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WINNING THE SALVO COMPETITION

REBALANCING AMERICA'S AIR AND MISSILE DEFENSES

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Contents

FIGURES

TABLES

Executive Summary

Over the last fifteen years, the Department of Defense (DoD) has spent more than $24 billion buying a mix of capabilities to defeat guided missile threats it views as a "cost-imposing challenge to U.S. and partner naval forces and land installations."[1] Despite DoD's urgency, these investments have fallen short of creating defensive architectures with sufficient capacity to counter large salvos of ballistic missiles, cruise missiles, and other precision-guided munitions (PGMs) that can now be launched by America's enemies.

This situation is partly the result of DoD's longstanding emphasis on fielding costly, long-range surface-to-air interceptors to defeat a small salvo of anti-ship cruise missiles or a handful of ballistic missiles launched by rogue states such as Iran and North Korea. It is also because the U.S. military has never fought an enemy who had the capability to strike distant targets with precision. Since the end of the Cold War, the Pentagon had the luxury of assuming that air and missile attacks on its bases and forces would either not occur or would be within the capacity of the limited defenses it has fielded. These assumptions are no longer valid, given that America's adversaries have taken advantage of proliferating guidance and missile technologies to create their own precision strike capabilities. China, Russia, Iran, and North Korea have developed multiple variants of guided missiles and other weapons that are capable of striking targets with increasing range and precision. Salvos of guided weapons launched during future engagements could overwhelm the defenses of U.S. forces, reducing America's ability to project power.

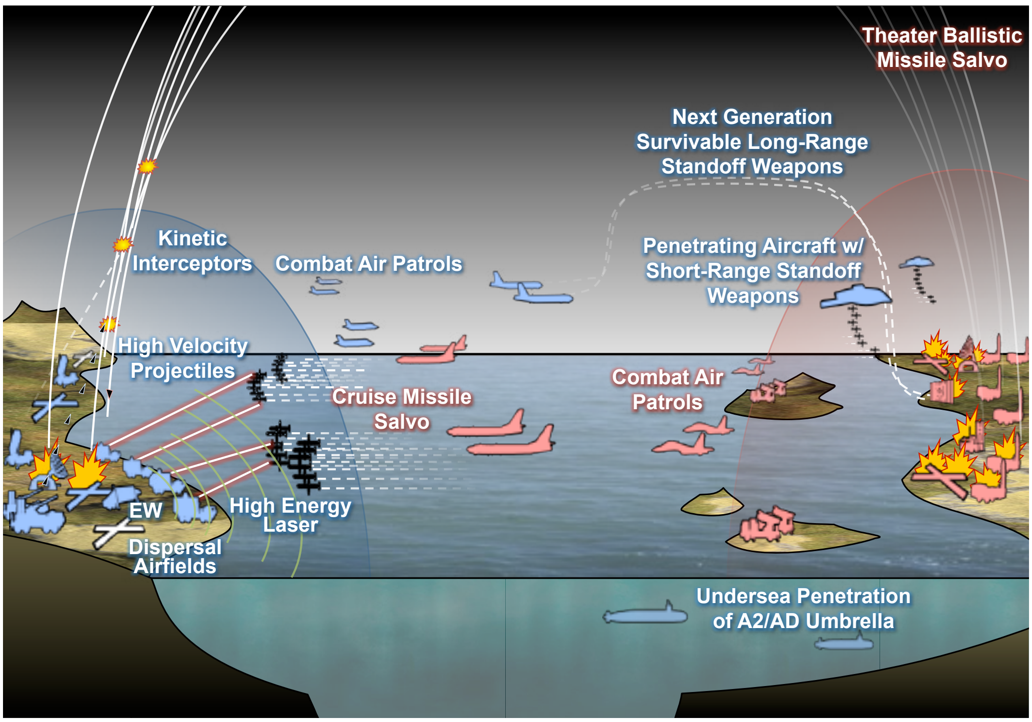
The number, accuracy, and reach of guided weapons fielded by China and Iran in particular represent significant conventional threats to the U.S. military's ability to operate effectively in regions that are critical to the security of our nation and its allies and partners. China has deployed one of the world's most sophisticated arsenals of anti-ship cruise missiles (ASCMs) and land-attack cruise missiles (LACMs) that can be launched from mobile ground launchers, aircraft, ships, and submarines. China's ASCMs and LACMs are complemented by multiple types of ballistic missiles that can reach America's Western Pacific bases and ships at sea. Newer versions of these missiles feature maneuverable reentry vehicles, and future variants

1 Department of Defense (DoD), *Quadrennial Defense Review 2014* (Washington, DC: DoD, March 2014), p. 6.

may be armed with hypersonic glide vehicles. While Iran's ballistic missiles lack the accuracy of China's long-range weapons, it seeks to obtain improved guidance systems from North Korea, China, and other missile technology proliferators that will give its next generation of weapons the ability to hit small, discrete fixed targets or moving targets such as ships.

This report proposes operational concepts and capabilities that could improve our nation's ability to counter guided weapon salvos that threaten its future ability to project power. As with a previous CSBA assessment on DoD's portfolio of PGMs, the report uses a "salvo competition" framework to assess promising operational concepts and capabilities for air and missile defense. This term refers to the dynamic between militaries that have PGMs and capabilities to counter one another's precision strikes (see Figure 1).[2] In a salvo competition, both combatants seek to gain advantages by improving their capabilities to attack with precision and defend against its opponent's strikes.

FIGURE 1: ILLUSTRATIVE PRECISION STRIKE "SALVO COMPETITION"



In contrast to previous salvo competitions that have mostly focused on offensive strike operations, today's salvo competition has both offensive and defensive aspects. In modern competitions, an adversary with effective air and missile defense capabilities could overcome an opponent's strike capacity.

2 See Mark Gunzinger and Bryan Clark, *Sustaining America's Precision Strike Advantage* (Washington, DC: Center for Strategic and Budgetary Assessments, 2015).

Report Purpose and Scope

The thesis of this report is that new operational concepts combined with a different mix of capabilities could help the U.S military achieve the air and missile defense capacity needed to prevail in future salvo competitions. Today's "layered" defenses expend multiple long-range interceptors against a single incoming ballistic or cruise missile, then medium-range interceptors, and, as a last resort, short-range defenses. This layered approach may be appropriate for defeating a handful of threats. Against large PGM salvos, however, it could quickly exhaust the U.S. military's defenses and leave its forces and bases open to successive strikes. By contrast, operational concepts that prioritize the use of medium-range interceptors and non-kinetic defenses such as electronic warfare and directed energy (DE) weapons could improve the U.S. military's capacity to counter PGM salvos—and do so at less cost than relying almost exclusively on using multi-million dollar long-range interceptors.

Assessments in this report focus primarily on concepts and capabilities to defend U.S. bases and force concentrations, including sea-based forces, from precision strikes. While the report does not provide comprehensive recommendations for national missile defense or the defense of ground units from guided rockets, artillery, mortars, and missiles (G-RAMM), its proposed approaches could also be applied to these operational challenges.

Recommendation: Develop Operational Concepts to Create Advantages in Future Salvo Competitions

Developing new operational concepts is a critical first step toward creating a new air and missile defense architecture for the U.S. military. The following concepts could reduce the size and lethality of enemy PGM salvos, which will have the same effect in salvo competitions as increasing U.S. defensive capacity:

Take greater advantage of theater bases located in lower threat areas. The U.S. military could reduce the size of PGM salvos by operating from bases and locations at sea situated outside the range of most enemy guided missiles and strike aircraft. A shift toward using more distant, secure operating locations where feasible could impose costs by inducing America's enemies to invest in more expensive, longer-range surveillance and strike systems. It could also increase the vulnerability of a key enemy center of gravity in salvo competitions: the command, control, communications, intelligence, surveillance, and reconnaissance (C3ISR) networks that enemies depend on to strike effectively over long ranges. Operating from longer ranges would, however, reduce the number of aircraft sorties U.S. forces could generate per day. These reduced sortie rates could be partially offset by increasing the number of long-range, large-payload strike aircraft in DoD's inventory and changing DoD's PGM mix toward smaller weapons that can be carried in greater numbers by strike aircraft.[3]

3 See Gunzinger and Clark, *Sustaining America's Precision Strike Advantage,* pp. 30–31.

Disperse within contested areas. Where feasible, the U.S. military should disperse its forces that must be based within contested areas. Distributing and frequently redeploying U.S. forces across a network of military, civilian, and expeditionary operating locations in contested regions would require an enemy to launch more weapons to attack the same number of targets. As a result, each individual operating location would receive a smaller salvo of strike weapons against which it must defend. Sustaining dispersed operations would require additional logistics capabilities and infrastructure compared to what is needed to operate from a small number of overseas main operating bases. This could be a major challenge in very large geographic areas such as the Western Pacific.

Conduct cluster base operations within contested areas. DoD should take advantage of clusters of theater bases and temporary operating locations to disperse its forces within localized areas. Cluster basing could dilute enemy strikes over larger target areas, enable U.S. defenses within each cluster to conduct mutually supporting operations, and increase overall U.S. threat engagement capacity. This concept may be more practical for future operations in Eastern Europe and the Persian Gulf region than in areas such as the Western Pacific that have fewer suitable clusters of military, civilian, and expeditionary airfields.

Increase the resiliency of U.S. bases. To the extent possible, DoD should take steps to harden or deeply bury high-value facilities on its existing bases and employ camouflage, concealment, and deception tactics as part of a comprehensive approach to create more resilient theater postures. These countermeasures would require enemy forces to launch more weapons at a base to ensure it can defeat the same number of targets, diluting their strikes against targets being protected by U.S. defenses.

Conduct "left-of-launch" operations. The U.S. military should be able to conduct offensive operations against enemy airbases, weapon launchers, and C3ISR networks used for targeting to reduce the size and frequency of enemy salvos. U.S. air forces should have sufficient long-range surface-to-air interceptors and capacity to sustain combat air patrols (CAPs) to defeat enemy strike aircraft before they can launch their weapons. Attacking an enemy's "archers" instead of its "arrows" could have a much greater impact on the size of its strike salvos, while a blinding campaign that combines cyber warfare, electronic warfare, and physical attacks on its C3ISR networks could greatly reduce its ability to find, fix, track, and strike U.S. targets with large salvos.

The following operational concepts could also help to increase the density of air and missile defenses that protect the U.S. military's overseas forces and installations:

Take an alternative approach for anti-air warfare. The Navy's current operational concept for anti-air warfare (AAW) uses a layered architecture intended to progressively intercept missile threats to surface ships at long ranges, then medium ranges, and finally short ranges. Vertical launch systems (VLS) on Navy ships have a finite capacity to carry AAW interceptors that could be quickly expended in high threat areas. Since VLS cannot presently be reloaded at sea, these ships would have to return to a secure port to reload, taking them out of the fight for days or weeks at a time.

A defensive AAW scheme that preferentially uses shorter-range interceptors and new kinetic and non-kinetic defenses could increase the number of air and missile threats individual ships can engage while retaining the ability for ships to protect each other. This approach could center on using medium-range (10–30 nm) interceptors such as the Evolved Sea Sparrow Missile (ESSM), four of which can be loaded in a single VLS cell compared to a single Standard Missile-2 (SM-2) or SM-6. The Navy could complement this alternative VLS loadout by equipping appropriate ships with electromagnetic railguns (EMRGs) and traditional naval guns that fire hyper-velocity projectiles (HVPs), solid state lasers (SSLs), high power microwaves (HPM) weapons, and electronic warfare (EW) systems. In contrast to kinetic air and missile defenses with finite magazines, SSL, HPM, and EW defenses will be capable of engaging air and missile threats as long as they are provided with sufficient power and cooling.[4]

Defend U.S. theater bases and forces against complex weapon salvos. Compared to the Navy's current AAW architecture, U.S. military theater bases and land-based forces have few defenses against PGM salvos. DoD has deployed a small number of Terminal High Altitude Area Defense (THAAD) and Patriot missile batteries to counter small-scale ballistic missile raids from North Korea and Iran. It is also deploying a limited ballistic missile defense (BMD) architecture in Europe consisting of radar sites, Aegis BMD ships in the Mediterranean Sea, and Aegis Ashore installations in Romania and Poland equipped with VLS-launched SM-3 IB interceptors. Overall, however, DoD lacks sufficient defenses against cruise missiles, G-RAMM, and other PGMs that could compose the weight of future attacks against its overseas bases and forces.

Similar to the defensive AAW alternative recommended above, the U.S. military could shift toward using medium-range interceptors and new weapon systems to counter PGM salvos. This shift could increase the density of its land-based air defenses and ultimately improve operating tempo at bases supporting U.S. offensive operations. Moreover, placing greater reliance on EW, lasers, HVP launchers, and HPM defenses that can counter individual threats for thousands and possibly hundreds of dollars per engagement has the potential to create advantageous cost exchanges for the U.S. military.

Recommendation: Invest in New Technologies and Capabilities to Defeat PGM Salvos

A shift toward operational concepts that will help the U.S. military to prevail in future salvo competitions will require investments in appropriate enabling technologies and capabilities. The following capabilities would help DoD to create a future air and missile defense complex that could counter enemy weapons salvos at a cost that is advantageous to the United States:

Lower-cost, medium-range kinetic interceptors. DoD should take advantage of mature technologies to develop and acquire lower-cost medium-range interceptors that will increase

4 High-energy lasers are affected by environmental conditions such as water vapor and particulates that absorb and scatter laser energy at distinct wavelengths of the electromagnetic spectrum.

the defense capacity of its ships and theater bases. These interceptors should incorporate advanced target seekers and other technologies that increase the number of effective engagements against enemy salvos in a given window of time and reduce the need for U.S. fire control systems to provide target updates to individual interceptors after launch.

Guns that launch guided or hypervelocity projectiles. DoD should develop and field mobile EMRGs and artillery that can launch guided projectiles to intercept air and missile threats within the next five to ten years. These capabilities promise to dramatically increase the U.S. military's salvo defense capacity. DoD is working on some medium caliber guns that can launch guided projectiles at high rates of fire to intercept threats at less than 5 nm. Capabilities in development would enable larger caliber guns to launch HVPs at air and missile threats over medium ranges (10–30 nm). DoD should also develop highly accurate radars to provide precise target information to cue guns and guide their projectiles toward incoming air or missile threats. Future HVPs should have on-board sensors that will guide them to threats that maneuver during their terminal stage of flight.

Directed energy weapons. DoD should augment its kinetic salvo defenses with non-kinetic SSLs and HPM weapons that can engage threats for as long as they are provided sufficient power and cooling. Shifting toward medium-range air defense schemes would enable the U.S. military to take advantage of the large magazine potential of these line-of-sight weapons, since they are constrained by the horizon. Given adequate resources, DoD should field within five years SSLs with sufficient power (150 kW to 500 kW) to counter unmanned aircraft, G-RAMM, and some cruise missiles. The Services should also prioritize the fielding of land-based and sea-based broadband HPM systems capable of defeating multiple threats in a salvo.

Electronic warfare countermeasures. Today, EW systems that jam, deceive, or decoy incoming missiles are often considered to be weapons of last resort that are only to be used after kinetic interceptors have failed or been expended. U.S. forces could partially reverse this dynamic by preferentially employing EW systems, SSLs, and HPM weapons against threats that are most vulnerable to their effects while reserving more expensive interceptors for threats requiring kinetic engagements. The Services should cooperatively develop complexes of jammers, decoys, and other counter-salvo EW capabilities that are networked, capable of autonomously sensing the electromagnetic (EM) spectrum, assessing air and missile threats, and supporting counter-targeting operations.

Battle management and fire control systems. DoD should pursue battle management systems capable of rapidly evaluating and responding to large salvos of PGMs over ranges of 10–30 nm. These systems should determine which threats to engage and in what order, assign non-kinetic or kinetic defenses to appropriate targets, and continuously reevaluate the operational picture to determine when salvos have been negated or respond to new PGM salvos. Current combat systems such as Aegis have this capability, but are designed to manage smaller numbers of threats using a layered defense approach, and they do not incorporate new capabilities such as SSLs and HPM countermeasures. Future battle management and fire control systems should also have the capacity to provide target updates and command guidance for multiple kinetic interceptors simultaneously, including HVPs and other guided projectiles.

Capabilities for left-of-launch salvo suppression operations. DoD should increase its capacity to suppress enemy land, sea, and airborne PGM launchers and degrade opposing C3ISR networks. Defeating enemy strike systems before they can launch their weapons will impose costs and help reduce the size of salvos to within the capacity of U.S. defenses. Missile suppression operations against land-based missile launchers will require sufficient long-range, penetrating ISR and strike platforms capable of enduring in contested and denied areas. In addition to advanced surface-to-air missiles (SAMs), DoD should develop and field long-endurance, large-payload manned and unmanned aircraft that can sustain counter-air CAPs over long ranges.

Overcoming Barriers to Rebalancing

Operating concepts and capabilities suggested above would help create a future air and missile defense complex capable of prevailing in future salvo competitions. For this to occur, however, DoD will need to address organizational and resource issues that hinder progress.

Clarifying responsibilities. Responsibilities within DoD for preparing to defeat salvo attacks are unclear, at best. While the mission of the Missile Defense Agency (MDA) is to create a ballistic missile defense architecture, it is not presently responsible for defining requirements and initiating programs to defeat cruise missiles. Guidance to the Services on who should prepare to defend U.S. forward bases against PGM salvos is ambiguous. Working with Congress, the Pentagon should clarify the responsibilities of the MDA, the Services, and other major DoD components to organize, train, and equip forces to defeat complex salvos that include cruise missiles, air-delivered PGMs, and ballistic missiles.

Insufficient resources. The Congress and DoD should allocate sufficient resources to build air and missile defense architectures on land and at sea that will help America's military to prevail in future salvo competitions. Of the $524 billion requested by the FY 2017 President's Budget for DoD, less than $3 billion was allocated to procure missile interceptors of all types. Continued funding at this level may prove insufficient to develop effective defenses against salvos of ballistic missiles, cruise missiles, and other guided weapons that threaten vital U.S. interests at home and abroad.

In summary, the U.S. military may be unprepared to counter large, complex salvos of ballistic missiles, cruise missiles, G-RAMM, and other guided weapons. Continuing to adhere to traditional concepts and capabilities for missile defense could invite America's adversaries to continue, if not accelerate, their investments in guided weapons, further eroding the U.S. military's ability to project power. Alternatively, DoD has the opportunity to employ operational concepts and field new kinetic and non-kinetic capabilities that could counter these threats and create more advantageous cost exchanges. This will require a willingness to reevaluate our nation's current approaches to air and missile defense and shift investments toward a more effective mix of capabilities.

CHAPTER 1

Introduction

Emerging Precision Strike Complexes

Since the end of the Cold War, America's adversaries have taken advantage of maturing missile and guidance technologies to create their own precision targeting and strike complexes. China, Russia, Iran, and North Korea have developed multiple variants of guided missiles and other weapons that are capable of striking targets with increasing precision. Salvos of guided weapons launched from the ground, in the air, and at sea during future engagements could overwhelm the defenses of U.S. forces, reducing America's ability to project power. According to the Defense Intelligence Agency (DIA):

> China, Iran, and North Korea . . . exercise near simultaneous salvo firings from multiple locations to saturate missile defenses. Countries are designing missiles to launch from multiple transporters against a broad array of targets, enhancing their mobility and effectiveness on the battlefield. Shorter launch-preparation times and smaller footprints are making new systems more survivable, and many have measures to defeat missile defenses.[5]

The number, accuracy, and reach of guided weapons fielded by China and Iran in particular may now represent the most significant conventional threats to U.S. ability to project military power into their respective regions.

China's growing guided missile complex

China has deployed one of the world's most sophisticated arsenals of ASCMs and LACMs that can be launched from mobile transporter erector launchers (TELs), aircraft, ships, and submarines (see Appendix 1). Their use in large and complex salvos against U.S. forces across the Western Pacific is a key element of China's anti-access/area-denial (A2/AD) strategy. For

5 Michael T. Flynn, Lieutenant General, U.S. Army Director, DIA, "Annual Threat Assessment," statement before the Senate Armed Services Committee, February 11, 2014, available at http://www.dia.mil/Portals/27/Documents/News/2014_DIA_SFR_SASC_ATA_FINAL.pdf.

example, each of China's H-6K bombers are capable of launching six long-range LACMs per sortie against military installations in Japan and Guam while remaining outside the effective range of many of the U.S. military's current surface-to-air interceptors. Coordinated ASCM strikes from different axes of attack could be a highly effective means of saturating the defensive capacity of high-value targets such as U.S. aircraft carrier battle groups. Threatening or attacking a multibillion-dollar aircraft carrier with salvos of $2 million cruise missiles would be the very definition of a "cost imposing" action.

FIGURE 2: PLAAF H-6K BOMBER WITH EXTERNAL WEAPON PYLONS AND A DF-21 ON A MOBILE LAUNCHER

Photo by Japan Ministry of Defense.

Photo by Air Power Australia.

