports considerably higher voltages, greater energy efficiencies, and frequency switching.¹¹⁵ Systems engineers could leverage these advantages to reduce the weight of radar sensors, allowing them to fit aboard smaller, stealthier, and more attritable aircraft that could patrol closer to potential launch sites. Alternatively, GaN technology could reduce tracking timelines by easing the range and resolution trade-offs inherent in radar system design. Though higher-frequency radars are more sensitive to atmospheric attenuation, they offer favorable spatial resolution—critical for boost-phase tracking. By increasing a radar's power, GaN could mitigate the range sacrifices that would stem from moving to a higher-frequency architecture.

TIME HORIZON

Many of these innovations could be incorporated into a defense system in the near to medium term. Commercially available IR sensors exceed the performance of earlier systems and are ready for implementation in future systems. GaN radar systems, meanwhile, have already entered military use, with the U.S. Marine Corps taking delivery of its first GaN radars in 2018 and the Army acquiring GaN-powered units in 2020.¹¹⁶ GaN systems are now planned for the next generation of U.S. ground-based radars and are widely available in consumer power supply products.¹¹⁷ The United States should leverage such next-generation sensor technologies if it chooses to realize a boost-phase missile defense layer.

The impacts of computational improvements on boost-phase sensing are less clear. Though significant hardware and software innovations have taken place, their potential for enhancing detection is unclear without public knowledge of their tracking algorithms and processing systems. What is apparent, however, is their considerable potential for future systems. New sensor systems with higher reliability, faster tracking, and higher data throughput are achievable with computing technologies available today.

CONCLUSION

In short, multiple avenues exist for increasing the performance and reducing the cost of boost-phase sensors. Several conditions are impossible to alter. The time taken for boosting missiles to pitch over cannot be changed, and the earth's curvature limits the maximum range of even an airborne sensor. But technological pathways exist to maximize performance within these bounds; improved clutter rejection and tracking algorithms, high-resolution IR sensors, and power-efficient radar all promise meaningful reductions in boost-phase detection and tracking. Though boost-phase missile defense remains a challenging technical problem, near- and medium-term sensing developments could make it more viable than before.

Appendix 3

Implications of Directed-Energy Technology

INTRODUCTION

The U.S. missile defense enterprise has long pursued directed-energy technologies as a means of defeating ballistic missiles. Unlike kinetic interceptors, directed-energy beams could reach targets near instantaneously, offer greater magazine depth, and decrease the relative cost of defending against advanced missiles. While directed-energy approaches could simplify requirements of boost-phase missile defense, they introduce new scientific, systems engineering, and operational challenges. Despite impressive advances in laser scaling, the near-term applicability of directed-energy technology to boost-phase defense remains uncertain.

REQUIREMENTS

Achieving a directed-energy capability for boost-phase missile defense requires lasers that approach or exceed the megawatt (MW) class. In addition to high power, such a system would need to produce beams with minimal divergence and high pointing precision.¹¹⁸

A directed-energy defense would also require atmospheric conditions conducive to long-distance optical transmission. Variations in atmospheric turbulence, haze, and other conditions have a substantial impact on the transmission of laser energy. This secondary requirement for favorable conditions has traditionally limited studies of directed-energy approaches to airborne platforms, which operate within a clearer portion of the atmosphere with extended lines of sight. This limitation, in turn, demands consideration of aircraft vibration and laser size, weight, and power (SWaP) performance.

PAST APPROACHES: CHEMICAL LASERS

Chemical lasers have represented the traditional approach to achieving megawatt-class output on an airborne platform. Beginning in the early 1990s, the Air Force and later the Missile Defense Agency funded the Airborne Laser (ABL) program, which used a chemical oxygen-iodine laser (COIL) to achieve an approximately 1-MW beam power.¹¹⁹

In a COIL, hydrogen peroxide and chlorine gas react to produce oxygen in an excited state, which transfers its energy (“pumps”) to an iodine amplification (“gain”) medium. The pumping process excites the atoms within the gain medium, causing them to release a cascade of photons with a similar wavelength—a laser beam. Unlike lasers that employ a solid gain medium, a COIL is efficient in dissipating waste heat, as the reaction products can be rapidly circulated out of the lasing cavity.¹²⁰

Despite their favorable power characteristics, COILs present logistical hurdles to realizing a workable concept of operations. The chemical reactants used for COIL lasing are exceptionally toxic and require complex subsystems to transport and store. The limited supply of chemicals available also limits their capacity for multiple engagements.

Consequently, ABL required a large platform—a modified 747 airliner—to support its subsystems. This introduced additional integration challenges. At its typical operating altitude, ABL was subject to higher turbulence and aerodynamic buffeting, necessitating the development of costly adaptive optics, pointing, and vibration isolation solutions. These conditions ultimately limited ABL’s range.¹²¹ In a 2010 test, ABL defeated targets in the short-range ballistic missile class “tens of kilometers” away—too close for a viable boost-phase defense.¹²² Concerns stemming from these complexity and performance issues ultimately scuttled the program by 2012.¹²³ Without significant improvements in SWaP, chemical approaches are unlikely to be feasible for cost-effective boost-phase missile defense.

EMERGING APPROACHES: ELECTRICALLY PUMPED LASERS

Following ABL’s cancellation, the air and missile defense enterprise has emphasized electrically driven laser development. Despite their lower beam powers, these lasers would not employ the volatile chemical fuels which hindered earlier concepts. Electrically driven lasers would also offer improved cost, beam quality, efficiency, and power-to-weight ratios over chemical lasers.¹²⁴

These classes of lasers typically employ an electrically powered diode to pump their gain media.¹²⁵ This represents a substantial improvement over earlier approaches, which used power-hungry flashlamps for pumping. With broad applications in the civilian and military sectors, diode pumping represents the dominant approach for powering an electrically driven high-energy laser.¹²⁶

Unlike ABL, a lightweight electrically powered laser might be operable from high-altitude platforms where atmospheric conditions are more favorable.¹²⁷ New classes of electrically driven lasers could also operate in more effective wavelengths of light or offer pulsing effects to increase intensity on the target—potentially doubling their efficiency over ABL.¹²⁸

Realizing these advantages would require significant advancements in electric laser beam power. Diode-pumped solid-state, combined-fiber, and alkali lasers have demonstrated power outputs from the tens to the low hundreds of kilowatts. To support the boost-phase mission, these lasers must scale to produce beams in the high hundreds of kilowatts or megawatt range.