China's ASCMs and LACMs are complemented by multiple theater ballistic missiles (see Appendix 2) that can reach America's Western Pacific bases and forces on land and at sea. China now has more than 1,200 short-range ballistic missiles (SRBMs) with sufficient range to strike across Taiwan and all U.S. military installations on the Korean Peninsula. Its road-mobile, solid-fuel medium-range ballistic missiles (MRBMs) such as the Dong Feng-11 (DF-11), the DF-15, and their putative replacement, the DF-16, can reach targets on Okinawa, Singapore, and the Philippines. Longer-range missiles include variants of the DF-21 and a new DF-26 "Guam killer" intermediate-range ballistic missile (IRBM) that could have a range of up to 4,000 km.[6]

China considers its DF-21D anti-ship carrier killer as one of its shāshǒujiàn (literally "kill, hand, mace," or assassin's mace) capabilities designed to prevent foreign militaries from intervening in the Western Pacific and offset the U.S. military's superior air forces.[7] Reportedly

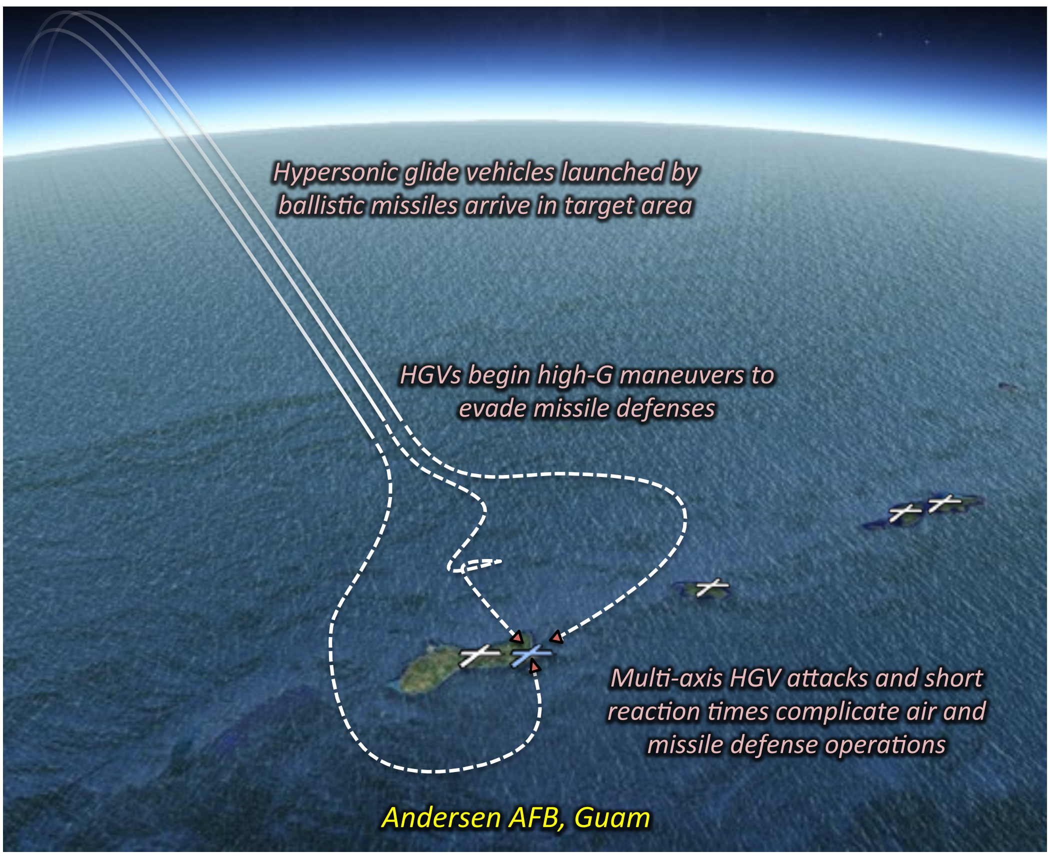
6 China has claimed that the DF-26, which may be based on the DF-21, is also an ASBM. IHS Jane's suggests the DF-26 could have a minimum range of 3,000 km and a maximum range of up to 4,000 km. IHS Jane's, "DF-26," *Jane's Strategic Weapons Systems*, September 11, 2015. Other sources suggest the DF-26 could reach out to 5,000 km. "Missile Display Demonstrates China's Ambitions," *The China Post*, September 4, 2015, available at http://www.chinapost.com.tw/taiwan/china-taiwan-relations/2015/09/04/445005/Missile-display.htm.

7 "Breaking China's DF-21D Missile Kill Chain: US Expert," *China.org.cn*, April 9, 2013, available at http://www.china.org.cn/world/2013-04/09/content_28491040.htm. According to a 2003 DoD report, China considers "fighter bombers, submarines, anti-ship missiles, torpedoes, and mines to destroy aircraft carriers" as assassin's mace capabilities. DoD, *Annual Report On the Military Power of the People's Republic of China* (Washington, DC: DoD, July 2003), p. 21.

based on a two-stage, solid propellant design similar to the retired U.S. Pershing II missile, DF-21Ds fly at hypersonic speeds over ranges that exceed 1,500 km and deploy a maneuverable reentry vehicle (MaRV) able to attack moving ships. The combination of high speed, maneuverability, and steep angle of attack typical of MaRVs present a formidable challenge for sea- and land-based BMD systems.

A more challenging missile-launched threat—hypersonic glide vehicles (HGVs)—may be on the horizon. HGVs are similar to MaRVs in that they are launched by rockets and have the ability to maneuver at high speeds to increase their likelihood of penetrating air and missile defenses. Unlike MaRVs, however, HGVs do not follow a ballistic trajectory after separation from their boosters. Rather, they glide to their intended targets at shallow angles, which increases their range compared to typical ballistic missile reentry vehicles. HGVs will also have guidance systems and flight controls allowing them to conduct maneuvers to complicate a defender's ability to track and target them. HGVs may be able to maneuver to attack targets from directions that may be less protected by air and missile defenses, as illustrated in Figure 3. This would complicate a defender's operations by making it necessary to counter attacks from multiple directions of attack.

FIGURE 3: HYPOTHETICAL HGV ATTACK



China has conducted at least six tests of their DF-ZF developmental HGV over the last two years. Operational HGVs could be launched by future variants of the DF-21 and DF-26.[8]

Guided weapons are key to Iran's A2/AD strategy

Iran's hybrid approach to denying access to the Persian Gulf region mixes the use of guided ballistic and cruise missiles with attacks by armed small boats, unmanned aircraft, and irregular proxy forces. Iran is postured to take advantage of the Persian Gulf's constrained geography and narrow entrance at the Strait of Hormuz to threaten U.S. forces with air-, land-, and sea-launched guided weapons that have shorter ranges and are less costly than more sophisticated Chinese PGMs. Through a combination of irregular tactics and guided weapons, Iran seeks to impose costs on militaries deploying to the region by first striking them over long distances and then attriting them using an increasingly dense array of threats as they approach its borders.[9]

To support its A2/AD strategy, Iran has procured or developed with assistance from other states multiple guided cruise and ballistic missiles that are, according to DoD, "capable of reaching targets throughout the [Middle East] region" (see Appendices 3 and 4).[10]

FIGURE 4: IRANIAN "SEJIL" MOBILE MRBM AND "GHADAR" CRUISE MISSILE

Photos by Fars News.

8 Richard D. Fisher, "US Officials Confirm Sixth Chinese Hypersonic Manoeuvring Strike Vehicle Test," *IHS Jane's Defence Weekly*, November 26, 2015.

9 For more on Iran's A2/AD strategy, see Mark Gunzinger and Chris Dougherty, *Outside-In: Operating from Range to Defeat Iran's Anti-Access and Area-Denial Threats* (Washington, DC: Center for Strategic and Budgetary Assessments, 2011).

10 DoD, *Annual Report on Military Power of Iran* (Washington, DC: DoD, January 2014), executive summary.

While its ballistic missiles lack the accuracy of China's long-range weapons, Iran seeks to obtain improved guidance systems from North Korea, China, and other missile technology proliferators that will give its next generation of weapons the ability to hit discrete targets such as hangers, runways, and fuel storage facilities. Iran may soon have operational anti-ship ballistic missiles that extend its sea control complex well out into the Arabian Sea, as well as ballistic missiles that are capable of attacking out-of-region targets in Europe and the United States.[11]

U.S. defenses lack capacity for emerging salvo competitions

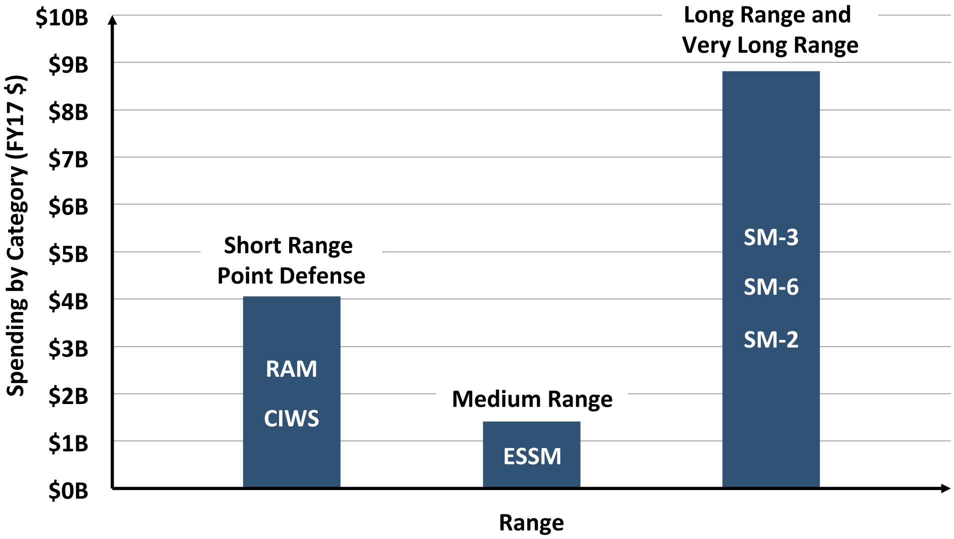
Conflicts against adversaries such as China and Iran who seek to gain advantages over the U.S. military by improving their capabilities to attack and defend with precision can be characterized as a salvo competition. In contrast to previous salvo competitions that mostly focused on offensive strikes, future competitions with adversaries that have fielded effective air and missile defenses will likely have both offensive and defensive aspects.

Unfortunately, U.S. theater air and missile defenses now lack the capacity to address large salvos of guided weapons. As described in Appendix 5, the Pentagon relies almost exclusively on a variety of surface-to-air interceptors to defend its forces at sea and ashore from enemy cruise missiles, ballistic missiles, and strike aircraft. The Navy has spent billions of dollars to equip its surface combatants with layered air and missile defenses designed to first intercept enemy missiles and aircraft at long ranges (from 50 nm to over 100 nm), medium ranges (from 10 nm to 30 nm), and short ranges (about 5 nm or less).[12] Navy anti-air warfare doctrine prioritizes using long-range SM-2s and SM-6s to intercept threats as far from its ships as possible, backed up by medium-range ESSM. Short-range self-defense weapons such as the Rolling Airframe Missile (RAM), Phalanx Close in Weapon System (CIWS) rapid firing 20-millimeter gun, and electronic warfare systems such as the SLQ-32 electronic countermeasures system are only employed as a last resort when long-range and medium-range interceptors have failed to defeat incoming threats.

11 According to DoD, "Iran has publicly stated it may launch a space launch vehicle by 2015 that could be capable of intercontinental ballistic missile ranges if configured as a ballistic missile." DoD, *Annual Report on Military Power of Iran*, executive summary.

12 Figures 5 and 6 include cumulative expenditures on expendable munitions only. They exclude the cost of sensors, launchers, and other capabilities that are part of DoD's air and missile defense architecture.

FIGURE 5: NAVY AAW INTERCEPTOR PROCUREMENT FUNDING SINCE 1999



Despite these investments, the Navy's ship-based defenses are insufficient to defeat large salvos of anti-ship ballistic missiles (ASBMs) and ASCMs, swarms of armed unmanned aerial vehicles (UAVs), and other guided weapon threats. One reason for this is that ships carry a small number of interceptors relative to the size and number of salvos that can be launched by enemies. Although about two-thirds of Navy cruiser and destroyer VLS are typically filled with AAW interceptors, these weapons could be quickly expended against missile salvos.[13] Since VLS magazines presently cannot be replenished at sea, ships may have to leave a fight for days at a time in order to return to a secure port and reload, reducing a deployed fleet's overall defensive AAW capacity.

The Navy's AAW operational concept, which gives preference to intercepting individual missile threats as far away as possible from its ships, is a second reason why it lacks sufficient capacity to defeat large weapon salvos. This concept drives requirements for interceptors that have long ranges and thus are very large, which reduces the total number of interceptors carried by surface combatants. Further, these long-range interceptors cost millions of dollars each, which constrains the number the Navy can ultimately afford to buy. For example, the Navy's newest long-range interceptor, the SM-6, has a gross weapon unit cost of about $3.8 million.

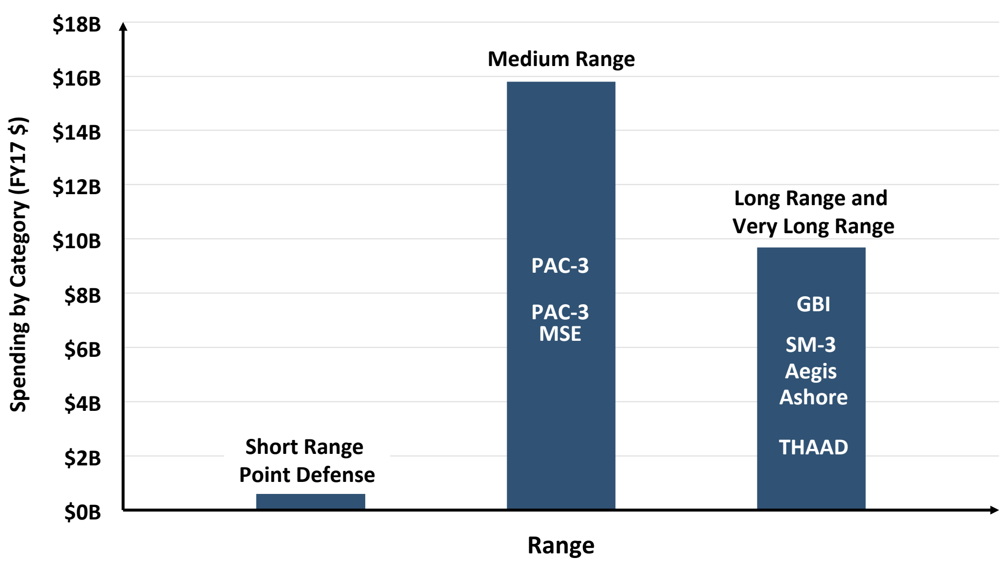
The Navy's AAW architecture is robust compared to missile defenses at U.S. bases located in the Pacific, Middle East, and Europe. The United States has deployed Patriot air defense

13 A typical anti-air warfare weapons complement for a U.S. DDG-51 destroyer could include thirty-two Evolved Sea Sparrow Missiles, thirty-two SM-2s, thirty-four SM-6s, and six SM-3s.

systems to the Middle East and Western Pacific and sold them to allies and partners in both regions. It has also deployed a battery of THAAD interceptors to Guam and is pursuing a cooperative effort with Japan to develop the next generation of SM-3 interceptors. In Europe, DoD is implementing a three-phase European Phased Adaptive Approach (EPAA) ballistic missile defense architecture. EPAA Phase 1 was implemented when DoD deployed Aegis BMD ships to the Mediterranean Sea, a radar system in Turkey, and a battle management system in Germany. Phase 2 improved defenses against SRBMs and MRBMs by homeporting four Aegis ships in Rota, Spain, and building an Aegis Ashore installation in Romania with VLS-launched SM-3 IB surface-to-air interceptors. As part of EPAA Phase 3, DoD will field an Aegis Ashore installation in Poland and provision the Polish and Romanian Aegis Ashore sites with twenty-four SM-3 Block 2A interceptors each.

DoD deployed most of these systems primarily to defend against small-scale nuclear ballistic missile attacks from Iran or North Korea. However, it has not fielded robust defenses that are capable of protecting its theater bases against large PGM salvos that include cruise missiles and other air-delivered PGMs. Furthermore, similar to the Navy, Army and defense-wide procurement of air and missile defenses has favored expensive surface-to-air interceptors (see Figure 6).

FIGURE 6: DOD CUMULATIVE LAND-BASED AIR AND MISSILE DEFENSE INTERCEPTOR PROCUREMENT FUNDING SINCE 1999



These investments have helped to create a situation where U.S. land-based air and missile defenses are now more capable of countering a small number of ballistic missiles rather than defeating large salvos of various kinds of PGMs. In particular, U.S. bases in the Pacific have very few if any defenses against cruise missile attacks.

The lack of effective cruise missile defenses is a critical capability shortfall, considering that LACMs and other PGMs launched by People's Liberation Army (PLA) aircraft, ships, and submarines are one of the most significant threats to America's Pacific bases. A plausible operational concept for China might be to launch a small number of ballistic missiles against Western Pacific airfields first to degrade the U.S. military's ability to mount defensive air patrols and coordinate air defense efforts. MRBMs such as the DF-21 have sufficient range to reach U.S. bases in Japan and Guam. MRBMs could each carry multiple submunitions designed to foul runways and damage or destroy unprotected aircraft and support facilities, such as fuel and weapons bunkers, command facilities, and hangers. China could then launch successive salvos of cheaper and more numerous LACMs and other air-delivered PGMs at U.S. bases. Collectively, China's bombers and fighters could deliver much larger salvos of weapons compared to the number of MRBMs and IRBMs that are now in its inventory. While U.S. bases may be able to quickly recover from small ballistic missile salvos, follow-on PGM strikes could degrade U.S. power-projection operations for an extended length of time.

Unfavorable cost exchanges

The estimated unit costs for adversary cruise missiles illustrate another challenge for a U.S. military that relies primarily on using expensive, long-range interceptors to defeat them. Based on the known costs of missiles with similar ranges and payloads, many of China's subsonic cruise missiles may cost $1 million or less to procure depending on their range, warhead size, and guidance/seeker packages. More advanced cruise missiles such as supersonic ASCMs may cost $2–3 million each.[14] This disparity could result in engagements that cost the U.S. military far more to defeat missile salvos than it costs an enemy to launch them, especially if defending forces continue to rely almost exclusively on expensive kinetic interceptors.[15] For instance, if a long-range interceptor such as SM-6 has a probability of kill (P_k) of 70 percent against a particular ASCM, an attacker could defeat the entire VLS magazine of a $2 billion DDG-51 with a salvo of thirty-two ASCMs, costing the attacker less than $100 million. Meanwhile, the DDG's unsuccessful defense would have cost more than $300 million.[16]

Long-range ballistic missiles may cost more than cruise missiles, but a continued emphasis on using very expensive interceptors to defeat ballistic missile attacks will create similar disadvantageous cost exchanges. Using long-range THAAD interceptors, U.S. forces could

14 This is the cost of the Russia/India co-developed BrahMos ASCM based on Russia's supersonic SS-N-26 Yakhont ASCM. The BrahMos ASCM is being actively marketed to Latin American and Southeast Asian militaries. See "Artillery: Indian Army Demands More Missile Regiments," *Strategy Page*, January 26, 2010; and "BrahMos Missile Can Be Exported to Southeast Asian, Latin American Nations," *Economic Times*, August 3, 2014.

15 Deputy Secretary of Defense Robert Work has made the point that it costs DoD "more to shoot down incoming missiles than it does to [launch] them." Paul McLeary, "DoD Shifts Acquisition, Tech Efforts Toward Major Powers," *Defense News,* November 23, 2014.

16 This assumes a desired overall engagement probability of success of 90 percent. An SM-6 costs about $3.7 million and a DDG-51 Flight II has ninety-six VLS cells.

spend at least $30 million to defeat one DF-21 MRBM that could cost approximately $15 million.[17] These exchanges would be unsustainable, especially in campaigns against enemies that have large inventories of less sophisticated SRBMs, short-range G-RAMM, and weaponized unmanned drones that cost thousands of dollars each.

The high cost of long-range missile interceptors also affects the number that DoD can ultimately afford to buy. Numbers matter, especially when attackers are capable of launching salvos of sufficient size and frequency to exhaust U.S. defenses. From an attacker's perspective, however, the metrics that matter most are the number and cost of weapons needed to neutralize specific targets. An attacker may be willing to launch multiple salvos of $2–3 million ASCMs or $15 million ASBMs to ensure at least one of the weapons hit a $2 billion *Arleigh Burke*-class DDG or a $13 billion aircraft carrier.

Summary

Over the last 25 years of U.S. precision strike operations, the U.S. military has not fought an enemy with the ability to conduct precision strikes over long ranges. It is highly unlikely that this will remain true for all future conflicts. China, Russia, Iran, and other revisionist states are fielding guided weapons capable of reaching targets across their respective regions and beyond. In response to this growing threat, DoD has invested billions of dollars to defend against a small number of ballistic missiles. It has not developed an air and missile defense architecture with sufficient capacity to defeat large salvos of cruise missiles and other PGMs, much less other guided weapon threats such as G-RAMM and armed drones.

The next chapter summarizes operational concepts that could help the U.S. military to thin enemy salvos more effectively before they reach their targets and increase the density of air and missile defenses protecting U.S. theater bases and forces. Chapter 3 addresses mature and maturing technologies needed to support these operational concepts. Chapter 4 then presents two case studies to illustrate advantages of medium-range air and missile defense architectures, including the potential to create more favorable cost exchanges for the U.S. military. Chapter 5 concludes by citing potential barriers to initiatives recommended by this report.

17 The DF-21 cost estimate is based on an extrapolation of the cost of a U.S. Pershing II missile. Given current missile defense doctrine, at least two interceptors are launched at each incoming missile to increase the probability of success and account for the limited time in which defenders can engage the missile threat. A THAAD interceptor has a gross weapon cost of $15 million.

CHAPTER 2

Operational Concepts For Countering Enemy Salvos

Chapter 2 describes operational concepts that could create advantages for the U.S. military in future salvo competitions. DoD uses operational concepts to assess requirements for new weapon systems; doctrine; and tactics, techniques, and procedures (TTP). Concepts addressed in this chapter focus primarily on achieving two objectives. The first is to reduce the size and effectiveness of an enemy's PGM salvos—by operating U.S. power-projection forces from locations that are at less risk of attack, dispersing forces that must operate within contested areas, and conducting offensive operations against enemy PGM "shooters" such as aircraft carrying cruise missiles. The second objective is to increase the U.S. military's overall air and missile defense capacity by shifting toward using a mix of medium-range interceptors and non-kinetic defenses such as EW systems and DE weapons.

Reducing the Density and Effectiveness of Enemy Salvos

To maintain an advantage in future salvo competitions, the U.S. military could more fully embrace operational concepts that have the potential to reduce the size and effectiveness of an enemy's PGM strikes. Combatants in a salvo competition will each seek to improve their ability to defeat salvos by using a mix of active and passive countermeasures that degrade its opponent's precision strike "kill chain."[18] Active countermeasures could include physical strikes or attacks through the electromagnetic spectrum to degrade sensor networks used to find, fix, track, and target U.S. forces. Passive countermeasures could range from geographically dispersing potential U.S. targets to employing concealment, camouflage, and deception tactics that complicate an opponent's ability to target with precision. All of these

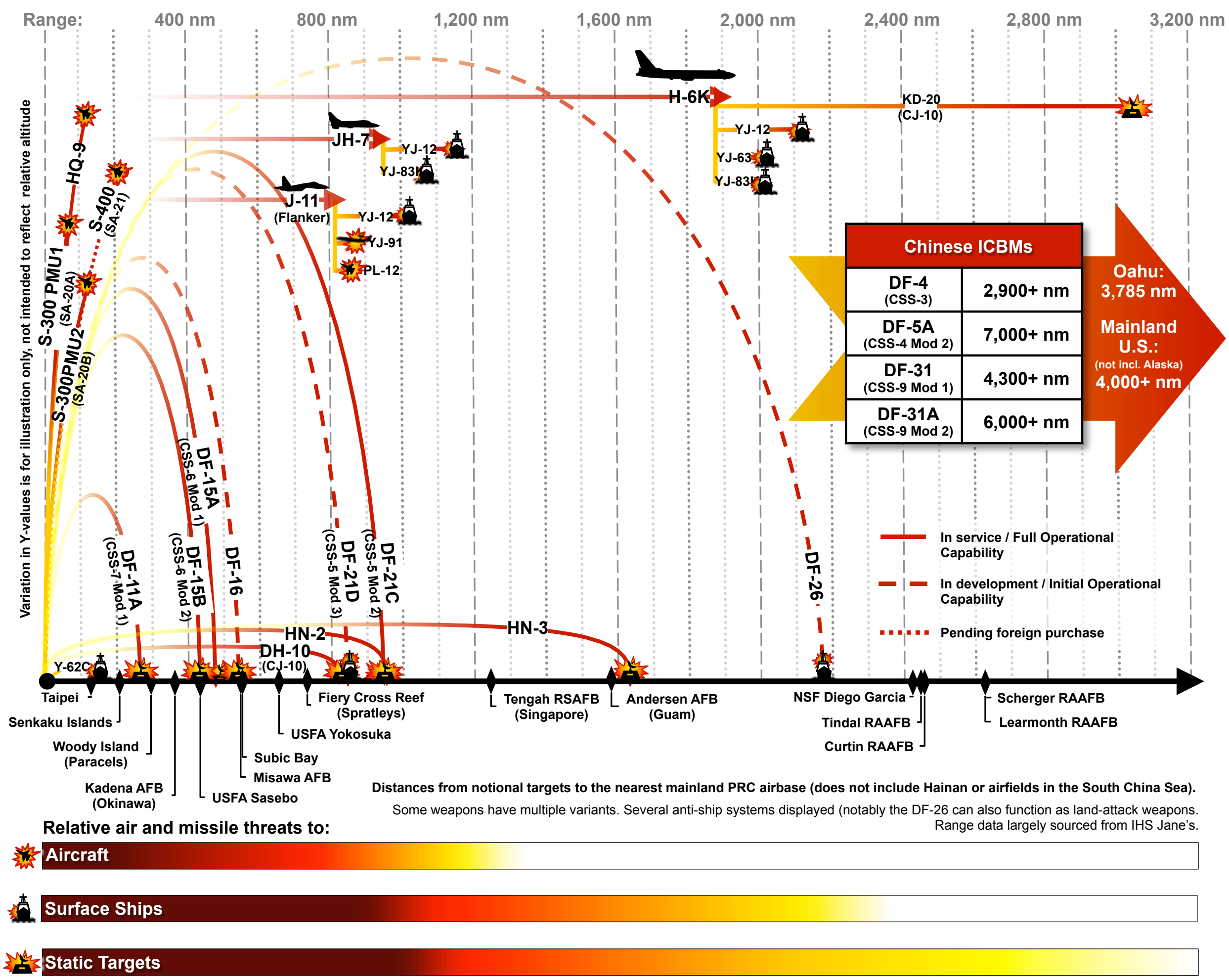
18 DoD describes its find, fix, track, target, engage, and assess cycle as a kill chain that applies to "all targets whether developed during deliberate targeting or dynamic targeting" planning. *Joint Targeting*, Joint Publication 3-60 (Washington, DC: Joint Chiefs of Staff, January 31, 2013), pp. II-1–II-36. See also Gunzinger and Clark, *Sustaining America's Precision Strike Advantage*.

countermeasures could reduce the number of enemy guided weapons that hit U.S. targets. For example, degrading an enemy's search and targeting sensors could cause it to refrain from launching strikes or induce it to launch weapons at false aimpoints. For the purposes of brevity, however, this section focuses on actions that could directly reduce the size of an enemy's PGM salvos rather than the more indirect effects achieved by degrading other elements its strike kill chain.

Stage U.S. power-projection forces from outside the range of most missile threats

The U.S. military could reduce threats to its power-projection forces by deploying them to operating locations that are outside the reach of most of an enemy's land-based missile threats.

FIGURE 7: OPERATING FROM LOWER THREAT AREAS



Operating from more distant, secure locations could compel attackers to expend their small inventories of long-range weapons. It could potentially impose costs by forcing adversaries to procure additional expensive long-range missiles, reducing the overall number of PGMs they can ultimately afford buy. Operating from range would also increase an attacker's reliance on long-range airborne, maritime, and space-based C3ISR systems that may be vulnerable to kinetic and non-kinetic (including DE, cyber, and EW) attacks. To a large extent, ISR networks needed to find, fix, track, target, and assess the effectiveness of strikes over long ranges are the Achilles' heel of A2/AD complexes. China's long-range sensor network includes satellites, over-the-horizon (OTH) radars, manned and unmanned aircraft, ships and submarines linked to its strike forces by communication satellites, command centers, data links, and a myriad of other systems. A blinding campaign that combines cyber, electronic warfare, and physical attacks on China's A2/AD intelligence, surveillance, and reconnaissance (ISR) and communications networks could greatly reduce the effectiveness of its salvos.[19]

Operating over long ranges would, however, also affect the tempo of U.S. precision strikes. Basing U.S. strike aircraft far from potential target areas would reduce their daily sortie rates compared to operating them from close-in bases.[20] These reduced sortie rates could be partially offset by shifting the U.S. military's mix of combat air forces toward long-range manned and unmanned aircraft that carry larger PGM payloads and by using more standoff weapons such as cruise and theater ballistic missiles. From a logistics perspective, shifting toward long-range operations would play to the advantage of the U.S. military, which now operates the world's largest and most fuel-efficient force of long-range strike aircraft, aerial refueling aircraft, and sea-based standoff strike platforms.

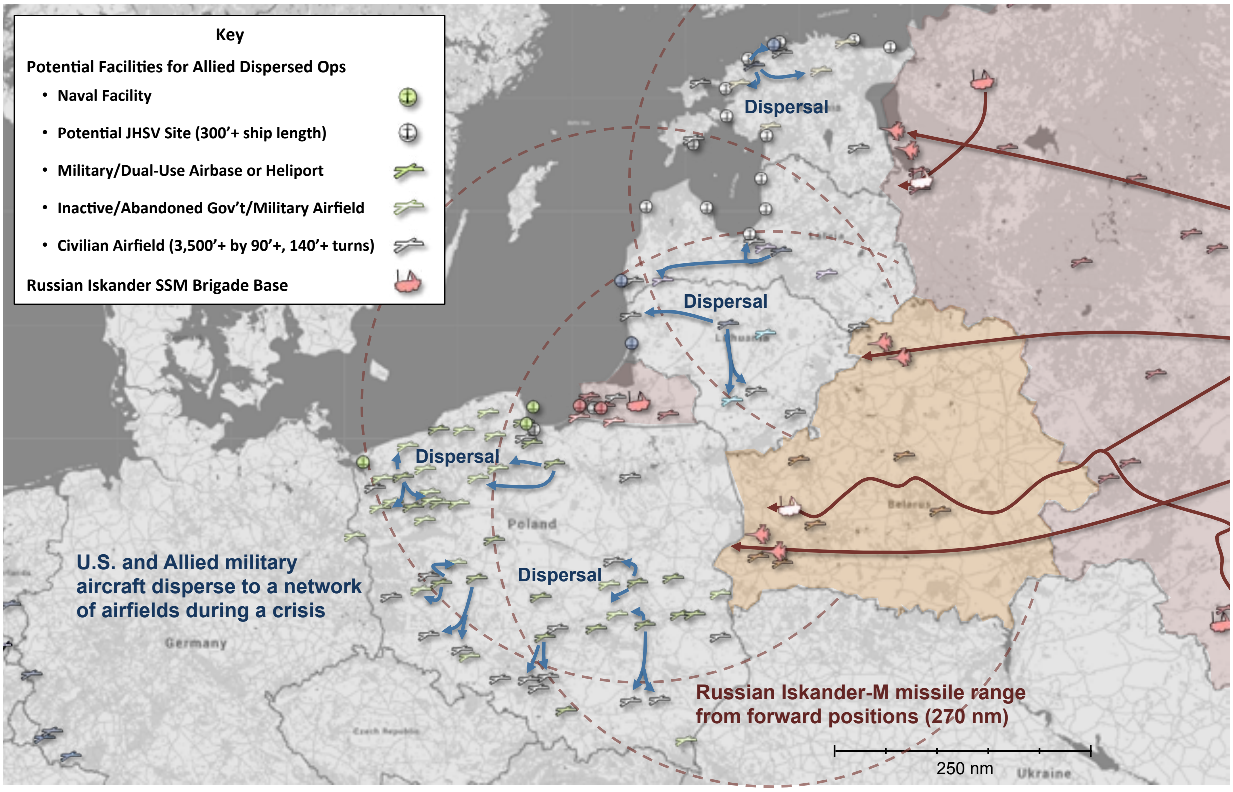
Conduct dispersed operations inside A2/AD areas

It would be impractical to operate large numbers of U.S. forces, such as fighter aircraft and ground forces dedicated to defending the homelands of U.S. allies and partners, from distant bases as suggested in the previous section. Forces that must operate within range of an enemy's precision strike capabilities should be able to disperse across a network of permanent, temporary, and improvised bases to the maximum extent possible (see Figure 8).

19 For a more in-depth explanation of a blinding campaign, see Jan van Tol, Mark Gunzinger, Andrew Krepinevich, and Jim Thomas, *AirSea Battle: A Point-of-Departure Operational Concept* (Washington, DC: Center for Strategic and Budgetary Assessments, 2010), pp. 56–62.

20 Gunzinger and Clark, *Sustaining America's Precision Strike Advantage*, pp. 30–31.

FIGURE 8: DISPERSING INSIDE A2/AD AREAS



Posturing power-projection forces at dispersed bases, then frequently moving them to new locations, could help the U.S. military to operate inside an enemy's deliberate targeting cycle, which can take several days to complete.[21] Dispersal and frequent redeployments would degrade an enemy's ability to target U.S. forces with precision and conduct timely damage assessments.

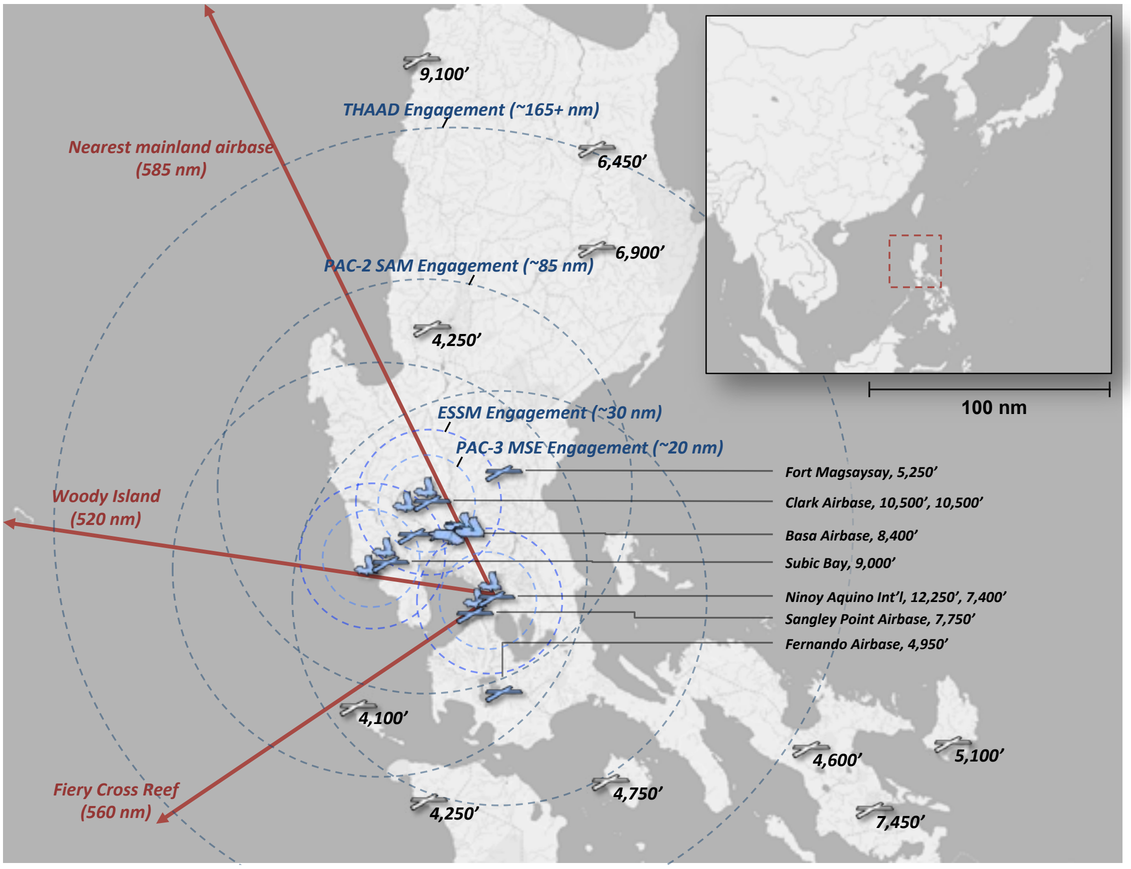
Operating from base clusters located in contested areas

Operating U.S. forces from clusters of military, civilian, and improvised bases located in close proximity to each other could serve two objectives. First, frequently repositioning forces across a base cluster could induce an enemy to dilute its strike salvos over a larger area and possibly waste weapons on false targets. This would reduce the size of salvos U.S. defenses have to defeat. Second, cluster basing could increase the capacity of U.S. air and missile defenses by enabling defensive systems in the cluster to conduct mutually supporting operations (see

21 Deliberate targeting cycles are multi-step processes that require time to complete. The U.S. military describes its joint targeting cycle as "a six-stage process: end state and commander's objectives, target development and prioritization, capabilities analysis, commander's decision and force assignment, mission planning and force execution, and assessment." *Joint Targeting*, p. xi.

Figure 9). Cluster basing would likewise allow U.S. forces to conduct mutually supporting logistics operations, thus improving their ability to generate offensive strikes.

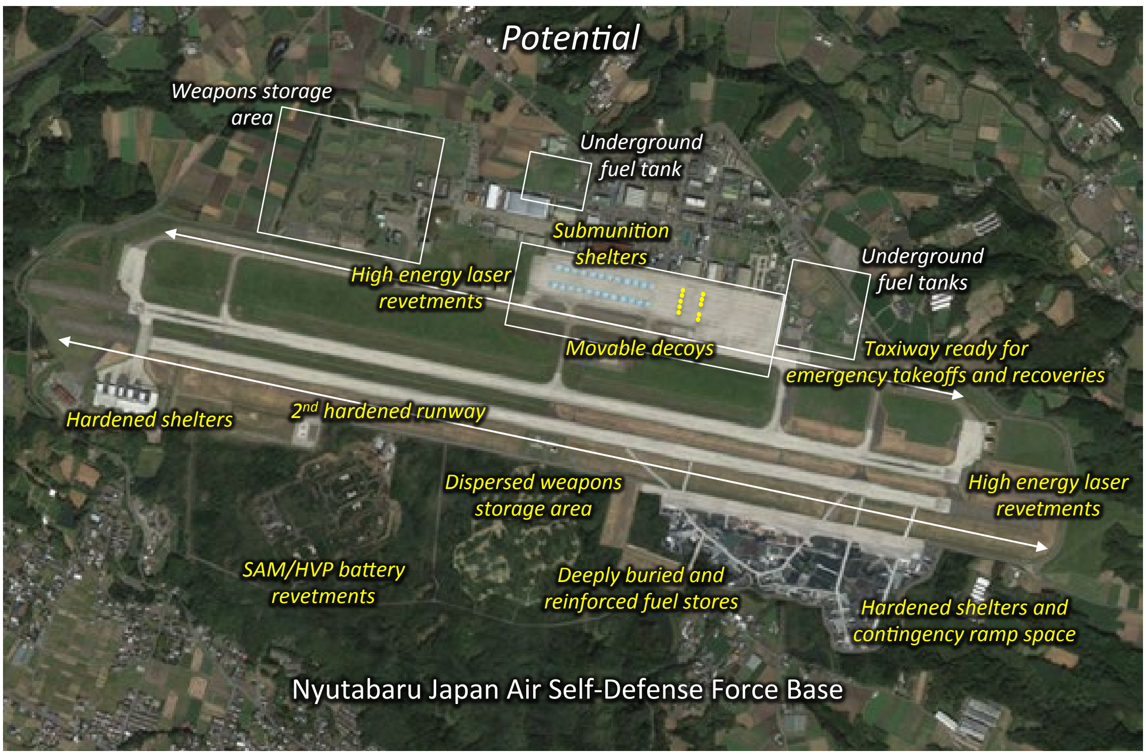
FIGURE 9: OVERLAPPING SALVO DEFENSES IN A NOTIONAL BASE CLUSTER



Fighting the base

The size and/or effectiveness of enemy salvos attacking individual bases could be further reduced by dispersing critical base facilities and functions; hardening some base facilities to improve their survivability; and exploiting camouflage, concealment and deception (CCD) tactics. Figure 10 illustrates measures that could increase the resiliency of a base located in Japan.

FIGURE 10: COMPLICATING AN ENEMY'S PRECISION TARGETING



Localized dispersal and CCD could dilute an enemy's salvos and cause it to expend PGMs on false targets. Deeply burying and/or reinforcing fixed facilities that are impractical to relocate frequently would help harden them against strikes. These hardened targets could induce enemies to use both greater numbers of weapons as well as expensive, specialized weapons carrying terminally guided, penetrating unitary warheads instead of less expensive cluster munitions that are most effective against unreinforced "soft" targets. From a defender's perspective, these actions would improve its ability to absorb strikes and generate its own offensive strike sorties, providing it with an advantage in salvo competitions.

Suppressing PGM salvos left of launch

U.S. forces could reduce the size and frequency of salvo threats by disabling and destroying enemy strike aircraft and TELs before they can launch their weapons. In other words, the U.S. military should be prepared to conduct offensive operations to kill an enemy's archers before they launch their PGM arrows.

During the Cold War, the Navy adopted the Outer Air Battle (OAB) operational concept designed to intercept Soviet aircraft before they could attack the U.S. fleet. The Navy implemented this concept because salvos from Soviet bombers threatened to exceed the defensive capacity of U.S. ships.[22] The bombers, therefore, had to be defeated before they could launch their ASCMs. The Navy separated OAB offensive AAW operations against bombers from defensive AAW operations against missiles, using different weapons for each mission. After the Cold War, the Navy and other U.S. military forces returned to an AAW approach centered on defeating all air threats, whether aircraft or weapons, as far as possible from defended targets and using the same interceptors for either operation. This places U.S. forces at a significant cost and capacity disadvantage. Long-range (50–100 nm) interceptors are much larger and more expensive than medium-range (10-30 nm) interceptors such as ESSM. As a result, U.S. forces could expend two or more interceptors that cost $3 million each to defeat a cruise missile that costs $2–3 million.