DIODE-PUMPED SOLID-STATE LASERS

Several pathways are available for amplifying a diode-pumped laser. Diode-pumped solid-state (DPSS) lasers apply diode pumping to traditional solid-state laser designs. In a DPSS laser, diodes pump a slab of crystalline gain media, which amplifies the outgoing laser beam. Following the maturation of diode-pumping technology, DPSS lasers rapidly increased in power, reaching peak outputs of up to 100 kW by 2010.¹²⁹ However, the 100–300 kW range may already represent an upper bound for rapidly attainable performance.¹³⁰ Waste heat is particularly difficult to extract from the thick slabs of gain media in DPSS lasers, imposing a thermal bottleneck on their operation.

One approach to overcoming the thermal barriers of DPSS lasers is to employ multiple, smaller gain media slabs. In such a design, known as a distributed-gain laser, the laser beam passes through a consecutive series of slabs that amplify its power. The thinner cross-section of these liquid-cooled slabs allows them to shed heat more effectively, raising the system's power threshold.¹³¹ Due to these favorable characteristics, the Office of the Secretary of Defense (OSD) has identified distributed-gain lasers as a candidate for future scaling efforts.¹³²

Without introducing new cooling technologies or novel gain media, however, diode-pumped slab lasers may not be scalable to the powers required for boost-phase missile defense.¹³³ Ceramic gain media with improved thermal conductivity represents one approach to unlocking further performance uplifts.¹³⁴ Innovations in heat management—such as with liquid or cryogenic cooling—could extract additional gains.¹³⁵

Solid-state lasers offer a mature approach to high-powered lasing, and the use of distributed-gain designs and new gain media could allow users to extract the full potential of diode pumping. It remains unclear whether distributed gain lasers can scale to the upper-megawatt powers desirable for boost-phase applications.¹³⁶ Other approaches to lasing—using glass fiber or alkaline gas gain media—might offer higher performance potential, but they possess varying degrees of technical readiness.

COMBINED FIBER LASERS

Combined fiber lasers could offer more headroom for scaling to strategic power levels. Frequently used in commercial applications, diode-pumped fiber lasers use doped glass fibers as a gain medium, offering 1.5 to 2 times higher efficiency and more surface area for active cooling than solid-state lasers.¹³⁷ Commercial sector investment in fiber lasers has accelerated the pace of technology development. Correspondingly, the beam powers of individual fiber lasers have grown from 3 kW in 2008 to over 15 kW in 2018, and multiple avenues exist for further scaling single-mode output.¹³⁸

Developers scale fiber laser power by combining multiple lasing units to create a single powerful beam.¹³⁹ Technical challenges in beam combination represent the largest bottleneck in producing a high-energy fiber laser weapon. The most efficient approach, termed “coherent combination,” joins multiple beams in the same phase to create a more powerful beam. Yet coherently combined lasers remain difficult to scale because the short wavelengths of laser light make it difficult to precisely match their phase.¹⁴⁰

A simpler approach is to combine lasers incoherently, either by shining separate beams in parallel or by joining beams of different wavelengths without matching their phase. The second approach, termed spectral combination, is more effective than simple incoherent combination in reducing

destructive interference. While early efforts to prototype laser weapons used simple incoherent combination, recent programs have emphasized spectral combination as the preferred approach.¹⁴¹ Spectrally combined fiber lasers have already demonstrated beam powers of up to 100 kW, exceeding the 30 kW recently achieved with coherently combined methods.¹⁴² Spectrally combined approaches represent the most likely pathway to realizing ~500-kW fiber lasers in the nearer term, while coherent combination promises higher upper bounds on performance.¹⁴³

DIODE-PUMPED ALKALI LASERS

Invented in 2003, diode-pumped alkali lasers (DPALs) offer a third pathway for scaling to strategic power levels. DPALs possess considerable scaling potential and represented a major focus of the Missile Defense Agency's (MDA) laser maturation effort.¹⁴⁴ By using a circulating loop of alkali vapor as a gain medium, DPALs combine the heat-dissipation advantages of COILs with the efficiency and magazine depth of solid-state systems.¹⁴⁵ Compounding these advantages is the exceptional beam quality and quantum efficiency of DPALs, which allow for reduced power consumption and heat generation.¹⁴⁶ The combination of these characteristics places the theoretical limit of DPAL performance beyond the single-megawatt range, offering considerable headroom for growth.

Despite their theoretical potential, DPALs present many unknowns for future scaling efforts. A central challenge concerns the narrow energy absorption bands of alkali-vapor gain media. To match the diode pumping wavelengths with the alkali's absorption wavelengths, researchers have attempted to mix buffer gases, pressurize the lasing chamber, or filter the pumping diodes, introducing downstream thermal, efficiency, and complexity issues.¹⁴⁷