As recommended by previous CSBA reports, DoD should more clearly separate its long-range offensive operations to suppress enemy missile launchers, airbases, surface combatants, and submarines from shorter-range defensive operations designed to defeat individual weapons after they are launched.[23] Specifically, updated operational concepts would preferentially use long-range SAMs such as the SM-6 to engage enemy strike aircraft before they can launch their weapons, focusing medium-range and short-range defenses on defeating PGMs after they are launched. As illustrated in Chapter 4, using more expensive interceptors against aircraft and less expensive shorter-range systems against individual PGMs could result in more

22 James Winnefeld, "Winning the Outer Air Battle," *Proceedings*, U.S. Naval Institute, August 1989, p. 37, available at http://www.usni.org/document/winnefeld-james-jr-1989-115-8-1038pdf?magazine_article=6720.

23 See Gunzinger and Clark, *Restoring America's Precision Strike Advantage*, p. 30; and Bryan Clark, *Commanding the Seas: A Plan to Reinvigorate U.S. Navy Surface Warfare* (Washington, DC: Center for Strategic and Budgetary Assessments, 2014), p. 17.

favorable cost exchanges. It could also better align U.S. defensive systems with the ranges they are likely to detect and classify different air threats. Since the range of electromagnetic sensors such as radars are limited by the horizon, shipboard and land-based targeting radars would be able to detect high altitude enemy aircraft at longer ranges than sea-skimming ASCMs and terrain-following LACMs.

Land- and sea-based operations to intercept enemy archers could be more challenging than OAB operations envisioned by the Navy during the Cold War. Modern ASCMs and LACMs may be capable of flying longer ranges after launch compared to their Cold War counterparts, and land-based ballistic missiles such as the DF-21D can reach targets located 800–1,000 nm from their launch points. As a result, U.S. aircraft may need to fly extended-range CAPs to intercept enemy bombers before they can launch their cruise missiles. Since air-launched missiles such as China's KD-20 LACM can have ranges of more than a thousand nautical miles, U.S. long-range CAPs would require significant support from aerial refueling aircraft. As illustrated in Figure 11, posturing U.S. fighter aircraft at fixed and temporary airbases located along the first island chain in the Western Pacific may be able to conduct defensive counter-air missions with less need for aerial refueling support compared to fighters that are staged from more distant airfields.

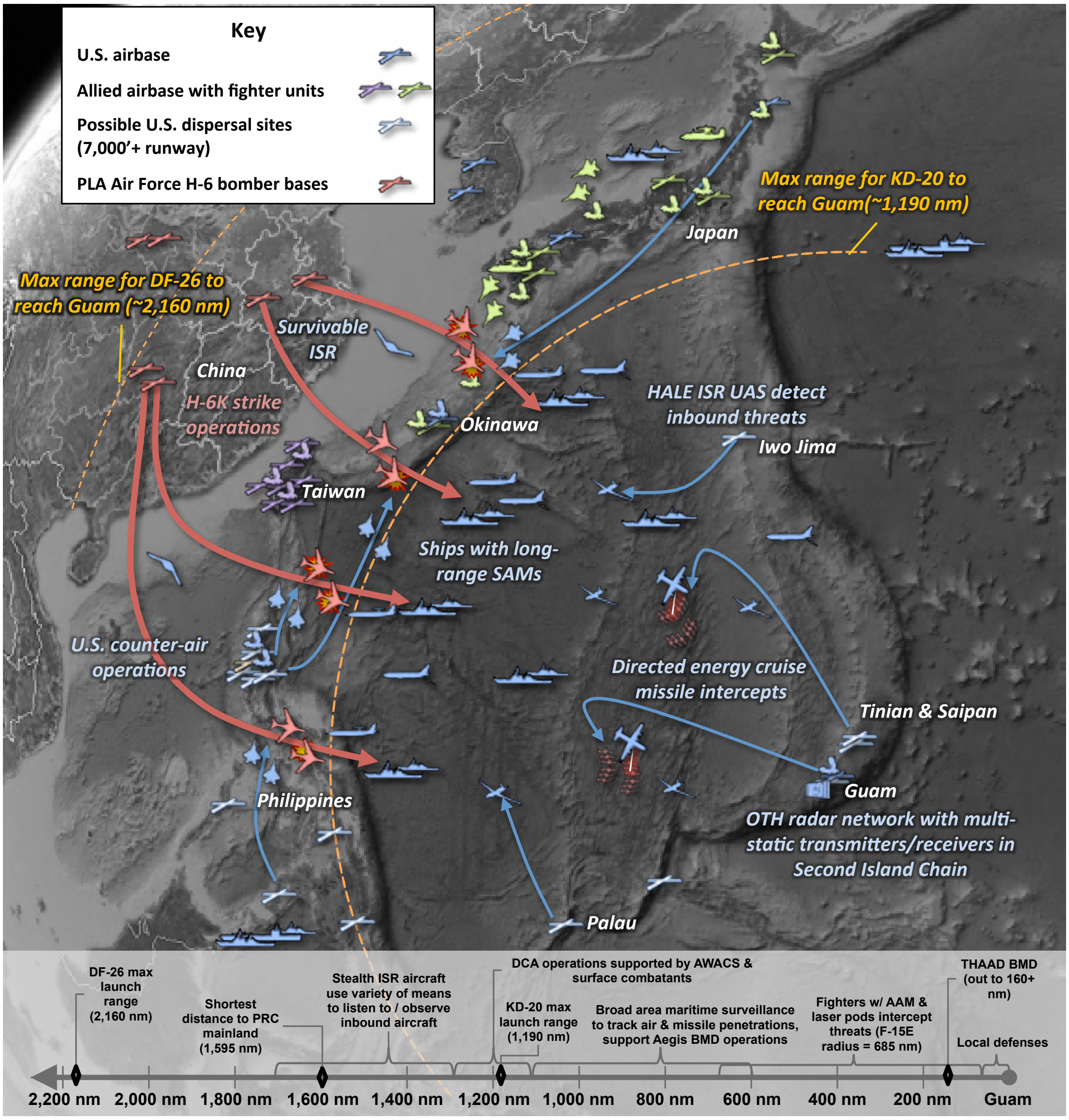
Figure 11 also illustrates a "right-of-launch" concept that uses unmanned ISR aircraft and C-130J aircraft equipped with SSLs to find and attack cruise missile salvos before they are within range of ground-based defenses located at U.S. military bases. This concept could allow defending aircraft to use their lasers to burn through the thin skins on the side of cruise missiles, vice ground-based point defense laser weapons, which may have to strike the hardened nosecones of incoming ASCMs and LACMs.[24]

Other extended range salvo suppression operations could include using penetrating ISR and strike aircraft to find, fix, track, target, and attack enemy land- and sea-based missile launchers. This will require the use of survivable stealth strike platforms such as the B-2, the future Long-Range Strike Bomber (now known as the B-21), submarines, and possibly land- and carrier-based unmanned combat air vehicles (UCAVs) capable of persisting in contested areas.[25]

24 Using lasers against the relatively soft sides of cruise missiles could reduce the amount of time needed to defeat them relative to the time needed to burn through their hardened nosecones. Chapter 4 expands on how the lethality of laser weapons are subject to a variety of factors, including their power, environmental factors, and characteristics of potential targets.

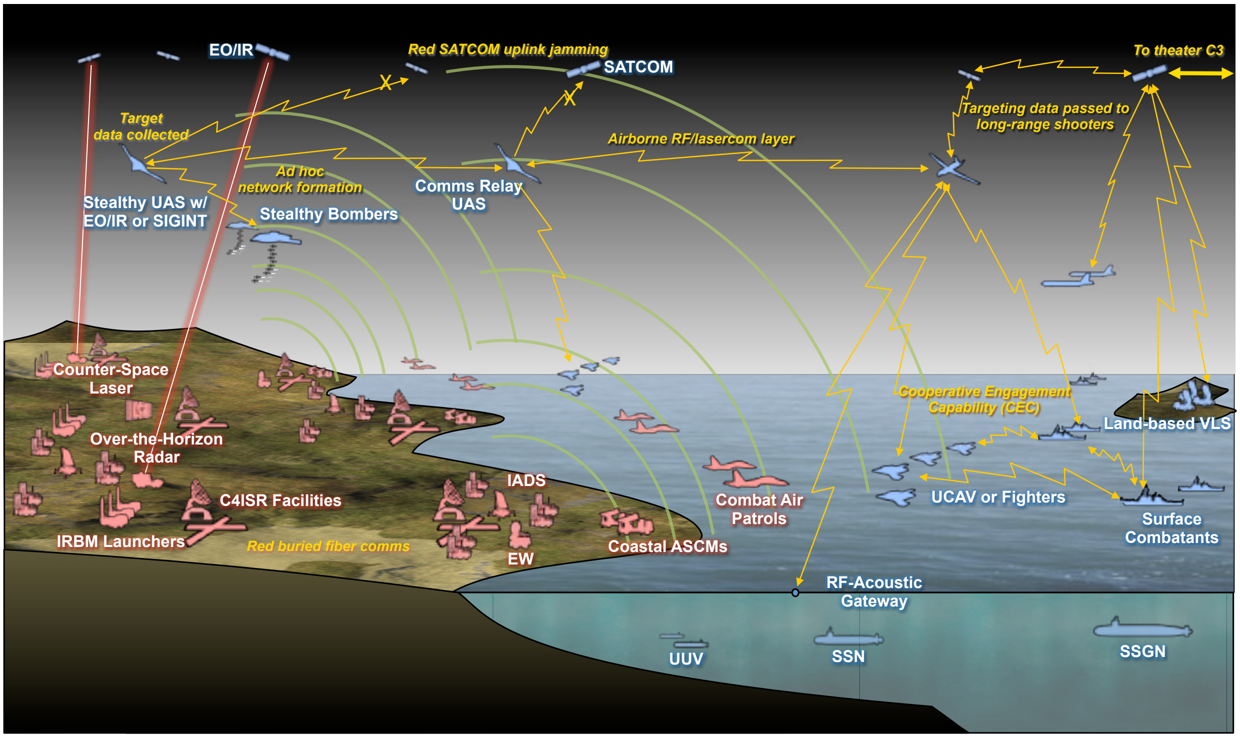
25 For more information on desirable capability attributes for future UCAVs, see Robert Martinage, *Toward a New Offset Strategy* (Washington, DC: Center for Strategic and Budgetary Assessments, 2014), p. 87.

FIGURE 11: INTERCEPTING THE ARCHERS



Over-the-horizon missile suppression operations will need the support of networks that are designed to link strike aircraft, airborne and space-based sensors, and standoff attack weapons into a single "sensor-shooter" complex. This complex could include a battle network similar to the Naval Integrated Fire Control-Counter Air (NIFC-CA) that integrates counter-air operations between Aegis ships, E-2D and E-3 early warning aircraft, and other sensors (see Figure 12).

FIGURE 12: NOTIONAL INTEGRATED FIRE CONTROL-COUNTER AIR NETWORK



In summary, the U.S. military should adopt operational concepts that could significantly reduce the size of an enemy's PGM salvos. Shifting toward operating from bases located in more secure areas, dispersing forces that must operate inside A2/AD threat rings, and cluster base operations would complicate an enemy's precision targeting and dilute its salvos. Offensively, operations to suppress enemy sea-based, ground-based, and airborne launch platforms before they can salvo their weapons could further reduce the challenge for U.S. air and missile defenses.

Increasing the Capacity of U.S. Air and Missile Defenses

CSBA's *Sustaining America's Precision Strike Advantage* report focused on how the range, cost, and size of PGMs may affect the U.S. military's offensive salvos. It determined that air-delivered standoff attack weapons with long ranges—greater than 400 nm—are usually so large that they reduce the overall number of PGMs (salvo size) that can be launched by individual aircraft, and they are typically more expensive than short-range PGMs. Using standoff weapons with less than 100 nm range, however, could require strike aircraft to penetrate advanced point defenses. Thus, the report concluded that PGMs with standoff ranges between 100–400 nm could help maximize the size of the U.S. military's strike salvos and reduce risk to its penetrating manned and unmanned aircraft.

Establishing the right balance between the range, cost, and density of weapons also applies to the defensive dimension of the salvo competition. DoD's air and missile defenses are now heavily weighted toward surface-to-air interceptors that have long ranges and are large, technically complex, and expensive. The sizes of these weapons reduce the number that individual launchers can carry, and their high unit costs create unfavorable cost exchanges in salvo competitions. The following sections address how operational concepts that preferentially use medium-range interceptors and non-kinetic capabilities could increase the density of the U.S. military's salvo defenses and create more favorable cost exchanges.

Sea-based defensive AAW operations

As mentioned in Chapter 1, the proliferation of anti-ship weapons may require the Navy to dedicate more of its ship-based VLS capacity to AAW weapons at the expense of VLS offensive weapons. The Navy could reverse this dynamic and free VLS capacity for offensive weapons by adopting the air defense approach described above that separates offensive AAW from defensive AAW.[26] Shifting toward a medium-range missile defense scheme while reserving long-range, costly SAMs to counter enemy strike aircraft could significantly increase the number of defensive AAW weapons surface ships can carry in their VLS magazines while retaining the ability for ships to protect one another from air threats.[27] This approach could center on using medium-range (10–30 nm) interceptors such as the ESSM, four of which can be loaded in a single VLS cell compared to a single SM-2 or SM-6. This would nearly quadruple a ship's defensive AAW inventory or free VLS capacity for offensive AAW and strike weapons. It could help create more favorable cost exchanges, because the cost of an ESSM is about one-third

26 For the purposes of this report, *offensive* AAW operations that defeat aircraft and other weapons platforms are separate from *defensive* AAW operations that defeat cruise and ballistic missiles and air-delivered PGMs. While anti-air warfare is a term used by the Navy and Marine Corps and not the Air Force, this taxonomy is a useful way to explain how the U.S. military could change its operational concepts to address salvo threats. This concept is described in greater detail in Clark, *Commanding the Seas*.

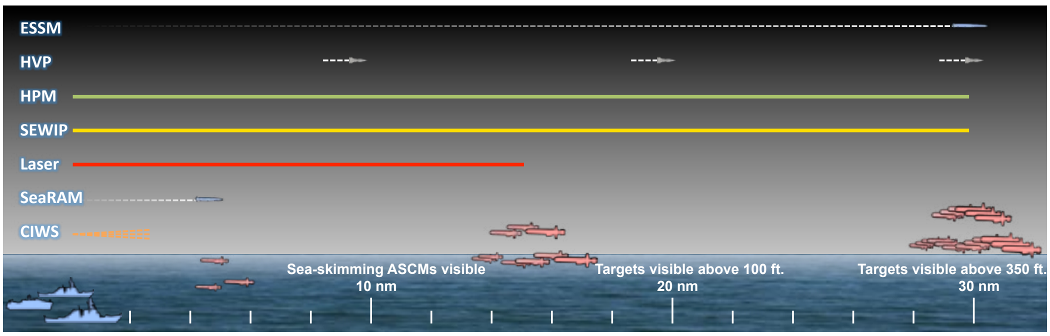
27 Shipboard air defenses intended to protect a nearby ship will need to have ranges of at least10 nm. This would enable the defending ship to engage threats at least 5 nm away from the ship being attacked while maintaining a safe navigational distance of 5 nm between the two ships.

that of an SM-6. Further, the new Block 2 variant of the ESSM will incorporate an active seeker similar to the SM-6.[28]

A medium-range missile defense operational concept would enable ships to better complement kinetic interceptors with traditional and electromagnetic guns, which could have ranges of 10–30 nm against missiles if equipped with hypervelocity projectiles. This new approach would also enable electronic warfare jammers and decoys, solid state lasers, and high power microwave weapons to contribute to air defense.[29] Although these systems have much greater capacity than kinetic interceptors, they are limited by the horizon and only used today as a last resort after long-range interceptors have failed.

Figure 13 illustrates the relative ranges of capabilities, including EW systems, that could support the Navy's defensive AAW operations.

FIGURE 13: ILLUSTRATIVE SHORT- AND MEDIUM-RANGE DEFENSIVE AAW CAPABILITIES



Now in development, EMRGs that fire GPS-guided or command-guided HVPs at hypersonic speeds (greater than Mach 5) could intercept threat aircraft and missiles at medium ranges. These projectiles will have a limited ability to adjust their trajectories to intercept a moving target. Therefore, the longer a target has to maneuver, the lower the probability an EMRG round will engage it successfully. For example, an HVP traveling at Mach 7 would take 20 seconds to reach a Mach 2 cruise missile located 30 nm from the HVP's launch point. Although the Navy's developmental 32-megajoule (MJ) EMRG is capable of firing an HVP about 100 nm

28 This approach includes the use of short-range kinetic systems such as RAM and CWIS.

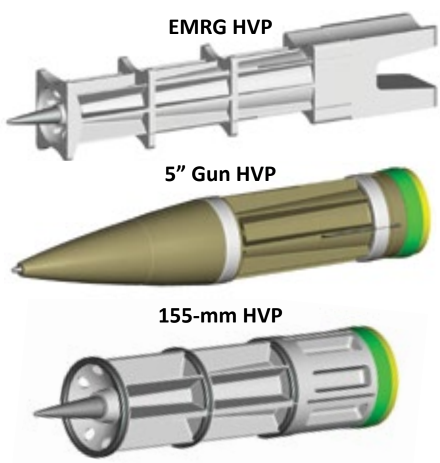
29 For an assessment of electromagnetic spectrum operational concepts and capabilities, see Bryan Clark and Mark Gunzinger, *Winning the Airwaves: Restoring U.S Dominance in the Electromagnetic Spectrum* (Washington, DC: Center for Strategic and Budgetary Assessments, 2015).

against a surface target, beyond 30–40 nm an unpowered HVP may not be able to adjust its flight path sufficiently to intercept a maneuvering cruise missile.[30]

HVPs fired by 5-inch guns carried by Navy destroyers and cruisers could complement EMRGs. While HVPs launched by these so-called "powder guns" may only achieve a velocity of Mach 3 when they leave their gun barrels, they may still have sufficient range and energy to intercept cruise missiles at 10 nm range. HVPs fired from the 6-inch guns carried by Navy DDG-1000 *Zumwalt*-class destroyers could intercept air and missile threats at slightly longer ranges.

Maturing DE capabilities such as high power microwave weapons and solid state lasers could also have sufficient power and range to contribute to air defense operations at sea. SSLs damage enemy weapons by rapidly heating their casings, whereas HPM weapons disrupt or destroy critical electronic components in PGM guidance and control systems. Because they cannot engage targets over the horizon and are affected by some atmospheric conditions, shipboard DE systems may be most effective as medium-range (10–30 nm) defenses against softer targets such as cruise missiles, UAVs, and G-RAMM rather than hardened ballistic missile warheads.

FIGURE 14: HYPERVELOCITY PROJECTILES FOR EMRG, 5-INCH GUN, AND 155MM ARTILLERY; NAVY LASER WEAPON SYSTEM ON USS PONCE



Concept graphics by BAE systems.

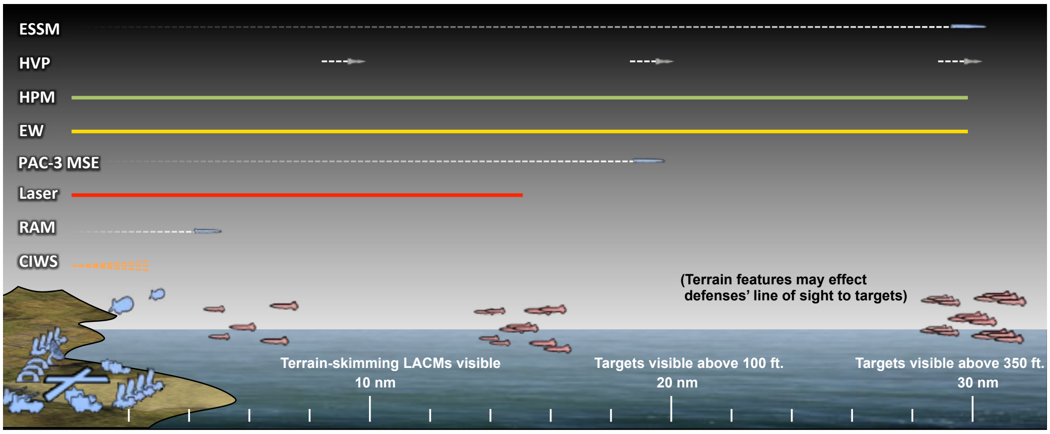
Photo by U.S. Navy.

30 The U.S. Navy completed a technology effort to develop a prototype railgun that generates 32 MJ of muzzle energy, which is sufficient to propel a projectile approximately 100 nm. The Navy's next step is to "concentrate on demonstrating a ten rounds-per-minute firing rate" for a railgun. Office of Naval Research, "Electromagnetic Railgun," available at http://www.onr.navy.mil/Science-Technology/Departments/Code-35/All-Programs/air-warfare-352/Electromagnetic-Railgun.aspx. In 2016, the Navy plans to mount a prototype railgun on a joint high speed vessel (JHSV) for testing.

An alternative operational concept for base defense

DoD could increase the density of air and missile defenses protecting its theater bases by using a similar operational concept as described above for sea-based forces. This new approach would continue to defeat relatively small ballistic missile salvos using long-range Aegis Ashore VLS-launched interceptors, THAAD, and Ground Based Interceptors (GBI) to intercept warheads in their mid-course and terminal phases of flight.[31] Against much larger LACM and G-RAMM salvos, base defenses would use a combination of short- and medium-range interceptors, HVPs fired by artillery and railguns, and DE weapons (see Figure 15).