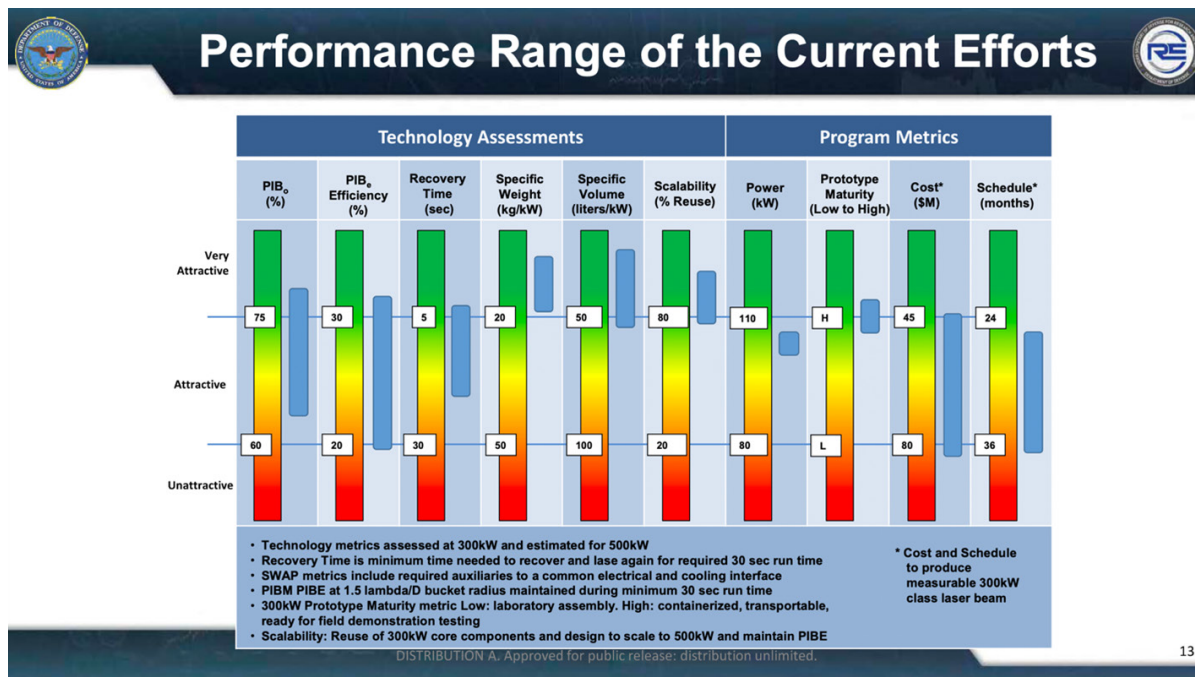
Nonetheless, DPALs remain a focal point for OSD and MDA research. From 2010 to 2020, MDA and Lawrence Livermore National Laboratory pursued a DPAL scaling effort, achieving power levels of 3.91 kW in 2013, 10 kW in 2014, 16 kW in 2015, and, most recently, 30 kW.¹⁴⁸ In 2020, OSD issued a request for information to transition DPAL technology, with the aim of scaling to 300 kW power levels by FY 2024.¹⁴⁹

FREE ELECTRON AND PULSED LASERS

Alternative laser technologies, while less mature, might also offer unique characteristics to exploit. Free-electron lasers (FELs) accelerate electrons into a magnetic oscillator to generate laser beams; such a system could scale to megawatt levels and actively adjust its wavelength to suit different atmospheric characteristics. However, today's FEL designs weigh considerably more than diode-pumped lasers and occupy large volumes, limiting them to shipboard applications.¹⁵⁰ Moreover, FEL systems remain at a low technical readiness level. Given these constraints, this approach has largely fallen out of favor as diode-pumped lasers mature.

Ultrashort pulse lasers could present another avenue for realizing lethal effects against boosting missiles. Unlike traditional, continuous-wave lasers, ultrashort pulse lasers generate successive nanosecond- to femtosecond-long bursts of high energy.¹⁵¹ With peak intensities of up to 1 terawatt, an electrically powered pulsed laser would cause "non-linear effect[s]" in the surrounding air that would allow propagation without losses from atmospheric turbulence.¹⁵² This could reduce the need for costly adaptive optics and sensors to compensate for atmospheric conditions.

Figure 19: Recent Technological State of the Art in HPM Technologies



Source: Thomas J. Karr, “The OSD HEL Laser Scaling Initiative” (DEPS Annual Science and Technology Symposium, West Point, NY, March 10, 2020)

A pulsed laser would also offer different lethality mechanisms compared to continuous-wave approaches. Their high peak intensities would allow them to erode—rather than melt—a target surface, vaporizing small amounts with each pulse. Moreover, pulsed lasers generate columns of conductive plasma around their beams that could transmit electronic interference. Army researchers first demonstrated this phenomenon in 2012, arcing electricity to a vehicle located a short distance away. Finally, a high-energy laser pulse could be set to decompose into blinding flashes of light, dazzling adversary sensors.¹⁵³

This multimission capability has attracted MDA and Army interest. In February 2021, MDA issued a request for information on ultrashort pulsed laser weapons.¹⁵⁴ Though such lasers remain in an early stage of development, they offer promising characteristics for simplifying future laser weapons systems.

RECENT DEVELOPMENTS

MDA, OSD, and the services have maintained several efforts to mature laser technologies and platforms. In recent years, the Office of the Under Secretary of Defense for Research and Engineering (OUSD (R&E)) assumed responsibility for executing defense-wide laser scaling science and technology (S&T) development. While MDA previously maintained a separate program for strategic laser maturation, it has not requested laser S&T funding for FY 2022. MDA previously received \$109 million for laser S&T in FY 2020 and was appropriated \$42 million to continue DPAL development after requesting no funding in FY 2021.

Under its High Energy Laser Scaling Initiative (HEL SI), OSD plans to mature several 300- and 500-kW laser systems by the mid-2020s.¹⁵⁵ In FY 2021, Congress appropriated \$113 million to OUSD (R&E) to demonstrate and transition a 300-kW high-energy laser. For FY 2022, OSD has requested \$107 million to

continue its laser scaling effort, \$46 million for applied research on diode pump sources, beam control, and laser propagation and effects, and \$15 million for basic research grants transferred from an earlier Air Force program.¹⁵⁶ Under these initiatives, OSD aims to demonstrate a 300-kW solid-state laser by FY 2022 and 500-kW electrically driven lasers by FY 2024.¹⁵⁷

Concurrent with these efforts are service-level initiatives to operationalize high-energy laser technologies. Between 2008 and 2014, the U.S. Navy demonstrated an incoherently combined fiber laser with 33-kW peak power, and in 2017, the Army took delivery of a 60-kW-class laser testbed.¹⁵⁸ By 2018, the Army had begun developing multiple laser prototypes, including a 100-kW-class spectrally combined laser, and the Air Force took delivery of a podded laser system in early 2021.¹⁵⁹ In coming years, the joint services plan to field several fiber or solid-state systems in the 50 to 300 kW range for dazzling and defense against small boats, artillery rockets, mortar rounds, aircraft, shells, and battlefield drones.¹⁶⁰

Table 14: Review of DOD Laser Scaling Efforts

Program	Contractor	Demonstrated Power (kW)	Scaling Goal (kW)	Date	Sponsor
Spectrally Combined Fiber Laser (SCFL)	Lockheed Martin	100 kW	300 kW	2022	OSD
Distributed Gain Laser (DGL)	General Atomics	150 kW	300 kW	2022	OSD
Coherently Combined Fiber Laser-1 (CCFL)	Nutronics (nLIGHT)	30 kW	100 kW Maturation, then 300 kW	2022	OSD
Coherently Combined Fiber Laser-2	Boeing	50 kW	100 kW Maturation	2020	MDA
Diode Pumped Alkali Laser (DPAL)	LLNL	30 kW	Technology maturation	2020	MDA

Source: Adapted from Karr, “The OSD HEL Laser Scaling Initiative.”

CONCLUSION

Since ABL’s cancellation, electrically powered laser technology has advanced rapidly, especially in fiber lasers and other systems with commercial applications. Though slab and spectrally combined fiber laser methods appear closest to offering tactical utility, the approaches needed for achieving megawatt-level power have not yet been demonstrated.

The technologies for achieving lasers relevant for boost-phase defense—advanced pointing technologies, low-SWaP subsystems, coherent beam combination, diode-pumped alkaline lasers, and pulsed systems—have few commercial applications and will require sustained government investment to mature. Despite MDA’s cyclical funding and divestment of directed-energy programs, congressional

leadership has retained its interest in strategic laser scaling.¹⁶¹ The technological pathway for enhancing tactical directed-energy capabilities is clear. The consistency of program management, pace of operational evaluations, and depth of legislative backing will determine whether they can scale to strategic applications.

Appendix 4

Implications of Advanced RPA Technology

Several prospective architectures for boost-phase missile defense employ remotely piloted aircraft (RPA) as basing platforms. Airborne basing is advantageous for sensors and interceptors, promising longer lines of sight and the potential for lowered kinematic requirements compared to surface-based systems. Unpiloted aircraft—specifically those optimized for high-altitude, long-endurance (HALE) missions—are especially suited for these roles, presenting longer endurance on station and lower cost and risk to personnel.

Advancements in remotely piloted and uncrewed aircraft technologies might make future boost-phase architectures more affordable. In 2012, the National Research Council estimated that three continuous orbits of Predator RPAs equipped with infrared (IR) sensors could cost up to \$5 billion over a 20-year lifecycle.¹⁶² Aircraft which could loiter longer would reduce the numbers needed to maintain continuous patrols. Moreover, higher operating altitudes would benefit both sensors and weapons, offering more favorable atmospheric conditions and a higher launch position for kinetic interceptors.

Various technological trends—increasing engine efficiency, structural controls, and advanced materials and structures—could help lower RPA operating costs.¹⁶³ Today’s Global Hawk RPA, developed in the 1990s, can loiter for 24 hours at an 18 km altitude, with standoff distances of up to 1,200 nautical miles.¹⁶⁴ Meanwhile, recent DOD studies have investigated systems with weeks-long endurances, reporting that up to 30 km loiter altitudes were possible “even in the near term.”¹⁶⁵ Future boost-phase missile defense sensor systems might leverage these near-term advancements to achieve better performance. With the burgeoning interest in HALE RPA technologies, new approaches are possible—approaches that earlier studies had not contemplated.¹⁶⁶

Table 15: Select Technology Enablers for High-Altitude RPAs

Discipline	Technology Pathways
Aerodynamics	<ul style="list-style-type: none"> ▪ Advanced laminar wing designs ▪ Variable camber ▪ Design for unique Re and CL requirements ▪ Active flow control ▪ High aspect ratio wings
Propulsion	<ul style="list-style-type: none"> ▪ Improved fuel consumption (25–30 percent via weight reduction; 20–30 percent via turboprop, turbofan, piston efficiency)
Structure/control	<ul style="list-style-type: none"> ▪ Weight reduction of 15–25 percent ▪ Extensive use of composites ▪ Reduced number of parts ▪ Smart structures ▪ Aeroelastic tailoring

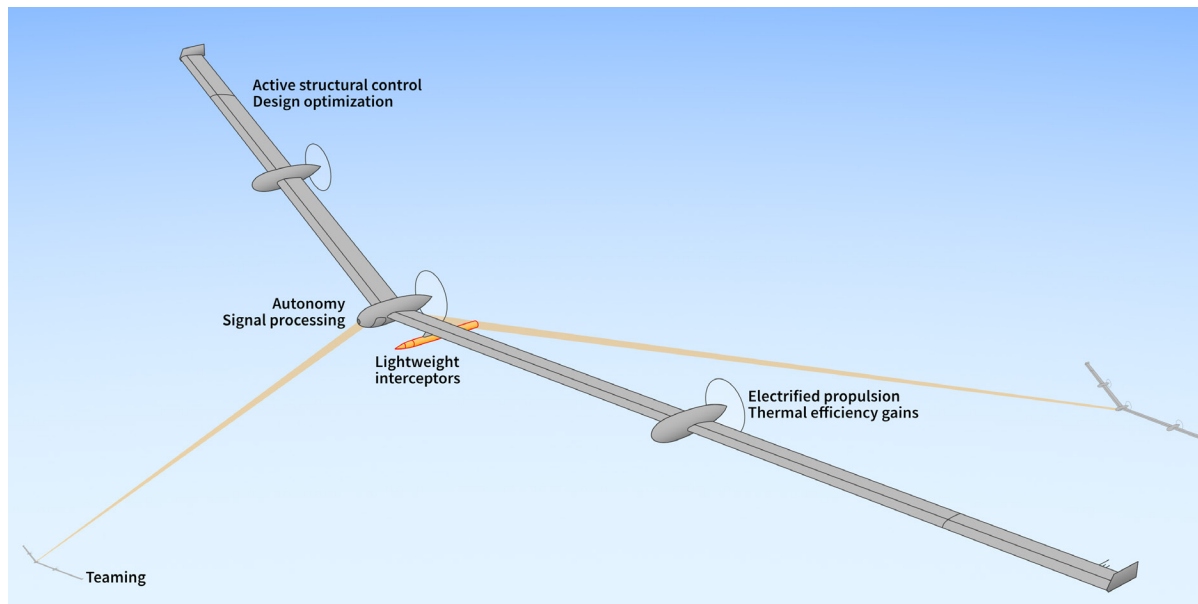
Source: Adapted from S. Tsach, “Development Trends for next generation UAV systems,” AIAA Infotech@Aerospace 2007 Conference and Exhibit, Rohnert Park, CA, May 7–10, 2007.