FIGURE 15: ILLUSTRATIVE SHORT- AND MEDIUM-RANGE BASE DEFENSES



This base defense architecture could incorporate smaller or less expensive medium-range (10–30 nm) interceptors such as PAC-3, shore-based VLS-launched ESSM, a variant of the David's Sling air defense weapon now operated by Israel, a derivative of an air-to-air missile such the Accelerated Improved Interceptor Initiative (AI3) weapon, or the Army's Indirect Fire Protection Capability (IFPC) Increment 2.[32] As with sea-based defenses, these smaller interceptors could be procured and deployed in greater numbers than their larger long-range counterparts. And while PAC-3 Missile Segment Enhancement (MSE) interceptors are relatively expensive ($5 million), their cost could be reduced by taking advantage of new technologies. All of these capabilities are mature and could be quickly moved into production.

Future medium-range base defenses could also include EMRGs, SSLs, EW systems, HPM weapons, and HVPs fired by powder guns like the Army's "Paladin" 155mm self-propelled

31 While Aegis ships could contribute to defending forward bases, using less expensive and more efficient shore-based BMD system options should be explored before dedicating multi-mission capable ships to base defense.

32 The AI3 uses the motor from an AIM-9M air-to-air missile and a low-cost, semi-active seeker. The IFPC launcher uses existing AIM-9X Block 2 air-to-air missiles.

howitzers.[33] Land-based electric weapons could be more capable and have longer ranges than their ship-based counterparts, since they would be less constrained by shipboard space, power, and cooling limitations. That said, land-based air and missile defenses will need to be road-mobile or relocatable in order to complicate an enemy's ability to counter-target them.

FIGURE 16: LAUNCH OF A DAVID'S SLING

Photo by Missile Defense Agency.

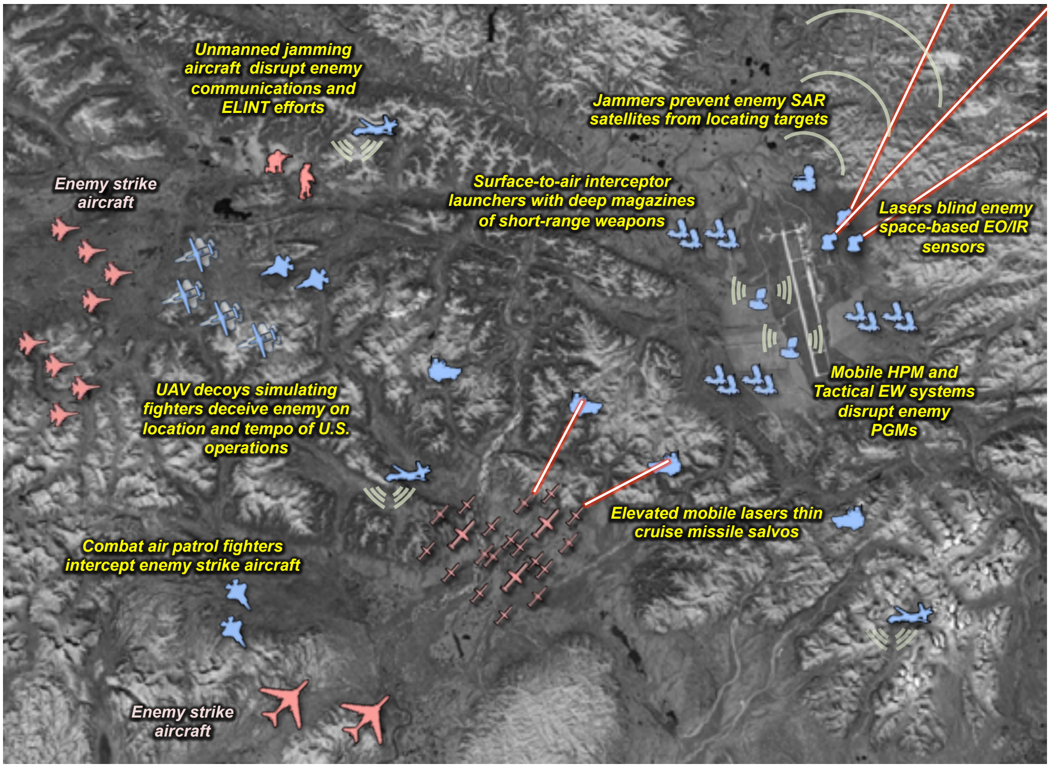
Land-based electric weapons have some characteristics that could make them easier to transport compared to interceptor-based systems. HVPs, for example, are relatively small. And although the supporting systems needed to generate and store enough energy to launch HVPs can be very large, advances in pulsed power technology and energy storage could shrink EMRGs to a size that could allow them to be carried by ground vehicles. Lasers and HPM weapons use less electric power than EMRGs and do not require storage and resupply of propellant charges or interceptors. Chapter 3 expands on the advantages and limitations of these future capabilities.

While laser and HPM weapons could improve the density of defenses protecting U.S. bases and forces, they will complement rather than replace kinetic interceptors. Unfavorable atmospheric conditions may occasionally preclude the use of laser weapons or reduce the amount of energy a laser weapon can place on targets at operationally useful ranges. Although HPM weapons are affected less by weather and other atmospheric conditions than lasers, basic physics dictates that their beams will project energy over a wider area than lasers, increasing the potential they could affect or damage friendly forces in immediate proximity to intended targets.

Figure 17 illustrates how a system-of-systems that includes electronic warfare for jamming enemy threat sensors and weapon guidance systems, decoys, directed energy defenses, and kinetic interceptors could help defend U.S. theater bases against PGM salvos.

33 HPM weapons will have a greater effect if details are known about the design and vulnerabilities of enemy networks. U.S. Air Force, "Fact Sheet: High Power Microwave Weapons," available at http://www.de.afrl.af.mil/pa/factsheets; and "US Air Force Moves Forward with High-Power Microwave Weapon," *Defense Update,* May 16, 2015, available at http://defense-update.com/20150516_champ.html#.VijFhdadLzI.

FIGURE 17: CONCEPT FOR AN INTEGRATED MEDIUM-RANGE BASE DEFENSE



These weapon systems in combination could enable U.S. forces to operate at higher tempos from bases located in contested areas. This will require DoD to determine requirements and fund programs that will integrate the operations of ground-based, airborne and space-based sensors with a dispersed network of kinetic and non-kinetic defenses. This system-of-systems will also need battle management systems and secure communications links in order to detect and characterize salvos, then match and sequence appropriate defenses against each incoming threat.

Creating defensive advantages

The concepts described above have the potential to increase the density of America's salvo defenses at sea and on land. An AAW scheme that prioritizes the use of medium-range interceptors, EMRGs, SSLs and electronic warfare systems could create a higher capacity defense than today's layered architecture. VLS cells and Patriot launchers can carry four ESSM or PAC-3-sized SAMs compared to a single SM-6 or PAC-2. And since electronic warfare systems, HPM weapons, and SSLs are capable of firing as long as they are provided with sufficient electricity and cooling, they would increase the total number of threat engagements possible without requiring significantly more space.

New operational concepts and a different mix of defenses also promise to shift salvo cost exchange dynamics in favor of defenders. Interceptors such as the ESSM are less expensive than most long-range interceptors now in the U.S. inventory (see Appendix 5). Electromagnetic energy from jammers, lasers, and HPM weapons capable of successfully engaging armed drones, G-RAMM, some cruise missiles, and other threats could cost less than $100 per threat engagement. At an estimated unit cost of $25,000–$50,000 depending on their size and capabilities, HVPs would be a bargain compared to the least expensive ASCMs and ballistic missiles they intercept. Chapter 4 presents several case studies that illustrate these advantages.

There are other benefits that could result from operational concepts that place a greater weight on using medium-range capabilities to defend against PGM salvos. In addition to increasing the density of a ship's defenses, a medium-range AAW concept could free up ship VLS capacity for strike weapons. It could also have a force multiplying effect, since ships with greater AAW capacity may be able to remain in contested areas for longer periods of time before they leave the fight to replenish their magazines.

In summary, overcoming the disparity between the size and cost of enemy salvos and U.S. air and missile defenses will require more than simply buying additional long-range surface-to-air interceptors. Concepts such as operating from range, dispersed basing, cluster base operations, and improving base resiliency could decrease the density and effectiveness of enemy salvos. Offensive operations against enemy airbases and launch platforms could further reduce the size and frequency of enemy strikes, while shifting toward concepts for fleet AAW and base defense that preferentially use medium-range kinetic and non-kinetic capabilities could increase the density of U.S. countervailing attacks. Chapter 3 further assesses the technological maturity and other factors affecting the development and fielding of a new generation of short- and medium-range AAW capabilities.

CHAPTER 3

Enabling Capabilities and Technologies

Chapter 3 addresses capabilities and technologies that will be essential to defeating large PGM salvos against U.S. forces and bases. Today's layered air and missile defenses have much less capacity than needed, partially because DoD has prioritized the use of capabilities to engage threats as far from their intended targets as possible. As a result, U.S. forces employ their largest and most expensive kinetic interceptors first, then employ less expensive and higher capacity shorter-range defenses if available, and only as a last resort.

Operational concepts that separate offensive from defensive AAW and prioritize the use of medium-range kinetic and non-kinetic defenses could significantly increase the number of potential engagements against large PGM salvos. Defensive AAW capabilities could include EW systems, DE weapons, HVPs fired by EMRGs and powder guns, and medium-range interceptors. High-capacity electric weapons such as EW and DE systems will be most effective when used against threats at short and medium ranges, since their range is limited by the horizon, beam spreading, and atmospheric conditions. Given these limitations, future electric weapons should be complemented by medium-range interceptors that incorporate new warhead, guidance, and propulsion technologies to reduce their size and unit cost. While long-range interceptors will remain an important part of the salvo competition, it may be more effective to preferentially use them for offensive AAW against enemy strike aircraft. Since long-range SAMs such as SM-6 and PAC-2 are sufficient for these applications, they are not discussed extensively in this chapter.

Kinetic Defenses

Current interceptors

The U.S. military has a small number of interceptors and gun systems capable of supporting short-range (less than 5 nm) to medium-range (10–30 nm) air and missile defense operations. Short- to medium-range interceptors now in the U.S. inventory include the RAM, ESSM, and

PAC-3 MSE interceptors. The Phalanx CIWS, originally fielded on Navy ships and subsequently deployed on a mobile ground vehicle by the Army, is now the main gun system used by U.S. forces for air and missile defense.

TABLE 1: CURRENT SHORT-RANGE TO MEDIUM-RANGE KINETIC DEFENSES[34]

Point Defense (less than 5 nm)	Targets	Firing Rate (per minute)	Approximate Max Range	Guidance	Unit Cost (FY17 $K)
RIM-119 RAM	Surface ships, aircraft, missiles	30–60	5 nm[35]–7.5 nm[36]	IR and passive RF	$795
SeaRAM (RAM plus CIWS radar)	Surface ships, aircraft, missiles	30–60	5 nm–7.5 nm	IR and passive RF	$795
Phalanx CIWS	Small boats and missiles	30–60	2 nm	Computer-controlled, radar-guided	Upgrades only
Counter-Rocket, Artillery, Mortar Intercept Land-Based Phalanx Weapon System	Rockets, artillery, and mortars.	600	2 nm	Computer-controlled, radar-guided	Upgrades only
Area/Terminal Air and Missile Defense (10–30 nm)					
RIM-162 ESSM	Surface ships, aircraft, and missiles	30–60	30 nm[37]	Semi-active radar	$1,432 VLS variant
PAC-3	Aircraft and missiles	30–60	~10–30 nm[38]	INS and active radar	$4,979 MSE variant

34 INS: Inertial Navigation System; IR: infrared; RF: radio frequency.

35 Arthur Paul Drennan III, A Coordination Policy for the Evolved Sea Sparrow Missile and Rolling Airframe Missile using Dynamic Programming (Monterey, CA: Naval Postgraduate School, September 1994), available at https://www.hsdl.org/?view&did=450815.

36 RAM Block 2 missiles have a range of 7.5 nm. See Raytheon Company, “Rolling Airframe Missile,” available at http://www.raytheon.com/capabilities/products/ram/.

37 Andreas Parch, “Raytheon RIM-162 ESSM,” Directory of U.S. Missiles and Rockets, available at http://www.designation-systems.net/dusrm/m-162.html.

38 This minimum range of 10 nm is against ballistic missiles. While the maximum range of PAC-3 against cruise missiles is classified, it should be able to intercept cruise missiles in the medium-range window of this report’s air defense concept. George C. Marshall and Claremont Institutes, “Patriot (PAC-1, PAC-2, PAC-3),” Missile Threat, available at http://missilethreat.com/defense-systems/patriot-pac-1-pac-2-pac-3/.

In addition to lower unit costs, the smaller sizes of interceptors in Table 1 would enable more of them to be carried by weapon systems compared to longer-range missiles. Four ESSMs can be loaded in a VLS cell compared to a single SM-2 or SM-6, and three PAC-3 MSEs can be loaded in a Patriot launcher cell designed to carry one PAC-2. RAM interceptors are about 25 percent smaller than an ESSM or PAC-3 missile and thus could be carried in even larger numbers by ships or mobile air defense systems.

FIGURE 18: RIM-162 ESSM AND RIM-116 ROLLING AIRFRAME MISSILE

Photos by U.S. Navy.

Although smaller interceptors have historically been less capable than their larger, longer-ranged counterparts, DoD is leveraging new technologies to upgrade them. RAM Block 2, which reached initial operating capability (IOC) in 2015, has a new engine and control systems to enhance its range and maneuverability and an improved passive RF seeker to track enemy sensors that are using low probability of detection (LPD) modes.[39] The Navy will field ESSM Block 2 missiles in 2020, which incorporate a fully active RF seeker so they will not depend on a ship's radar to guide them to targets.[40] This "launch and leave" capability will enable ships to engage as many missile threats as there are interceptors available rather than being limited by radar resources.[41]

Despite planned improvements, RAM, ESSM, and PAC-3 interceptors alone will not provide the capacity needed to defeat large salvos of missiles and other PGMs that are likely to be launched by adversaries such as China or Iran. DoD will need to increase its medium-range air defense capacity by fielding kinetic defenses now in development that are small, low cost, and can effectively engage threats at ranges between 10 and 30 nm.

39 Megan Eckstein, "Navy Declares IOC on Rolling Airframe Missile Block 2," *USNI News,* available at http://news.usni.org/2015/06/11/navy-declares-ioc-on-rolling-airframe-missile-block-2.

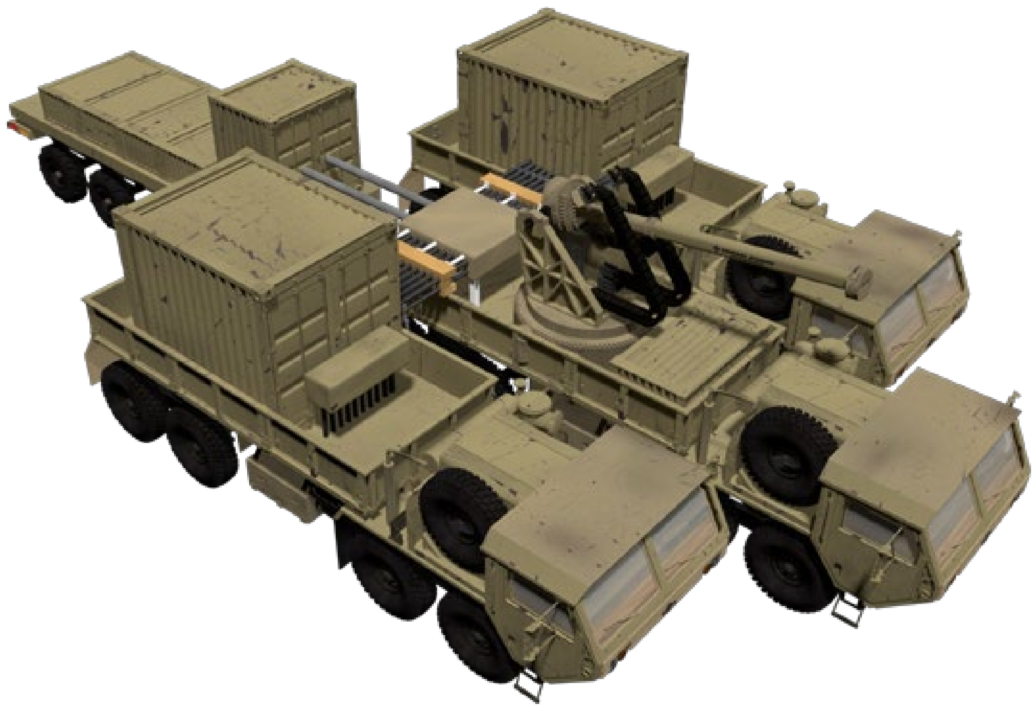
40 John Keller, "Raytheon Moves to Full-Scale Development of RIM-162 ESSM Block 2 Ship-Defense Missile," *Military & Aerospace Electronics,* April 17, 2015, available at http://www.militaryaerospace.com/articles/2015/04/essm-seasparrow-emd.html.

41 The ESSM Block 1 is a semi-active missile that homes in on a target using a radar illuminator from the launch platform. A ship has a finite number of radar illuminators.

Emerging kinetic defenses

Potential future interceptors. Air defense capacity could be further increased by shifting toward using smaller, less expensive missiles optimized for medium-range intercepts. Today the Army is developing Increment 2 (Inc 2) of the IFPC air defense system, which combines the 15-cell Multi-Mission Launcher (MML) with the AIM-9X air-to-air missile. Whereas IFPC Inc 1 uses a Stinger surface-to-air missile that is only capable at short ranges against relatively slow-moving aircraft, IFPC Inc 2 will be able to defeat aircraft and supersonic cruise missiles at ranges of 10-20 nm. Since an AIM-9X interceptor costs about $420,000, IFPC Inc 2 systems could significantly reduce the cost of LACM defenses compared to interceptors that cost $5 million or more each. Although IFPC Inc 2 offers to dramatically improve current air defenses, the Army plans to deploy it in small numbers with selected maneuver units, rather than to defend bases or other large force concentrations.

FIGURE 19: INDIRECT FIRE PROTECTION CAPABILITY MULTI-MISSION LAUNCHER



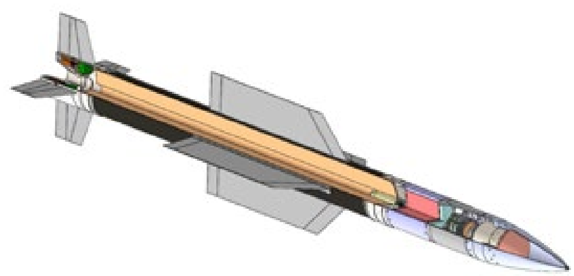
Concept graphic by GA-ASI.

The Army is also developing new air defense interceptors with even lower unit costs than the AIM-9X. The Service's Aviation and Missile Research, Development, and Engineering Center (AMRDEC) is pursuing a low-cost, longer-range, and smaller interceptor called the Lower Cost Extended-Range Air Defense Interceptor (Lower-AD). This program is taking advantage of new technologies in fuel loading, motor casings, smaller warheads, and thermal barriers to achieve a range of 15–20 nm and be effective against cruise missiles and UAVs. The cost objective for a Lower-AD missile is $400,000, about half the cost of a RAM.

The Accelerated Improved Interceptor Initiative is another example of a new less costly, small interceptor. AI3 uses an AIM-9M engine, the Small Diameter Bomb II's low-cost active seeker, and a new explosively formed warhead. The weapon is estimated to cost about $100,000, five to ten times less than the unit cost of interceptors listed in Table 1. And while the range of AI3 will initially be limited to 5–7 nm, future variants could have propulsion units that extend their flight profile to medium ranges.[42]

DoD could take advantage of efforts to develop land-based weapon systems such as AI3 and Lower-AD to field new sea-based defenses. For example, a future RAM with a range of at least 10 nm could be a sea-based area defense interceptor rather than a point defense system of last resort. It would also significantly increase shipboard defensive AAW capacity, since a RAM is half the diameter of an ESSM and could be adapted so that a single VLS cell could carry eight to sixteen RAMs.

FIGURE 20: LOWER-AD INTERCEPTOR AND AI3 INTERCEPTOR



Concept graphic by U.S. Army.

Photo by Raytheon.

Future gun systems. Current air defense gun systems such as CIWS engage enemy missiles with unguided rounds fired from a radar-steered barrel. Because they are unguided, hundreds of CIWS rounds may be expended in each engagement as the gun barrel is steered to intercept a moving target. Further, gun system ranges are constrained by the need to minimize the time available for the target to maneuver while gun rounds are in flight.