PROPULSION

Engine improvements are one domain where designers could realize loiter-time improvements. Since the Global Hawk’s introduction in 1998, turbofan engine efficiencies have increased by 7 to 10 percent per decade, with a projected 30 percent headroom for additional growth.¹⁶⁷ New fossil-fuel-driven engine technologies—new generations of geared turbofans, higher-bypass turbofans, improved high-temperature materials, and additive manufacturing techniques—could further increase HALE RPA endurance.¹⁶⁸ Embracing new engine architectures might also enable more radical shifts; open-rotor fan designs and other propulsion types could open additional pathways for growth.¹⁶⁹

In the longer term, new engine technologies and power sources might promise other pathways to increase endurance.¹⁷⁰ Battery- or hydrogen-electric propulsion systems, while currently heavier than combustion-powered alternatives, present unique efficiencies for unmanned systems. Liquid hydrogen fuels offer high energy-to-mass ratios and could allow for the use of more efficient electrical motors. Moreover, techniques to reduce the weight of hydrogen tanks could make such approaches viable for larger aircraft.¹⁷¹ Several vendors have already demonstrated hydrogen-powered RPAs with exceptionally long endurance.¹⁷² The maturation of these technologies could improve the cost and operational feasibility of airborne boost-phase defenses.

Figure 20: RPA Technology Enablers



Source: CSIS Missile Defense Project.

Photovoltaic power sources could also be viable for smaller systems, enabling exceptionally long endurance. Since 2012, photovoltaic panels have increased in efficiency, while fuel cells and batteries have declined in weight.¹⁷³ By 2018, commercial players had already demonstrated new generations of solar-powered RPAs to provide wireless networking services, with endurance times measured in weeks.¹⁷⁴ Though future iterations of these systems are unlikely to provide Global Hawk-like payload capacity and power generation, future avionics and sensors will impose significantly lower power and mass penalties. Future boost-phase sensor architectures may not employ single orbits of heavy, high-end sensors but constellations of long-endurance, electrically powered aircraft with smaller, lighter, and networked sensors.¹⁷⁵ Favorable trends in sensor and computing technologies could converge with RPA advancements to facilitate new approaches to boost-phase detection and tracking.

AEROSTRUCTURES, FABRICATION, AND DESIGN

New approaches to aircraft design and construction could also enable endurance gains. Improved computational modeling has allowed designers to optimize aircraft structures, reducing weight with existing materials.¹⁷⁶ Contemporary understanding of high-altitude wing stresses has also advanced since the Global Hawk and Predator systems' first flights. Active structural control techniques, for example, could reduce the weight of HALE RPA wings by up to 20 percent.¹⁷⁷

Mature composite fabrication techniques promise enhanced strength, weight, and flexibility. Electrically driven control surfaces, landing gear, and other subsystems could reduce weight and increase reliability. Improved airfoils could promise more efficient flight, and modern software development and product lifecycle management approaches could further reduce acquisition costs.¹⁷⁸ These, combined with improvements in flight profiles, lighter-weight avionics, and other innovations, would allow for the development of longer-endurance HALE RPAs in the near term.

CONCLUSION

Despite promising technical developments, the DOD has not yet fielded a large next-generation HALE RPA. Significant prototyping efforts, such as the Boeing Phantom Eye or AeroVironment Global Observer, failed to reach maturity due to operational and fiscal constraints. DARPA's Vulture program, meanwhile, has refocused from prototyping RPAs to maturing long-lead propulsion technologies. Scientific and commercial actors have also sustained recent investments in this space. From 2016 to 2018, Meta (Facebook) Inc. flight-tested a prototype 90-day-endurance RPA.¹⁷⁹ In 2020, the Alphabet and Softbank corporations flight-tested a HALE RPA, evolved from an earlier AeroVironment design, for use as a telecommunications node.¹⁸⁰ NASA and other actors have similarly invested in long-endurance aerial vehicles. Given this progress, the defense enterprise should review new RPA technologies for missile defense sensors and weapons.¹⁸¹

In short, MDA—and the DOD writ large—should reevaluate existing HALE RPA technologies for missile defense sensing, communications, or engagement. Longer-endurance, higher-altitude platforms could change current assumptions about the cost, viability, and performance of boost-phase missile defenses. Larger constellations of smaller, cheaper HALE RPAs, or next-generation successors to Global Hawk-like platforms, could make an airborne boost-phase defense more viable.

Appendix 5

Historical Overview of Boost-Phase Missile Defense Efforts

Nearly every major U.S. ballistic missile defense architecture of the past 50 years has included, at least on paper, an aspirational boost-phase layer. These efforts began as early as 1960, when the Department of Defense (DOD) initiated the Ballistic Missile Boost Intercept (BAMBI) project. BAMBI envisioned a constellation of missile-armed satellites to intercept boosting missiles.¹⁸² Since then, the United States has explored numerous other concepts across multiple domains, including land-, sea-, air-, and space-based approaches.

Despite this ambition, no boost-phase programs have progressed past the early development stages. While each had unique circumstances surrounding their cancellation, their examination uncovers some common challenges.

- Technological hurdles, particularly with programs using directed energy;
- Operational shortcomings, such as challenging basing requirements or low survivability;
- Inconsistent political and budgetary support; and
- Treaty restrictions and unclear strategic justification.

The history of missile defense development has a natural cleavage between the Anti-Ballistic Missile (ABM) Treaty and post-ABM Treaty eras. But apart from treaty restrictions, the technical, budgetary, and policy hurdles to boost-phase defense represent a throughline that bridges both eras.

ABM TREATY ERA

SDI and GPALS

Under the Strategic Defense Initiative (SDI), the Reagan administration emphasized boost-phase missile defense. Reinvigorating concepts from the BAMBI program, the first phase of SDI included

large numbers of space-based interceptors for boost- and midcourse-phase defense along with orbiting sensors. While the Reagan administration envisioned such a system complementing SDI's midcourse interceptor architecture and "destroy[ing] a small fraction" of incoming Soviet missiles, the boost-phase system remained a critical element in SDI's Phase One architecture planned for 1995 to 2000.¹⁸³

SDI Phase Two, projected for deployment between 2000 and 2010, would incorporate various sensing satellites and field more advanced space-based interceptors. It also proposed space-based laser weapons for boost-phase engagement. These efforts were intended to eventually supplant an architecture based on kinetic interceptors, which SDI planners viewed as imperfect. Though the DOD deemed efforts to miniaturize kinetic interceptors "promising," SDI's architects concluded that "the affordable mass production of rocket-carrier vehicle systems for space deployment maintenance would remain a major challenge."¹⁸⁴

Despite SDI's optimism over future boost-phase defenses, the program reduced emphasis on space-based interceptors by the late 1980s. In October 1988, the Strategic Defense Initiative Office (SDIO) cut the number of orbital interceptors in half and increased its planned procurement of land-based midcourse interceptors by 70 percent.¹⁸⁵ Upon entering office in 1989, the George H.W. Bush administration further recalibrated U.S. missile defense ambitions to focus on defeating limited ballistic missile threats, cutting SDIO's five-year funding timeline from \$40 billion to \$33 billion.¹⁸⁶ The surviving space-based interceptor program, named Brilliant Pebbles, continued to perform static and hover tests through this period.¹⁸⁷

The Brilliant Pebbles initiative became increasingly unpopular in Congress.¹⁸⁸ In August 1990, the U.S. Senate voted to shift SDI funding to focus on ground-based interceptors, cutting Brilliant Pebbles funding from the Bush administration's requested \$329 million to \$129 million for FY 1991.¹⁸⁹

By 1991, the Bush administration unveiled the Global Protection Against Limited Strikes (GPALS) missile defense architecture, which reoriented SDI planning toward limited ground-based missile defenses and a 1,000-interceptor Brilliant Pebbles constellation.¹⁹⁰ Congressional opposition to Brilliant Pebbles continued to mount. To critics, Brilliant Pebbles was too expensive, destabilizing, and technologically risky to put into service.¹⁹¹ Following the Soviet Union's collapse, the House of Representatives questioned the continued necessity of Brilliant Pebbles and voted to slash the SDI budget from \$4.6 billion to \$2.7 billion and eliminated the Brilliant Pebbles program in May 1991.¹⁹² Congress eventually compromised on a defense budget of \$4.15 billion for SDI in 1992 but omitted any provisions to develop Brilliant Pebbles.¹⁹³ Following its inauguration in 1993, the Clinton administration reoriented its missile defense strategy toward theater missile defense, canceling Brilliant Pebbles in December 1993.¹⁹⁴

Despite years of effort, SDI and GPALS failed in implementing space-based boost-phase missile defense. The programs failed to address fundamental questions over technical feasibility, strategic need, schedule, and cost. Meanwhile, the technologies envisioned as eventually replacing Brilliant Pebbles—space-based directed-energy weapons—remained in their infancy. As the Soviet threat disappeared, it became increasingly difficult to justify an expensive, long-term boost-phase project to Congress or the broader public. By the Clinton administration, the United States had shifted its strategic emphasis from national to regional missile defense.¹⁹⁵ Space-based boost-phase defenses had little place in this vision. Coupled with concerns over the militarization of space, ABM Treaty compliance, and government spending, even a downsized program could not survive.

Airborne Boost-Phase Architectures for Theater Defense

Following Iraq's use of SCUD missiles in the Gulf War, the United States initiated several boost-phase defense efforts to counter regional threats such as Iraq, North Korea, and Iran. In October 1992, the Ballistic Missile Defense Organization (BMDO), the successor organization to SDIO, commenced a one-year study on boost-phase intercept.¹⁹⁶ Many of these 1990s-era attempts involved air-launched kinetic interceptors.

- **Peregrine / Airborne Interceptor**

One proposal, named Peregrine, envisioned kinetic interceptors launched from manned combat aircraft. The two-stage Peregrine missile was designed for carriage on the B-52, but the project office also proposed a slower, single-stage variant for loading on fighter aircraft. Both interceptors would integrate critical technologies developed under other BMDO programs, such as propulsion components from the Standard Missile-3.¹⁹⁷

In 1993, the BMDO evolved the Peregrine concept into the Airborne Interceptor Program, which would demonstrate a boost-phase interceptor on an airborne platform. After issuing operational requirements, BMDO planned to produce two fighter-based interceptors: a two-stage, 621-kg, 4.3 km/s missile for the Air Force and a single-stage, 334-kg, 3.1 km/s system for the Navy. Though the Air Force Scientific Advisory Board concluded in 1995 that the concept was ready for near-term procurement, the project was later canceled.¹⁹⁸

- **Raptor/Talon**

A second BMDO concept, the Responsive Aircraft Program for Theater Operations and Theater Applications – Launch on Notice (RAPTOR/TALON), aimed to mount a 20-kg, 3 km/s interceptor (TALON) on a high-altitude RPA (RAPTOR). According to a 1993 report, RAPTOR would either be a solar- or gasoline-powered unmanned aircraft manufactured from composite materials.¹⁹⁹ TALON, the interceptor, would be a liquid-fueled “high endoatmospheric or exoatmospheric” missile with a domed seeker window and aerospike to prevent excessive window heating.²⁰⁰

In November and December 1993, Lawrence Livermore National Lab conducted static engine tests of the Advanced Single-stage Rocket Interceptor Demonstration (ASTRID), a prototype for the TALON propulsion system.²⁰¹ In February 1994, Lawrence Livermore flight tested the 23-kg ASTRID rocket for the first time, successfully demonstrating the performance of its novel liquid-propellant motor.²⁰² The original Raptor/Talon program ended in 1994.²⁰³