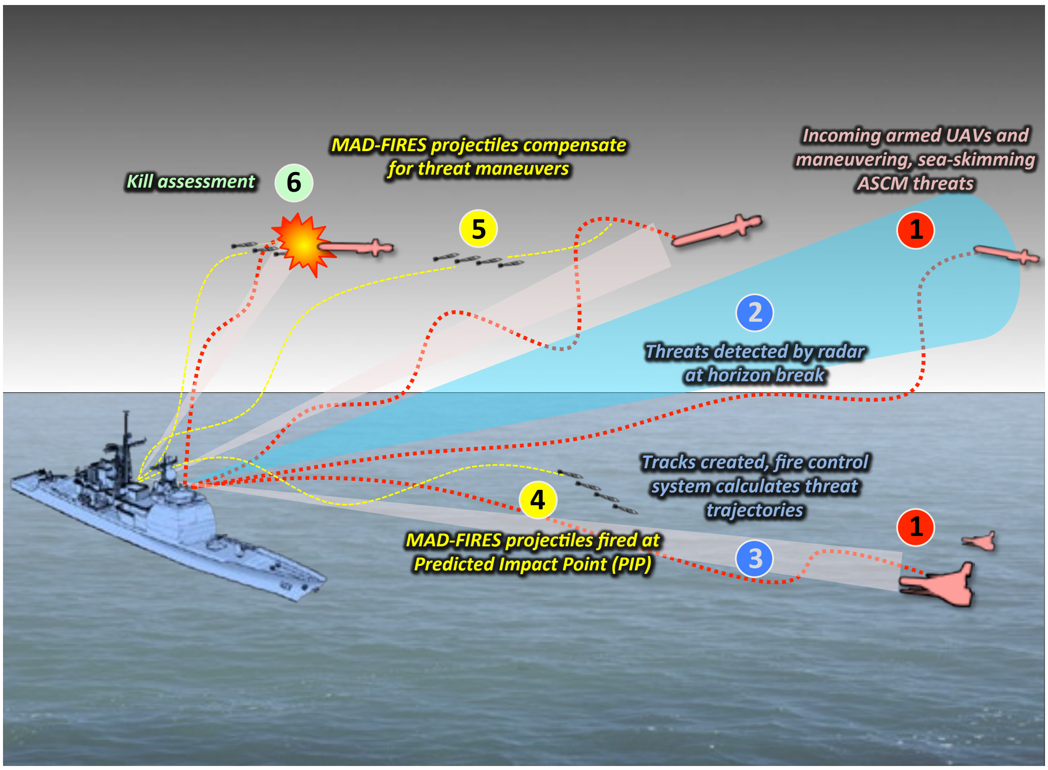
These shortfalls could be mitigated by future gun systems that fire guided projectiles. They may also offer the best opportunity to quickly increase U.S. air and missile defense capacity,

42 Jen Judson, "Army Seeks More Adaptable, Modular Missile Systems," *Defense News,* October 12, 2015, available at http://www.defensenews.com/story/defense/show-daily/ausa/2015/10/12/army-seeks-more-adaptable-modular-missile-systems/73841226/.

since gun systems are organic to a large number of DoD's platforms and units, and they are supported by mature sustainment and logistics infrastructure.

DoD is pursuing several programs for guided projectiles. The Defense Advanced Research Projects Agency (DARPA) Multi-Azimuth Defense Fast Intercept Round Engagement System (MAD-FIRES) program is developing a medium caliber (approximately 20mm to 76mm) artillery round with an on-board seeker capable of guiding it to a target.[43] The smaller rounds will be able to provide point defenses at 5 nm or less, whereas longer-range rounds will be able to reach 10 nm or more to support medium-range defensive operations. Figure 21 illustrates a ship-based MAD-FIRES concept capable of intercepting multiple threats such as cruise missiles and armed UAVs in a short period of time.

FIGURE 21: ARTIST'S CONCEPT OF MAD-FIRES THREAT ENGAGEMENTS



Larger guided projectiles will be able to intercept air and missile threats at 10–30 nm ranges. The Office of Naval Research (ONR) is pursuing guided hypervelocity projectiles that could be

43 Jerome Dunn, "Multi-Azimuth Defense Fast Intercept Round Engagement System (MAD-FIRES)," Defense Advanced Research Projects Agency, http://www.darpa.mil/program/multi-azimuth-defense-fast-intercept-round-engagement-system.

fired from powder guns and EMRGs and directed to intercept air and missile targets rather than using an on-board seeker.[44] HVP variants could be used in the 5-inch Mk 45 Naval Gun System, the Paladin self-propelled howitzer, and possibly the Excalibur artillery system.

FIGURE 22: 155MM HOWITZER

Photo by Staff Sgt. Nelia Chappell, U.S. Army.

Current HVP designs have control surfaces, small thrusters, or weights to enable them to change course and compensate for small target location errors and target maneuvers. Even equipped with 10- to 20-pound warheads, HVPs would still need to either directly hit or explode in close proximity to their targets. To attain these close intercepts, HVPs and their targets will need to be tracked by very precise systems such as an interferometric radar or a modified version of today's fire control radars. This tracking data must be provided to HVPs via a datalink to ensure they intercept their targets. Some HVP variants now in development will use seekers to consummate engagements, eliminating the need for a more accurate radar to provide them with guidance. These efforts will have to overcome the effects created by flight at hypersonic speeds, which produces a plasma of hot gas at the nose of HVPs.

44 Office of Naval Research, "Hypervelocity Projectile," September 2012, available at http://www.onr.navy.mil/~/media/Files/Fact-Sheets/35/Hypervelocity-Projectile-2012B.ashx.

HVPs will reach speeds of about Mach 3 when launched from powder guns, giving them a closing speed of about one mile per second against cruise missiles that are also flying at Mach 3.[45] As described in Chapter 3, the need to reduce the time available for a target to maneuver, combined with the ranges of gun systems will limit powder gun-launched HVPs to engagement ranges of about 10–20 nm against maneuvering air targets and 40–50 nm against slower moving or fixed surface targets.[46]

HVPs could achieve longer ranges and greater precision if launched from EMRGs which use pulsed magnetic fields to accelerate their rounds along a gun-like armature to speeds of Mach 5 to Mach 7.[47] The Navy is developing land-based 20 MJ and 32 MJ EMRG prototypes that launch HVPs against surface targets at ranges of 50–100 nm.

FIGURE 23: PROTOTYPE EMRG AND ARTIST'S CONCEPT OF AN EMRG ON THE USNS TRENTON

Photo by U.S. Navy. Concept graphic by U.S. Navy.

An EMRG's higher muzzle velocity reduces an HVP's time-of-flight, improving its ability to accurately engage threat missiles at longer ranges relative to powder guns.[48] Faster muzzle velocities of HVPs launched from EMRGs could make them useful air defense weapons out to 30–40 nm, the edge of the medium-range envelope.

Since EMRGs use a magnetic field to accelerate HVPs instead of chemical propellants that require special magazines, EMRG weapons may enable a larger number of rounds to be carried by ships or mobile launchers compared to powder gun systems. Achieving the strong magnetic fields needed by an EMRG, however, will require a significant amount of electrical

45 The speed of sound at sea level is about 700 nm per hour, which results in a closing speed of about 4,200 nm per hour or about 1.2 nm per second. See Sam LaGrone, "Updated: Navy Researching Firing Mach 3 Guided Round from Standard Deck Guns," *USNI News*, June 1, 2015 (updated June 2, 2015).

46 This results in a time-of-flight of about 10–20 seconds. Of note, the range of an HVP from a 6-inch Advanced Gun System on DDG-1000 is estimated to be about 70 nm. See BAE Systems, "Hyper Velocity Projectile Datasheet," March 2015, available at http://www.baesystems.com/en/product/hyper-velocity-projectile-hvp.

47 This is similar to how a magnetically elevated train is propelled along its track.

48 Sam LaGrone, "Navy Wants Rail Guns to Fight Ballistic and Supersonic Missiles Says RFI," *USNI News,* January 5, 2015.

power—approximately 10–20 MW for the developmental 32 MJ gun.[49] This amount of power is not available on the Navy's current surface combatants, but could be provided by new *Zumwalt*-class destroyers which have an overall electrical generating capacity of about 70 MW that can be apportioned to weapons, sensors, or ship propulsion. The Navy is considering installing an EMRG on one of its *Zumwalt*-class destroyers, the last two of which are under construction.[50] In the near-term, the Navy is considering deploying an EMRG prototype on the Expeditionary Fast Transport (EPF) USNS Trenton in 2016 using a set of auxiliary generators to supply the necessary electrical power.[51]

Power capacity may be less of a concern for land-based EMRGs. For instance, the self-contained 10 MJ railgun weapon system concept shown in Figure 19 uses existing technologies for pulsed power, energy storage, and other technologies derived from the Navy's developmental EMRGs. Now in development, the relocatable EM railgun would be capable of launching HVPs at similar rates to Navy EMRGs and use accompanying vehicles carrying generators to recharge the weapon's energy magazine, a cooling system, and HVP reloads.[52]

Firing rates, ranges, and cost will be important considerations when determining appropriate combinations of gun systems to counter large PGM salvos. An Mk 45 5-inch gun can fire HVPs at about twenty rounds per minute, whereas the Navy's objective for EMRGs is six to ten rounds per minute and the ground-based system in Figure 19 could reach rates of twenty rounds per minute.[53] In comparison, a 155mm howitzer can fire at about six to eight rounds per minute.[54]

It is likely that future enemies will attempt to launch PGM salvos designed to saturate U.S. defenses by having a large number of missiles arrive within a one- to two-minute window. To affordably provide the high capacity needed against these salvos, an air defense system could include a small number of relatively expensive EMRGs to engage targets at 30–40 nm and a large number of less expensive powder guns to engage targets at 10–30 nm. Further analysis is needed to more fully evaluate tradeoffs between the longer ranges of EMRGs against the increased firing rates of powder guns as these capabilities mature.

49 Kris Osborn, "Navy Plans to Test Fire Railgun at Sea in 2016," *Military.com,* April 7, 2014, available at http://www.military.com/daily-news/2014/04/07/navy-plans-to-test- re-railgun-at-sea-in-2016.html; and "Electromagnetic Rail Gun (EMRG)," *Global Security,* May 19, 2014, available at http://www.globalsecurity.org/military/systems/ship/systems/emrg.htm.

50 Sam LaGrone, "Navy Considering Railgun for Third *Zumwalt* Destroyer," *USNI News*, February 5, 2015 (updated February 11, 2015); Mike McCarthy, "Navy Aiming To Put Railgun On Third *Zumwalt* Destroyer," *Defense Daily*, February 6, 2015; and Kris Osborn, "Navy Will Test its Electromagnetic Rail Gun aboard DDG 1000," *DefenseTech*, April 15, 2015.

51 Naval Sea Systems Command Office of Corporate Communication, "Navy to Deploy Electromagnetic Railgun Aboard JHSV," *Navy News Service,* April 7, 2014, available at http://www.navy.mil/submit/display.asp?story_id=80055.

52 The concept illustrated in Figure 19 would have 220 HVPs in a ready rack feeding the gun, 880 additional HVP rounds to reload the ready rack, and an organic thermal management system.

53 Kelsey Atherton, "The Navy Wants to Fire Its Ridiculously Strong Railgun from the Ocean," *Popular Science*, April 8, 2014, available at http://www.popsci.com/article/technology/ navy-wants- re-its-ridiculously-strong-railgun-ocean.

54 An M777A 155mm howitzer can fire six rounds a minute; the 155mm Paladin gun system can fire up to eight rounds a minute.

Table 2 provides additional details on these potential kinetic air and missile defenses.

TABLE 2: FUTURE KINETIC DEFENSES

Point Defense (less than 5 nm)	Targets	Firing Rate Per Minute	Approximate Max Range	Guidance	Unit Cost (FY17 $)
Accelerated Improved Interceptor Initiative	Aircraft and missiles	30–60 depending on launcher	57 nm	Active radar	$100k
Area/Terminal Air and Missile Defense (10–30 nm)					
Medium-caliber rapid-fire gun with MAD-FIRES projectile	Small aircraft, missiles, possibly surface threats	80	5–10 nm	Active radar	Five-round burst $125k
Powder gun with HVP	Surface ships, aircraft, G-RAMM	6–20	10–20 nm	INS, command guidance	HVP $25k to $50k
Electromagnetic Railgun with HVP	Surface ships, aircraft, missiles	6–10	10–40 nm	INS, command guidance	HVP $25k
IFPC Inc 2	Aircraft and missiles	30–60 depending on launcher	10–20 nm[55]	Passive IR	$420k
Lower-AD	Aircraft and missiles	30–60 depending on launcher	15–20 nm	Active radar and passive IR	$400k

Mature and Maturing Technologies for Non-Kinetic Salvo Defenses

A combination of kinetic and non-kinetic capabilities would create more robust defenses against large weapon salvos that China, Russia, Iran, and North Korea are capable of launching at targets located near their borders. Over the next decade, DoD could complement its kinetic defenses with non-kinetic electric weapons such as SSL, HPM, and EW systems that use electromagnetic energy to divert, damage, or destroy incoming salvos. Since these defenses will use electricity to create their beams, they would provide deployed U.S. forces with nearly unlimited magazines capable of engaging threats as long as they are provided with sufficient power and cooling.

While non-kinetic weapons promise to increase the capacity of U.S. salvo defenses, several factors may limit their effective ranges to 10–30 nm depending on the types of targets they are attacking and target engagement geometries. Since electromagnetic energy travels in a straight line, surface-based non-kinetic defenses may not be able to target low-flying weapons such as cruise missiles until they are less than 10 nm away. This would give their operators less than

55 Federation of American Scientists, "AIM-9 Sidewinder," available at http://fas.org/man/dod-101/sys/missile/aim-9.htm.

20 seconds to counter an incoming salvo. Non-kinetic defenses such as lasers and HPM systems carried by manned or unmanned aircraft could achieve longer ranges against low-flying threats. In addition to being constrained by the horizon, the lethality of non-kinetic defenses decreases with increasing range as their energy is deposited over a wider area; this will likely limit the effective range of shipboard and mobile land-based systems to 10–30 nm.

The number of threats that can be engaged by non-kinetic defenses in a short period of time may also be limited by their kill mechanisms. Future SSL weapons will need to place a high-power beam on an incoming threat for a number of seconds in order to sufficiently damage its guidance system or structure before moving on to a new threat. While a single EW system may have multiple beams, each can only engage one threat at a time and must continue to dwell on the threat until it appears likely to miss the intended target. Similarly, HPM weapons can have multiple beams and will likely need to dwell on a target until it appears to be defeated. The reaction of an incoming missile to an HPM attack, however, will likely be more significant than to an EW attack, so an HPM weapon may be able to engage more threats in a salvo.[56]

Shifting toward medium-range air defense schemes would enable the U.S. military to take advantage of the large magazine potential of electric weapons while mitigating their limitations. Today, these capabilities are often considered to be weapons of last resort, only to be used after kinetic interceptors have failed to defeat a threat or been expended. Operational concepts proposed by this report would partially reverse this dynamic by preferentially using electric weapons against targets that are most vulnerable to their attacks while reserving interceptors for targets requiring kinetic engagements.

High power lasers

Lasers generate high-energy beams of electromagnetic energy by using photons from banks of light-emitting diodes (LEDs) to "pump" a lasing medium that emits intense light in a very narrow wavelength range. The emitted light can be focused and combined with beams from multiple "pumps" to form a single, high-energy output beam that can destroy threats such as UAVs and G-RAMM or cause them to become aerodynamically unstable enough to miss their intended targets.

The lethality of a laser weapon is subject to a variety of factors, including its power, environmental factors, and characteristics of potential targets. Furthermore, the efficiency of a laser weapon system affects its overall size and weight.

Laser power. The amount of energy a laser can place on a target (fluence) is predominantly dependent on the laser's power and how well it can focus its beam (beam quality). Large chemical lasers such as the chemical oxygen iodine laser (COIL) developed for the MDA Airborne Laser (ABL) demonstrator have achieved megawatt levels of power, giving them the

56 Future HPM weapons could damage a missile's guidance and control systems, which may cause it to quickly depart from controlled flight, while an EW system will deceive the missile as to the true location of the intended target, causing it to miss.

potential to damage or destroy most air and missile threats in a matter of seconds. Smaller SSLs better suited to ships, tactical aircraft, and ground vehicles are approaching power levels of 300 kW or more. Future SSLs may have less than 1 MW of output power due to deterioration of their lasing medium at high power levels.

Meteorological conditions. Atmospheric water vapor and particulates absorb and scatter laser energy at distinct wavelengths of the electromagnetic spectrum. The IR and visible wavelengths often used for lasers are affected more by water vapor rather than rain and snow. This makes maritime environments particularly challenging for lasers. Scattering and absorption effects can be mitigated by reducing the distance (or path length) a laser beam must travel in denser, water vapor and particulate-laden low altitude atmospheres. Using laser weapons for air-to-surface and air-to-air applications that reduce the amount of dense atmosphere their beams must traverse can increase their range and effectiveness.

Target characteristics. Because overheating is a primary target damage mechanism for high energy laser weapons, the material and design of a target's surface will significantly impact the laser's effectiveness. Targets such as the nosecones of ballistic missile warheads and supersonic cruise missiles that are hardened to handle the heat associated high-speed travel through the atmosphere are less susceptible to laser damage. A very high power (megawatt-class) laser may have to illuminate such targets for longer periods of time, potentially as long as 15 seconds, to achieve desired effects. In comparison, the thin sides of small boats, UAVs, and most missiles may require only a few seconds of high power laser light to be penetrated.

Time on target. Longer laser beam dwell times on targets can increase the amount of damage created. For this reason, slow-moving targets such as UAVs and small boats are generally much easier to engage with lasers. Faster-moving targets such as missiles are harder to engage unless they are crossing in front of a laser weapon rather than approaching it head-on. Since longer lasing times reduce the number of targets within a salvo that a single laser can engage in a given time period, it will be important to quickly determine when a shot has been successful, then quickly target a new threat.

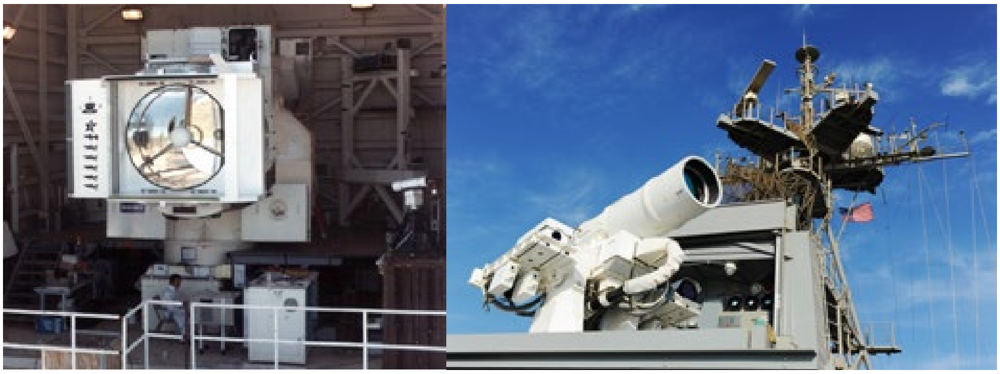
While a variety of lasing media have been used since lasers were first developed, they can generally be separated into two basic types. SSLs use a solid crystal medium in the form of a slab, a thin disk, or fiber optic cable. This makes SSLs smaller and less complex than chemical lasers that use liquid or gas media in order to generate their beams.[57]

DoD previously pursued chemical laser weapons such as the ground-based Mid-Infrared Advanced Chemical Laser (MIRACL) developed by the Navy during the Cold War and the ABL demonstrator. While these developmental weapons generated megawatt-class beams, they were very large and complex, making the operationally impractical for all but fixed-site, ground-based applications. Because the chemicals they use are toxic and in many cases

57 The Airborne Laser used a megawatt-class chemical oxygen iodine laser (COIL) that depleted its chemical "fuel" after a number of laser shots.

highly caustic, storing fresh chemicals and disposing of expended liquids creates major logistics challenges.

FIGURE 24: BEAM DIRECTORS FOR THE MIRACL LASER AND LAWS DEPLOYED ON THE USS PONCE



Photos by U.S. Navy.

SSLs generally are capable of lower power levels than chemical lasers. Since future high energy SSLs will require high levels of electrical power while firing, it is likely that mobile platforms such as aircraft and ships will need to use batteries or capacitors to meet laser surge power requirements. These energy storage systems will incur some power losses. Additional power as well as cooling will be needed to dissipate waste heat created when electrical energy flows into a laser's LEDs and as light from the LEDs is pumped through lasing medium. For these and other reasons, the electrical efficiencies of the best contemporary SSLs average approximately 30 percent. New lasing media and energy storage technologies in development will likely improve the electrical efficiency of SSLs.

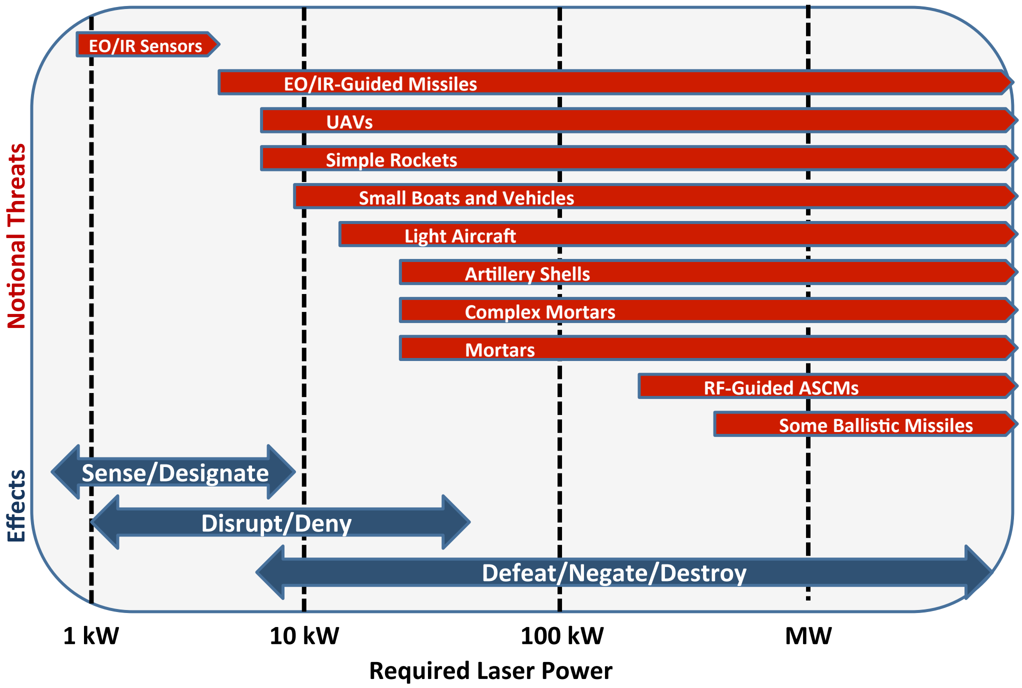
DoD is developing new materials and power management capabilities that will improve the efficiency and effectiveness of SSLs for offensive and defensive applications. In 2014, the Navy fielded the U.S. military's first operationally-deployed SSL, the Laser Weapon System (LaWS), on the Afloat Forward Staging Base-Interim USS Ponce.[58] The 30 kW LaWS is smaller and much less complex than its chemically fueled predecessors, and it is capable of defeating small UAVs and electro-optical/infrared (EO/IR) sensors such as those found on missiles and aircraft. Its deployment to the Persian Gulf helped DoD to develop initial employment doctrine, concepts of operation, and key policies for the use of high power laser weapons, including rules of engagement and procedures to avoid fratricide against friendly satellites and forces.

The Services and DARPA are interested in SSLs capable of power outputs in the 150–300 kW range. This power range is a breakpoint for laser weapons. Lasers at the lower end of

58 Eric Beidel, "All Systems Go, Navy's Laser Weapon Ready for Summer Deployment," Office of Naval Research, press release, April 7, 2014, available at http://www.onr.navy.mil/Media-Center/Press- Releases/2014/Laser-Weapon-Ready-For-Deployment.aspx. LaWS built on the Maritime Laser Demonstrator (MLD), which the Navy previously tested at sea.

this range will likely be able to destroy small UAVs and boats, as well as damage unhardened cruise missiles with "crossing shots" and G-RAMM. Lasers with 300–500 kW of power could damage a wider range of missiles from more aspects and disable or destroy larger UAVs and vessels. SSLs capable of 150 kW or more have already been demonstrated in laboratory settings. Given adequate funding, mature SSL technologies could transition to operational weapons within the next three to five years.[59]

FIGURE 25: ILLUSTRATIVE LASER POWER LEVELS FOR VARIOUS TARGETS



The Air Force is pursuing an SSL for its AC-130J gunships which could be based on DARPA's developmental High Energy Liquid Laser Area Defense System (HELLADS) or another maturing system.[60] Current technology is sufficiently mature to support the Service's objective of fielding a high power SSL within five years that could conduct air-to-surface and air-to-air attacks against appropriate targets, possibly including attacks against enemy cruise missiles as illustrated in Figure 11. High power SSLs that are effective against enemy SAMs and AAMs could improve an AC-130J gunship's ability to operate in contested airspace. The Air Force's

59 Matthew Klunder, United States Navy Chief of Naval Research, "The Fiscal Year 2015 Budget Request," statement before the Intelligence, Emerging Threats and Capabilities Subcommittee of the House Armed Services Committee, March 26, 2014, available at http://www.acq.osd.mil/chieftechnologist/ publications/docs/FY2015_Testimonyonr_klunderusnm_20140326.pdf; and DARPA, "High Energy Liquid Laser Area Defense System (HELLADS)," available at http://www.darpa.mil/program/high-energy-liquid-laser-area-defense-system.

60 Richard Whittle, "General Atomics Plans 150kW Laser; Eyes AC-130, Avenger," *Breaking Defense,* December 21, 2015, available at http://breakingdefense.com/2015/12/general-atomics-plans-150kw-laser-tests-eye-on-ac-130-avenger/.

Self-protect High Energy Laser Demonstrator (SHiELD) initiative is developing a smaller laser for fighter-sized aircraft that could defeat surface-to-air and air-to-air threats.[61] Leveraging experience gained from its developmental LaWS, the Navy is "exploring a 150-kilowatt system to go onboard a DDG-51 class platform for experimentation and prototyping."[62] The Navy's Solid State Laser-Tech Maturation (SSL-TM) program is pursuing an SSL with the intent of fielding a 100–150 kW weapon on its USS Paul D. Foster test ship in 2018.[63]

FIGURE 26: HELLADS MOCKUP AND THE MARITIME LASER DEMONSTRATOR

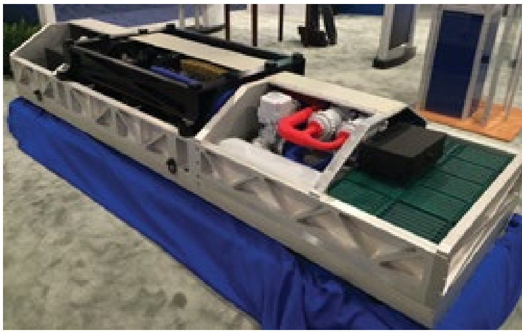


Photo by Graham Warwick/AW&ST.

Photo by U.S. Navy.

High power radio frequency defenses

High power radio frequency weapons, commonly referred to as high power microwave weapons, generate very high power, short-duration pulses of electromagnetic energy at discrete frequencies using waveforms that are designed to damage sensitive electronic components such as a PGM's guidance, seeker, or control systems. HPM pulses can interfere with or cause damage by inducing a current in a targeted circuit that exceeds the circuit's rating, causing it to overheat and fail, similar to blowing a fuse.[64] Because HPM beams attack specific elements such as input/output boards or amplifiers located inside threats such as PGMs, they are less affected by heat shielding on a missile's exterior. Further, since semiconductor circuits are very sensitive they can be over-biased or damaged by very small increases in current. As a result, HPM weapons can induce spurious operation or destructive effects at lower incident

61 Sydney Freedberg, "Air Force Moves Aggressively On Lasers," *Breaking Defense,* August 7, 2015, available at http://breakingdefense.com/2015/08/air-force-moves-aggressively-on-lasers/.

62 Justin Doubleday, "Navy exploring high-powered laser for Arleigh Burke-class destroyer," *Inside Defense,* January 12, 2016, available at http://insidedefense.com/daily-news/navy-exploring-high-powered-laser-arleigh-burke-class-destroyer.

63 Graham Warwick, "General Atomics: Third-Gen Electric Laser Weapon Now Ready," *Aviation Week & Space Technology,* April 20, 2015, available at http://aviationweek.com/technology/general-atomics-third-gen-electric-laser-weapon-now-ready; and Peter Morrison and Dennis Sorensen, "Developing a High Energy Laser for the Navy," available at http://futureforce.navylive.dodlive.mil/2015/01/high-energy-laser/.

64 U.S. Air Force, "Fact Sheet: High Power Microwave Weapons," available at http://www.kirtland.af.mil/shared/media/document/AFD-070404-036.pdf.

power levels than lasers or engage targets over longer ranges than a laser operating at the same power levels.[65]

DoD has developed some HPM weapon prototypes, most notably the Counter-electronics High-powered Microwave Advanced Missile Project (CHAMP) which combined a mature cruise missile with a HPM transmitter payload.[66] As a proof of concept, CHAMP used a broadband HPM pulse to cause lock-ups and damage in a variety of electronic systems rather than targeting a specific set of components.

While CHAMP was a prototype of an offensive counter-electronics weapon, within five years DoD could develop HPM defenses that take advantage of known or suspected electronics vulnerabilities to defeat a range of air and missile threats. Future ship-based or land-based HPM weapons could emit pulses designed to damage specific unshielded circuits in cruise missiles and UAVs. It is also technically feasible to develop more sophisticated HPM control processors and signal generators that could rapidly step through a large number of power levels and waveforms suspected of being effective against known threats.

Conducting "front door" attacks through apertures already built into PGMs for components such as a datalink antenna or seeker is another technique that could reduce the incident power needed by HPM weapons.[67] These apertures are by their nature largely transparent to electromagnetic energy in some portions of the spectrum. An HPM pulse targeted at components associated with the aperture could potentially create damage at much lower power levels compared to attacks through seams in a weapon's external skin. Furthermore, if a target missile's seeker is actively transmitting, an HPM weapon could potentially synthesize a pulse at the same frequency as the seeker to maximize damage to the seeker's electronics.

Electronic warfare

Militaries have used RF jammers and decoys to degrade enemy battle networks since the early 20th century. The use of active RF countermeasures became more widespread during World War II as Allied and Axis forces both sought to defeat their opponent's radars and radio communications. The advent of guided munitions mid-Cold War prompted militaries to adapt these systems to attack individual weapons by disrupting their datalink signals or confusing and deceiving their RF or IR seekers.

65 Specialized electromagnetic shielding similar to a Faraday Cage could help protect components from HPM pulses. A Faraday Cage is a lattice of material with high electrical conductivity, such as copper, able to withstand higher current flows that the sensitive components inside the cage. When exposed to an electromagnetic pulse, the cage dissipates it by generating currents through the lattice.

66 "US Air Force Moves Forward with High-Power Microwave Weapon," *Defense Update,* May 16, 2015, available at http://defense-update.com/20150516_champ.html#.VijFhdadLzI/.

67 Technologists refer to this as a "front door" attack to distinguish it from a "back door" attack that penetrates the outer surface of a threat.

Active jammers, decoys, and other forms of electronic attack are now used against each link of an opponent's precision strike kill chain, from finding and fixing target locations, to engaging targets, then assessing battle damage. For this report's discussion of the salvo competition, the most direct applications of EW are against weapon seekers, GPS and other on-board weapon navigation systems, and datalinks connecting weapons to sources of guidance information. While all three of these avenues of attack are often possible against PGMs that are designed to strike moving targets, an increasing number of land-attack munitions are equipped with seekers, navigation systems, and datalinks to improve their precision and allow controllers to redirect them after launch.

CSBA's *Winning the Airwaves* more fully describes the trajectory of electronic warfare.[68] In essence, two trends are driving militaries toward using passive detection and low probability of intercept/low probability of detection (LPI/LPD) communications and countermeasures instead of high-power active sensors, radios, and countermeasures. First, the increasing range and effectiveness of PGMs, such as SAMs, ASCMs, and ASBMs, may require U.S. forces to operate at greater standoff ranges from an enemy. Greater standoff distances would require U.S. aircraft, ships, and other mobile forces to increase the power levels of their sensors beyond what they are capable of generating. Second, improvements in passive sensors are increasing the risk that U.S. forces emitting high-power RF energy will be detected and attacked by an enemy.

Increasing the air and missile defense capacity of U.S. forces in this operational environment will require it to develop LPI/LPD self-protection jammers that confuse seekers and disrupt guidance systems in enemy PGMs. U.S. jamming platforms and weapons now predominantly emit at high power levels that could be detected by enemy passive sensors or circumvented by PGMs with passive seekers. LPI/LPD jammers should be complemented by long-endurance decoys that provide more attractive targets for enemy fires.

Given these considerations, counter-salvo EW systems should have the following characteristics:

Networked. Due to their low power outputs and short ranges, LPI/LPD jammers will be most effective when used to protect platforms that carry them. Protecting larger formations such as carrier strike groups from detection and attack will require multiple manned and unmanned platforms with LPI/LPD jammers that are capable of coordinating their transmissions across a wide area. Further, jammers and decoys will need to be networked to integrate their operations and avoid unintended actions, such as diverting threats toward friendly platforms.

Agile. Advanced seekers will enable enemy weapons to operate across wider portions of the electromagnetic spectrum and "move" within the spectrum to avoid U.S. countermeasures. To defeat these weapons and reduce risk of counter-detection, U.S. jammers and decoys will need greater agility in their frequencies, beam patterns, and directionality of their emissions.

68 See Clark and Gunzinger, *Winning the Airwaves*.

Multifunctional. Networking multiple self-protection jammers and expendable decoys over large areas could require an expensive and cumbersome collection of transmitters, receivers, and processors. A future EW network would be easier to achieve, and possibly less expensive, if individual jammers are able to autonomously sense the EM environment, communicate with other systems, and coordinate their operations against enemy sensors and salvos.

Adaptive. Today's jammers and decoys are automated, meaning they execute pre-planned responses after detecting characteristics of enemy sensors or weapons seekers that are stored in their on-board threat libraries. Since new seeker and processing technologies will enable enemy weapons to create new signals that may not be in predetermined threat libraries, future U.S. EW systems should be able to sense the EM environment, break signals into their component parts, and then autonomously develop and employ effective courses of action.

DARPA and the Services are pursuing technologies that could lead to new EW systems with these characteristics.[69] Missing, however, are operational concepts that would better enable EW to contribute to air and missile defense. As explained in *Winning the Airwaves,* one set of operational concepts that could change how U.S. forces use the EM spectrum would be to shift from today's high-power sensor and countermeasure approaches to concepts that employ LPI/LPD sensors, communications, and countermeasures.[70] Other concepts could routinely combine EW operations with the use of kinetic interceptors to create a more effective air and missile defense network instead of resorting to EW as a last-ditch defense against "leaker" threats which have penetrated kinetic defenses.

Battle Management: A Critical Enabler

While short- and medium-range defenses could significantly increase the capacity of U.S. air and missile defenses, they would also reduce the time available to engage incoming threats and the number of times a specific threat in a salvo could be engaged. New battle management systems could mitigate these disadvantages and help the U.S. military to realize the full benefits of operational concepts summarized in this report. More specifically, future battle management systems should be able to evaluate threats, determine which should be engaged, assign kinetic and non-kinetic defenses to appropriate targets, and continuously reevaluate the operational picture to respond to new threats or determine when current ones have been negated.

Current air defense battle management systems such as Aegis and Patriot have some capability to match weapons to targets and automatically engage incoming threats.[71] However, the type of automation these systems use is "doctrinal" in nature, which means an operator

69 These efforts are described in detail in Clark and Gunzinger, *Winning the Airwaves*.

70 See Clark and Gunzinger, *Winning the Airwaves,* p. 19 for more details on these concepts for EM spectrum warfare.

71 U.S. Navy, "Aegis Weapon System," *U.S. Navy Fact File*, updated January 5, 2016, available at http://www.navy.mil/navydata/fact_display.asp?cid=2100&tid=200&ct=2; and U.S. Army, *Air Defense Artillery Reference Handbook*, Field Manual 3-01.11 (Washington, DC: Headquarters, Department of the Army, October 31, 2000), chapter 6, available at http://www.globalsecurity.org/military/library/policy/army/fm/3-01-11/ch6.htm.

establishes a set of rules for the fire control system to use when responding to an attack. These rules typically:

- Associate characteristics that fire control systems can measure to differentiate types of threats such as ASCMs, ASBMs, and G-RAMM;
- Direct the order in which threats should be engaged and by which systems, such as using an EMRG followed by a HPM system;
- Set priorities for engaging different threats, for instance, by directing EW and HPM systems to defeat a supersonic ASCM before engaging other threats in a salvo; and
- Prioritize and assign defensive systems to various threats.[72]

Rules-based automated fire control systems are limited in their ability to engage threats they do not recognize, are not able to compensate for new threat tactics, do not fully integrate non-kinetic and kinetic defenses, and may not be able to adapt when conditions increase the effectiveness of some defensive capabilities or make specific threats more or less dangerous.

Future air and missile defense fire control systems should be increasingly agile and autonomous so they can rapidly engage threats, continuously evaluate appropriate countermeasures, then employ defenses that are most effective against each threat as illustrated in the following examples:

<u>Supersonic sea-skimming ASCMs.</u> Assuming enemy ASCMs are detected beyond the horizon, battle management systems could first target them with ESSMs or PAC-3s and engage with line-of-sight DE and EW systems after surviving threats break the horizon.

<u>Supersonic LACMs.</u> Battle management systems could engage higher flying LACMs with HPM systems at long ranges, then use other air defense systems emplaced away from likely U.S. targets to achieve crossing shots against surviving threats.

<u>ASBM warheads.</u> Battle management systems could use EMRGs to engage high-altitude ASBM warheads at 30–40 nm, followed by kinetic interceptors at 10–30 nm, then employ DE and EW systems against warheads' terminal seekers at closer ranges if operational conditions permit.

<u>Land attack ballistic missile warheads.</u> Ballistic warheads hardened to withstand atmospheric reentry could be less susceptible to some electric weapons such as lasers and EW systems. In this instance, battle management systems could engage warheads at 30–40 nm with HVPs fired by EMRGs, followed by surface-to-air interceptors if needed.

72 John Hersh, "Doctrinal Automation in Naval Combat Systems: The Experience and the Future," *Naval Engineer's Journal,* 99, No. 3, May 1987, pp. 74–79.

Developing technologies for intelligent salvo defense battle management systems is a surmountable challenge. Some new DoD command and control programs, such as the Army's Integrated Air and Missile Defense Battle Control System (IBCS) and Navy's Aegis Combat System, are incorporating these features, while research is improving their real-time ability to adapt to new adversary tactics.[73] The more significant obstacle may be cultural in nature. U.S. air defense forces are comfortable with current layered approaches in which every air or missile threat is initially engaged as far away as possible and repeatedly engaged until defeated, or until it arrives at a target. Shifting to a scheme in which a preponderance of threats is engaged in a 10–40 nm range band by autonomous systems will remove the redundancy of today's approach and turn over decision making to machines. Assumptions that layered air defense schemes are more robust than a single layer and that humans will be more effective than machines at battle management are both false. Rather than fighting future air defense battles in real time, U.S. defenders will have to increasingly rely on machines and short- to medium-range defenses to defeat large salvos while focusing their attention on setting up their systems and preparing for follow-on salvos.

73 Sanguk Noh and Unseob Jeong, "Intelligent Command and Control Agent in Electronic Warfare Settings," *International Journal of Intelligent Systems,* 25, No. 6, June 1, 2010, pp. 514–520; and Joseph Croghan, Myron Cramer, and Joan Hardy, "Implementing Advanced Artificial Intelligence Concepts in Ada: A Case Study of a Prototype Expert System for a Real-Time Electronic Warfare Application," *WADAS '90 Proceedings of the seventh Washington Ada symposium on Ada,* Association for Computing Machinery, July 1, 1990, pp. 255–231.

CHAPTER 4

Case Studies

The following case studies further illustrate how concepts and capabilities recommended in previous chapters could shift the defensive dimension of the salvo competition in favor of the U.S. military. The first case assesses how an alternative AAW approach could increase the capacity of sea-based forces to engage ASCM and ASBM salvos. The second illustrates the impact of a similar mix of defenses protecting military bases on the island of Guam. Both cases focus on current and proposed long-range (50–100 nm) and medium-range (10–30 nm) air and missile defenses. Short-range or point defenses (5 nm and less) such as RAM and CIWS are not addressed since they are common to both the current and proposed mix of defenses, and since they contribute less than twenty additional engagements per system.

Case Study 1: Alternative Defensive AAW Capabilities Mix

Chapter 2 proposes shifting the Navy's defensive AAW operations toward the use of medium-range surface-to-air interceptors, 5-inch guns with hypervelocity projectiles, and electric weapons including railguns, solid state lasers, high power microwave systems, and electronic warfare. This shift could increase the density of the Navy's defenses against missile salvos and create more favorable weapon and cost exchanges.

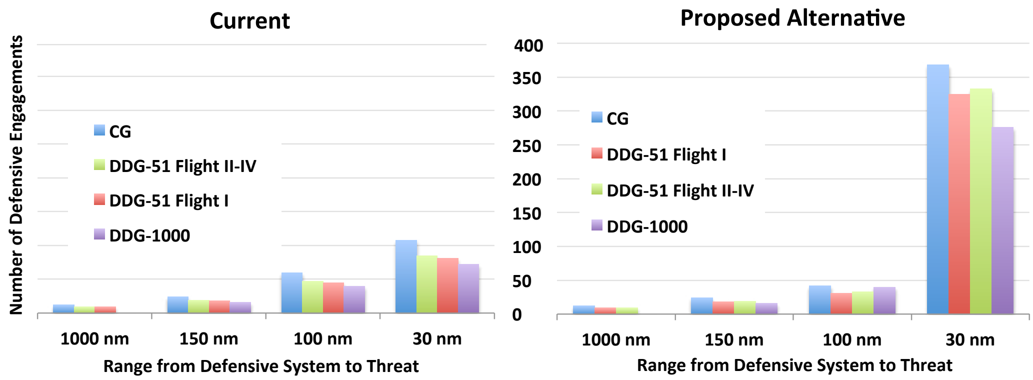
Increasing capacity to engage air and missile threats

Figure 27 compares how a proposed alternative medium-range defensive AAW scheme could increase the total number of engagaments that can be launched by a cruiser (CG) or a DDG-51 destroyer at air and missile threats.[74] Both the current and proposed cases include the same number of SM-3 and SM-6 interceptors per ship and the Navy's planned AN/SLQ-32(V)6

74 Chapter 4 case studies use the term "engagements" instead of the term intercepts. For kinetic weapons such as SM-6s or EMRGs, one engagement is equal to the expenditure of one missile or one HVP. For DE weapons such as SSLs and HPM systems, a six-second emission is considered one engagement.