In 1995, the Office of the Secretary of Defense conducted a study of boost-phase intercept concepts, concluding that an RPA-based kinetic boost-phase intercept system could provide the lowest-risk option for defeating theater ballistic missiles in the near term. The study panelists concluded that such an architecture should integrate a high-altitude RPA and 3 km/s interceptor—a speed low enough to avoid the technological challenges associated with seeker window cooling. BMDO initiated a second RPA boost-phase intercept program in 1996, which largely remained in the conceptual phase through 1999.²⁰⁴

▪ Israeli Boost Intercept System

In 1994, Israel completed a feasibility study to develop the Israeli Boost Intercept System (IBIS), an airborne boost-phase architecture.²⁰⁵ Under the IBIS concept, Israel would develop or procure a HALE RPA and the Moab, a Python-4 missile modified for boost-phase missile defense.²⁰⁶ Candidate launch platforms for the Moab included the F-15I and the HA-10, Hermes 1500, and Global Hawk RPAs. The Rafael-built Moab system would have a maximum velocity of 1.5 to 2 km/s and maximum range of 80 to 100 km. The Israelis chose such a low speed to reduce missile unit costs, as higher speeds would necessitate the production of infrared seeker window cooling systems for the interceptor.²⁰⁷ Due to competition with other missile defense priorities, IBIS never received any significant funding and Israel reoriented the program toward RPA-based left-of-launch operations in 2000.²⁰⁸ From 1994 to 1999, Israel and the United States spent roughly \$30 million on IBIS feasibility studies.²⁰⁹

POST-ABM TREATY

This pattern of aspiration-experimentation-cancellation continued following withdrawal from the ABM Treaty in 2002. The George W. Bush administration pursued several boost-phase efforts, including space-based interceptors and space-based directed-energy platforms. Many of these efforts were short-lived and ended after 2004. The most mature boost-phase programs were the Kinetic Energy Interceptor (KEI) and the Airborne Laser (ABL). KEI was a surface-launched interceptor program discontinued in 2009. ABL, effectively canceled by 2011, demonstrated the ability to destroy a boosting ballistic missile target with a high-powered chemical laser. Technical and operational hurdles and cost overruns beset both programs.

Airborne Laser

ABL represented one of the largest U.S. boost-phase defense programs. The first effort began in the 1970s, when the Airborne Laser Laboratory (1971–1983) shot down five AIM-9 missiles and one BQM-34 drone using an onboard laser.²¹⁰ By 1992, the Air Force had solicited proposals to study “the implications of installing a high energy laser and beam control system on a large, high-performance airframe,” aiming for a demonstrator system with a 100 km range.²¹¹ In 1995, the Air Force and Pentagon demonstrated several technological milestones critical to the program’s survival.²¹² Of the many boost-phase programs investigated by the Air Force, only ABL received full funding through the DOD’s 1995 five-year budget plan. ABL became a major acquisition program in November 1996.²¹³

BMDO officials stated to Congress that the Air Force would field an ABL demonstrator by 2002 and reach an initial operational capability by 2006.²¹⁴ In 1996, defense contractors successfully tested a prototype chemical oxygen-iodine laser (COIL) and beam control system for ABL, winning a \$1.1 billion contract for the system’s Program Definition and Risk Reduction phase.²¹⁵ In May 1998, ABL passed its Preliminary Design Review, receiving the formal designation as the YAL-1A Attack Laser.²¹⁶

Operational, technical, and political challenges began to slow the program. In 1997, the Government Accountability Office (GAO) expressed concerns over the program’s failure to collect optical turbulence measurements or validate its beam control system.²¹⁷ Members of Congress also expressed concern over the ABL platform’s core operational concept. Lawmakers cut \$25 million from the Air Force’s \$292 million funding request for FY 1999.²¹⁸ In April 2000, ABL completed its first Critical Design Review.²¹⁹

On July 18, 2002, ABL took its maiden flight, which took place without the laser weapon installed. At the same time, the BMDO warned that the program was likely to face cost overruns and delays.²²⁰ Speaking to Senate appropriators in early 2003, MDA director Ronald Kadish testified that ABL could run from 15 to 20 percent over initial cost estimates.²²¹ In May 2004, GAO reported that ABL had cost more than double its original projections and that costs could rise between \$431 and \$943 million through the program's early flight tests.²²² Facing these unanticipated technical challenges, BMDO—reorganized as MDA—restructured ABL. It added \$1.47 billion in funding and canceled plans for a second aircraft and ground test site.²²³ In January 2005, MDA projected that ABL would attempt a target intercept in 2008.²²⁴

Costs and delays continued to mount.²²⁵ In 2005, GAO projected that the first ABL unit's construction cost would exceed \$3 billion.²²⁶ Moreover, ABL faced competition from alternative boost-phase missile defense programs such as KEI.²²⁷ By February 2006, the Air Force deferred the purchase of five additional ABL aircraft and recategorized ABL as a demonstrator project, again delaying an ABL weapons test.²²⁸ In 2008, MDA tested the COIL inside the grounded ABL aircraft, firing the laser against an onboard measurement and calibration system.²²⁹ That same year, ABL fired its first shot through its nose turret, firing two sub-second bursts on the ground.²³⁰

Upon assuming office, the Obama administration carried out a broad review of ongoing missile defense policy programs. In April 2009, it restructured MDA, cutting \$1.4 billion from its budget. It also further recategorized ABL as a technology demonstrator effort, the Airborne Laser Test Bed (ALTB).²³¹

On February 3, 2010, a flying ALT B destroyed its first target, a liquid-fueled sounding rocket flying over Point Mugu on the California coast. One week later, ALT B tested its laser against a solid-fueled sounding rocket, which it “successfully engaged” but deliberately did not destroy.²³² Despite these test successes, problems persisted in achieving the range and survivability necessary for fielding an airborne laser system. Congress ceased funding the program in late 2011.²³³

Despite significant budgets, ABL could not overcome its fundamental technical and operational limitations. Air Force planners consistently underestimated the ABL program's risk. Engineers faced difficulties integrating the 1980s-era chemical laser—purportedly a mature technology—with the Boeing 747 airframe and encountered unexpected challenges in attempting to scale its power. Every subsystem of ABL—the adaptive mirror, turret, illumination laser, and chemical laser modules—was a technical undertaking; combining them posed a considerable systems integration challenge.

These challenges came alongside skepticism over ABL's operational utility. As early as the late 1990s, Congress raised concerns that the 747-based ABL would not be survivable enough to conduct theater missile defense. Moreover, the aircraft proved more expensive to sustain than anticipated, and the operational requirements for ABL were extreme. As Secretary of Defense Robert Gates noted in 2009:

It would have required buying a fleet of about twenty 747s. And the other difficulty is that they have to orbit close enough to the launch site so that, if it were Iran, the orbit would be almost entirely within the borders of Iran, and if it were against North Korea, it would be inside the borders of North Korea and China. And I just think operationally that's not going to happen.²³⁴

What was intended to become a path-breaking theater defense system instead became the Air Force's second-largest procurement effort behind the F-22 fighter aircraft. Despite its promise, ABL lacked the technical maturity to operationalize into a functional weapons system.

Kinetic Energy Interceptor

Initiated in 2002, KEI was to be a testbed for kinetic boost-phase intercept and a hedge against the ABL program's potential failure. MDA envisioned KEI as a sea- or land-based interceptor comprised of a high-velocity booster with a specialized kill vehicle.²³⁵

After a \$20 million concept definition effort, MDA awarded its first eight-year contract to develop KEI in December 2003.²³⁶ In its initial configuration, KEI would consist of an air-transportable mobile launcher and a battle management and communications system. According to MDA, a KEI battery would consist of five launchers, each with a launch trailer and six Humvees equipped with command and control, communications, and fire control systems.²³⁷

The three-stage KEI interceptor would use a 0.9-m, 7,400-kg booster to reach a maximum velocity of approximately 6 km/s. KEI's kill vehicle was a hybrid of two off-the-shelf components: the two-color seeker from the Standard Missile-3 kill vehicle and the Divert and Attitude Control System (DACS) from the Ground Based Interceptor's Exoatmospheric Kill Vehicle.²³⁸ MDA planned initial flight tests for 2008, with full deployment expected between 2010 and 2012.²³⁹

Skeptical of KEI's terrestrial basing mode, its concept of operations, and its overlap with the competing ABL program, lawmakers funded KEI at lower levels than MDA proposed.²⁴⁰ In FY 2003, KEI was funded at \$99.6 million—less than the \$198.2 million projected in its FY 2003 Future Years Defense Program. From FY 2003 to FY 2007, MDA continually overestimated the level of funding available for the program, projecting growing budgets that never materialized.²⁴¹

In early 2005, MDA restructured KEI to focus on ascent- and midcourse-phase defensive capabilities and reduced its requested funding for the program. Facing additional cuts from Congress, MDA proposed that KEI could be modified to provide a terminal defense capability for ships.²⁴² Legislators ultimately funded KEI for the \$215 million requested in MDA's FY 2006 budget.²⁴³

Persistent lack of funding and technical risks associated with booster and seeker algorithm development would cause the KEI program to progress "slower than anticipated" for the remainder of its life.²⁴⁴ After a 2005 decision to refocus the program on the land-based KEI system, the program constrained its scope to developing the KEI booster.²⁴⁵ While the program completed fire control system demonstrations in 2005, multiple static motor tests of Stages 1 and 2, and several high-speed wind tunnel tests, the program canceled its development of mobile launchers due to a lack of funding.²⁴⁶

In May 2009, the Obama administration announced KEI's cancellation. According to the administration, "considerable technical issues . . . such as repeated first and second booster case failures, thrust nozzle concerns, overheating of avionics, thermal battery canister failure, and C-band transponder failure" contributed to the decision.²⁴⁷ Moreover, the administration expressed concern over the individual unit cost of the KEI interceptor, which was "estimated at more than \$50 million per unit."²⁴⁸ Likewise, administration officials noted land basing challenges and characterized the interceptor as too large to base at sea.²⁴⁹ Congress approved the program's cancellation in mid-2009.²⁵⁰

Network-Centric Airborne Defense Element and Air-Launched Hit-To-Kill

Proposals for airborne boost-phase intercept would re-emerge intermittently through the mid-2000s. In April 2006, MDA began reviewing two additional concepts for fighter-based airborne interceptors: the Network-Centric Airborne Defense Element (NCADE) and Air-Launched Hit To Kill (ALHTK).²⁵¹ Designed to defeat short- and medium-range ballistic missiles, NCADE was a modified AMRAAM missile with a high-performance liquid-fueled second stage.²⁵² While its speed and burn time were left unspecified, NCADE would weigh 150 kg and possess identical external dimensions to the AMRAAM.²⁵³ ALHTK, meanwhile, was a proposed air-launched variant of the PAC-3 interceptor.²⁵⁴

Between July 2006 and January 2007, MDA awarded a \$1 million risk reduction and concept definition contract for NCADE and a \$3 million contract for ALHTK.²⁵⁵ In May 2007, Raytheon and Aerojet successfully tested NCADE's liquid-fueled propulsion system, which would use an exotic new monopropellant fuel.²⁵⁶ In December 2007, the Missile Defense Agency tested NCADE's seeker technologies, downing an Orion sounding rocket using two air-launched AIM-9X air-to-air missiles.²⁵⁷ NCADE would use an identical seeker to the AIM-9X, installed with an aerospike to minimize sensor window heating.²⁵⁸

In September 2008, MDA called for "far-term" research into miniaturized agile kill vehicles and infrared seekers for air-launched boost-phase missile defenses.²⁵⁹ Due to funding constraints, neither NCADE nor ALHTK became a program of record.²⁶⁰

Extended Range Weapon

In October 2018, the U.S. Air Force and MDA initiated the Extended Range Weapon (ERWn), a rapid prototyping project to develop a "multirole" air-launched interceptor. For FY 2020, the Air Force and MDA requested \$246 million and \$10 million, respectively, for ERWn design, testing, integration, and risk-reduction efforts.²⁶¹ The program quickly collapsed after the Air Force and defense industry failed to negotiate contract terms. Shortly after May 2019, the program ended after both parties concluded contract negotiations.²⁶²

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