Surface Electronic Warfare Improvement Program (SEWIP) Block 3 system.[75] The alternative mix replaces some SM-2s (one per VLS cell) with ESSMs (four per VLS cell), and provisions each ship with HVPs for its existing Mk45 5-inch gun, a 400 kW SSL, and an HPM weapon capable of creating effects across a wide frequency band.

FIGURE 27: AAW CAPACITY COMPARISON FOR A CRUISER OR DESTROYER



Weapon	CG and DDG-51	DDG-1000
SM-3	10% VLS	0% VLS
SM-6	20% VLS	20% VLS
SM-2	30% VLS	30% VLS
ESSM	10% VLS	10% VLS
Tomahawk	25% VLS	40% VLS
VLA	5% VLS	0% VLS

Weapon	CG and DDG-51	DDG-1000
SM-3	10% VLS	0% VLS
SM-6	20% VLS	20% VLS
SM-2	15% VLS	30% VLS
ESSM	25% VLS	10% VLS
Tomahawk	25% VLS	40% VLS
VLA	5% VLS	0% VLS
1 Mk-45 gun/ship with HVP	20 rounds per minute	
1 400kW laser/ship	6 seconds per missile defeat	
SEWIP Block 3	36 simultaneous targets	
1 HPM broadband system/ship	36 simultaneous targets	

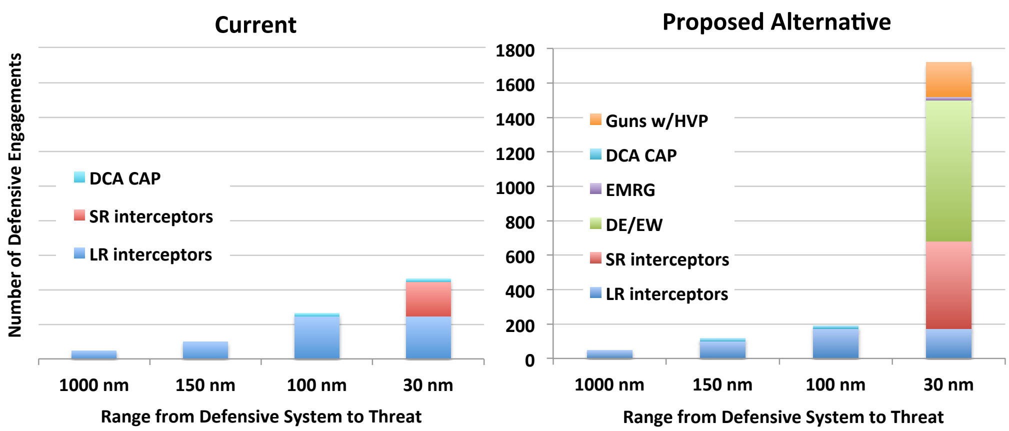
As shown by the bar charts for the cruiser and destroyer example, reapportioning 15 percent of VLS capacity from SM-2s to ESSMs and equipping each ship with gun-launched HVPs, EW, an SSL, and an HPM weapon could significantly increase their total threat engagement capacity. In the case of DDG-51 Flight II–IV destroyers represented by the green bars, a current AAW VLS loadout would give each the ability to launch about 160 engagements against incoming threats. In contrast, the alternative would increase a destroyer's total AAW capacity to slightly over 342 engagements: nine SM-3 engagements against threats at 1,000 nm range from the ship, nineteen SM-6 engagements at 150 nm, thirty-three engagements using a mix of SM-6s and SM-2s at 100 nm, and 333 engagements at 30 nm or less using HPM, EW, lasers, SM-2s, and ESSMs. Note that the number of engagements indicated in Figure 27 will be less for ASBM warheads which move too quickly to be defeated by ESSMs and have hardened

75 Figure 27 and similar bar charts in Chapter 4 show engagements by lasers, HPM weapons, and EW systems in the "30 nm" band on the X-axis. This is not meant to imply these capabilities will always be effective against all air and missile threats out to a distance of 30 nm. As line-of-sight weapons, they will reach missiles that are more than about 1000 ft. in altitude at about 30 nm away and sea-skimming missiles at about 10 nm away.

exteriors that are unlikely to be damaged by lasers. These threats will still be vulnerable to faster interceptors such as Standard Missiles and to EW or HPM used against their seekers.

The potential advantage is even more evident for a carrier strike group (CSG) that includes one cruiser and four destroyers with similar alternative AAW defenses. The bars in Figure 28 show a notional CSG with today's air defenses has the potential to launch 512 separate engagements compared to 1,784 engagements by the proposed defenses.

FIGURE 28: AAW CAPACITY COMPARISON FOR A CARRIER STRIKE GROUP



1 Carrier and 4 DDG-51, each with the following

SM-3	10% VLS
SM-6	20% VLS
SM-2	30% VLS
ESSM	10% VLS
Tomahawk	25% VLS
VLA	5% VLS

1 Carrier and 4 DDG-51, each with the following

SM-3	10% VLS
SM-6	20% VLS
SM-2	15% VLS
ESSM	25% VLS
Tomahawk	25% VLS
VLA	5% VLS
1 Mk-45 gun/ship with HVP	20 rounds per minute
1 400kW laser/ship	6 seconds per missile defeat
SEWIP Block 3	36 simultaneous targets
1 HPM broadband system/ship	36 simultaneous targets

While Figures 27 and 28 illustrate how an alternative capabilities mix could improve the density of ship defenses, engagements shown by the bars do not equate to threats successfully intercepted. Each defensive system has a different probability of engagement success (PES) against different types of threats.[76] Multiple interceptors are launched at an incoming threat to ensure it is defeated, and non-kinetic systems such as HPMs, EW systems, or SSLs engage a threat until it shows indications that it has been defeated.

76 For a description of probability of engagement success, see U.S. General Accounting Office (GAO), *Missile Defense: Actions Are Needed to Enhance Testing and Accountability* (Washington, DC: GAO, 2004), available at http://www.gao.gov/assets/250/242142.html.

Creating more favorable cost exchanges

The defensive AAW scheme proposed in Chapter 2 also has the potential to shift cost exchanges in favor of U.S. defenses. Figure 29 compares the cost of defeating an ASCM using long-range interceptors (SM-6s and SM-2s) with the cost of defeating it using the alternative capabilities from Figure 27. Assuming for illustrative purposes that all defensive weapons have a PES of 60 percent against an ASCM variant, it would cost $7 million in recurring costs to defeat the ASCM using long-range interceptors compared to $1.5 million in recurring costs using medium-range defenses.[77]

This comparison does not include the non-recurring cost of missile launchers, EMRGs, SSLs, powder guns, and HPM and EW systems. These costs should be weighed against the defensive capacity the systems will provide when evaluating the best mix of AAW weapons to protect sea-based forces. In particular, the procurement cost of an EMRG is likely to be tens of millions of dollars. Assuming the DoD's objective firing rate of ten rounds per minute is correct, an EMRG will only provide about twenty of the 1,784 overall engagements in the CSG example. To get the greatest air defense capacity for a given amount of funding, the Navy may be better served buying more EW and HPM systems, SSLs, and medium–range interceptors than EMRGs. EMRGs, however, can also conduct relatively high-volume, over-the-horizon strikes on surface targets at sea and ashore. Instead of fielding EMRGs for air defense, their strike capability could be provided by deploying EMRGs on select surface combatants such as the DDG-1000.

FIGURE 29: COMPARING COSTS TO DEFEAT EACH ASCM IN A SALVO[78]

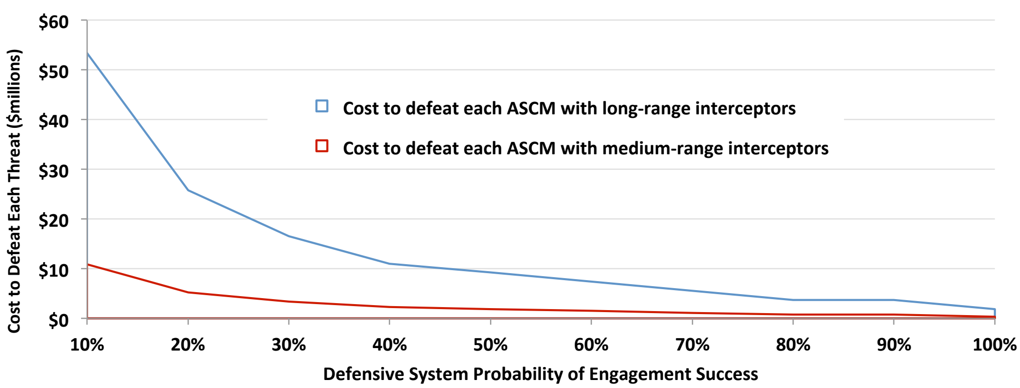


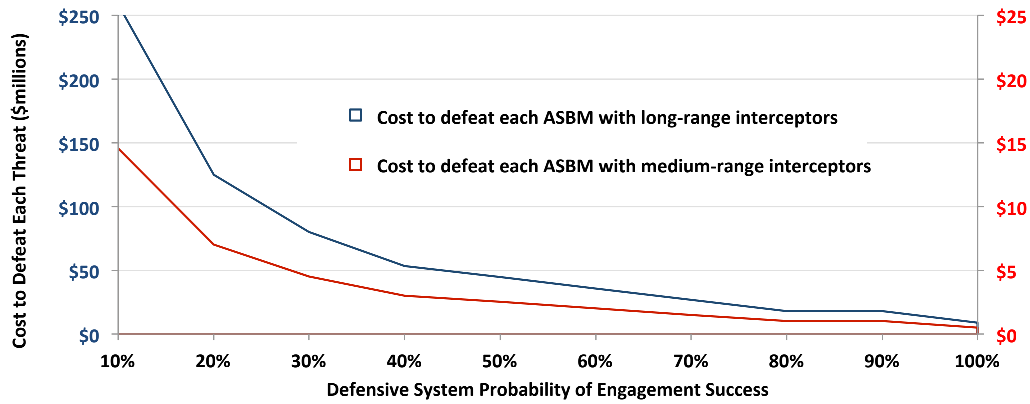
Figure 30 illustrates how the alternative AAW approach could result in more favorable cost exchanges against ASBMs. Again assuming a PES of 60 percent, it would cost about $36

77 This example is for illustrative purposes only, since each AAW capability will have different P_{ES} values for different threats.

78 Unit costs used in figures 29, 30, 33, and 34 are pulled from Table 2 and Appendix 5 of this report.

million (blue line, left axis) for a ship to defeat an ASBM with long-range interceptors, compared to $1.5 million (red line, right axis) using ESSMs, guns and EMRG-launched HVPs, HPMs, and SEWIP.

FIGURE 30: COMPARING COSTS TO DEFEAT EACH ASBM IN A SALVO



Medium-range defenses could free VLS capacity for additional offensive strike capabilities such as Long-Range Anti-Ship Cruise Missile (LRASM) and Tomahawk and cruise missiles. In the context of a salvo competition, the Navy today is caught in an unfavorable dynamic where it is sacrificing capacity to conduct offensive precision strikes in order to defend its surface forces from air and missile threats. Shifting toward the proposed alternative AAW concept could help reverse this dynamic and restore the Navy's offensive punch.

Case Study 2: Increasing the Density of Base Defenses

As summarized in Chapter 1, U.S. missile defense capabilities deployed overseas are oriented on defeating a small number of ballistic missiles. While THAAD and upgraded Patriots are far more capable than interceptors used against Iraqi Scud missile attacks during Operation Desert Storm in 1991, they are expensive and deployed in too few numbers to defeat large salvos of ballistic missiles, LACMs, G-RAMM, and other PGMs that threaten U.S. theater bases.

Long-range guided weapons developed by China and North Korea pose critical threats to the U.S. territory of Guam, which is host to more than 12,000 U.S. military members, DoD civilians, and their dependents stationed at Naval Base Guam, Marine Corps Activity Guam, and Andersen Air Force Base. Located nearly 1,600 nm from China, DoD has long considered the island to be a secure staging area for projecting military power throughout the Western Pacific and Indian Ocean regions. China's DF-26 IRBM is now "capable of striking Guam with a conventional warhead from a homeland-based launcher," and the PLA Air Force (PLAAF) operates a fleet of H-6K bombers which can each launch six LACMs at Guam from standoff distances of 800 nm or more.[79] North Korea's KN-08 road-mobile ICBM, assessed as operational by the U.S. military, has sufficient range to reach Guam as well as the United States. The KN-08 is a primary reason DoD decided to place, at least on a rotational basis, a THAAD battery in Guam.

FIGURE 31: CHINA'S DF-26 IRBM AND NORTH KOREA'S KN-08 ICBM

Photo stills from official state footage.

Other than a battery of THAAD ballistic missile interceptors equipped with hit-to-kill warheads, Guam has few defenses against PGM salvos. To address this shortfall, DoD could field a mix of medium-range kinetic and non-kinetic defenses on Guam that would greatly increase its ability to defeat salvos of ballistic missiles, cruise missiles, HGVs, and other PGM threats.

Figures 32 through 34 illustrate the potential to increase the density of defenses protecting Guam and other U.S. bases from complex weapons salvos and create cost exchanges favoring the U.S. military. The first figure compares using Patriot and THAAD batteries and an airborne CAP, with a proposed Guam defense architecture that includes an EMRG, IFPC launchers, 155mm Paladins with HVPs, SSLs, HPM weapons, and a land-based SEWIP.[80] The current architecture would be able to conduct ninety-six engagements in two minutes, whereas the proposed base defense could support 393 engagements in the same period of time.

79 Andrew Erickson, "Academy of Military Science Researchers: 'Why We Had to Develop the Dongfeng-26 Ballistic Missile'—Bilingual Text, Analysis & Related Links," December 5, 2015, available at http://www.andrewerickson.com/2015/12/academy-of-military-science-researchers-why-we-had-to-develop-the-dongfeng-26-ballistic-missile-bilingual-text-analysis-links/.

80 The proposed defense also replaces some PAC-2 GEM/C with more capable PAC-3s. Similar to the AAW case study, this example assumes that each HPM or EW system has the potential to engage seventy-two targets in two minutes, and each SSL and railgun can engage up to twenty targets in two minutes.

FIGURE 32: GUAM AIR AND MISSILE DEFENSE ENGAGEMENT COMPARISON

Defensive System	Current	Proposed
Patriot battalion	4 PAC-2 and 2 PAC-3 launchers	2 PAC-2 and 4 PAC-3 launchers
THAAD battery	6 launchers	6 launchers
DCA CAP	4 fighters each with 4 AIM-120C	4 fighters each with 4 AIM-120C
IFPC Increment 2-1		3 IFPC launchers each with 15 AIM-9X Block II
400 kW Laser		6 lasers, assume 6 seconds per missile defeat
Paladin gun w/HVP		6 guns, assume 8 rounds per minute each
SEWIP Block 3		1 SEWIP, assume 36 simultaneous targets
HPM broadband system		HPM, assume 36 simultaneous targets

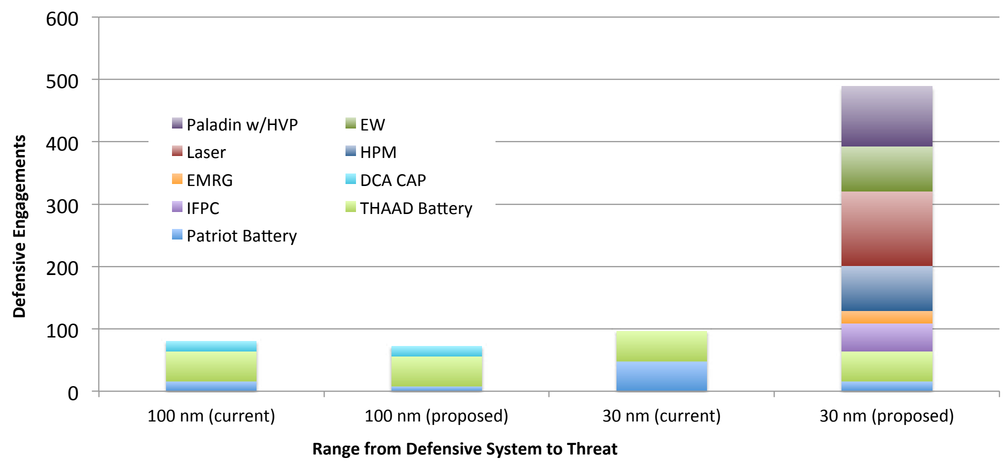
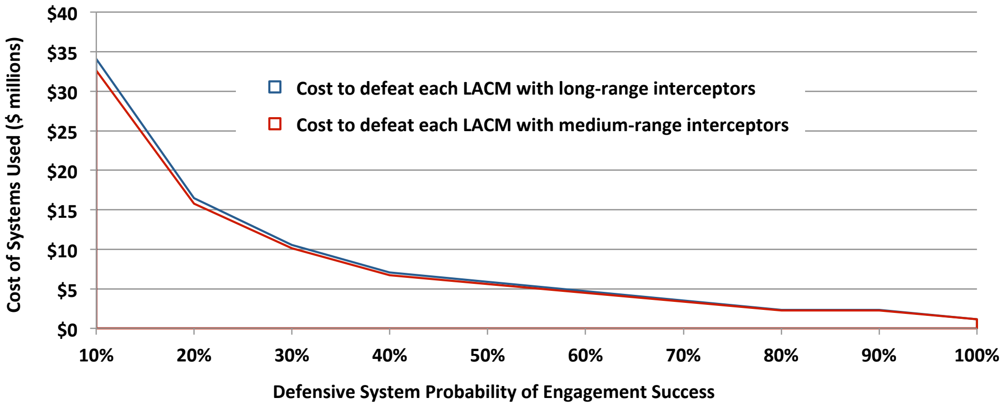


Figure 33 shows the cost to defeat a LACM or ballistic missile using the proposed mix of medium-range defenses is slightly less than the cost to successfully engage missiles with long-range interceptors. Assuming a PES of 60 percent, it would cost about $4.7 million to defeat a LACM using PAC-2 and defensive counter-air (DCA) CAP aircraft with AIM-120C interceptors, compared to $4.5 million using the alternative defenses of PAC-3, IFPC, 400 kW lasers, EW, HPM weapons, and an EMRG with HVPs.[81] The higher cost to defeat a LACM compared to defeating an ASCM is because PAC-3 MSE interceptors cost about three times as much as ESSMs.

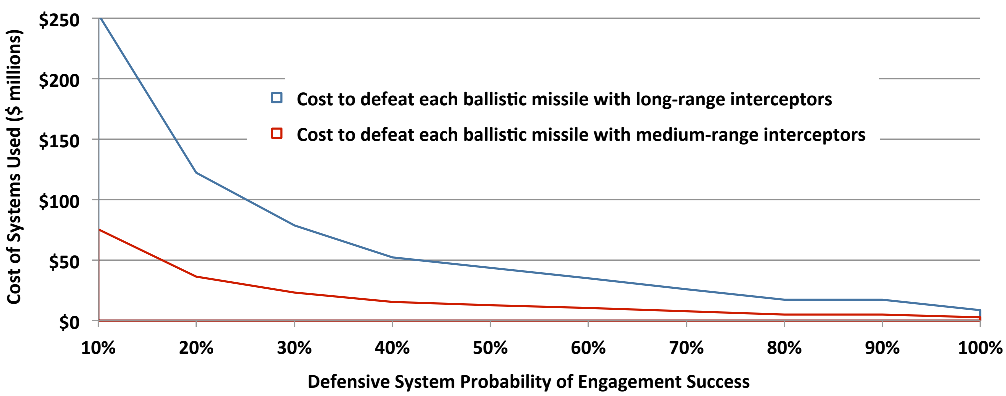
81 EW systems act against a missile's guidance system. Although a land attack missile may not have a seeker like an anti-ship missile, new, more precise ones have seekers to identify specific target aimpoints and GPS systems to guide them to specific geographic locations. These guidance systems are vulnerable to EW jamming and decoy effects.

FIGURE 33: COMPARING COSTS TO DEFEAT EACH LACM IN A SALVO



Ballistic missile defense will also be less expensive using the proposed air defense concept. Assuming defensive systems have PES of 60 percent, it could cost approximately $35 million on average to successfully intercept a ballistic missile using only THAADs and PAC-3s, compared to $10 million using a mix of PAC-3 interceptors and HVPs from EMRGs or Paladin guns (see Figure 34).

FIGURE 34: COMPARING COSTS TO DEFEAT EACH BALLISTIC MISSILE IN A SALVO



These kinetic and non-kinetic defenses should be distributed across Guam, increasing their potential to achieve crossing shots against inbound missiles and reducing their vulnerability to enemy counterstrikes. As in the previous case studies, the proposed salvo defense complex would preferentially use longer-range interceptors against some ballistic missiles and enemy strike aircraft. Moreover, given that the PLAAF's H-6K bombers could launch cruise missiles a thousand miles or more from Guam, sustaining fighter CAPs within range of potential launch areas would be a major logistical challenge. In the future, this mission may be more suitable for manned and unmanned platforms that have longer ranges and greater endurance in addition to carrying capacity SSLs and large payloads of air-to-air weapons.

Summary

In summary, the case studies presented in Chapter 4 suggest that a rebalanced mix of air and missile defense capabilities has the potential to increase the U.S. military's ability to counter complex salvos of guided weapons. They also promise to create more favorable cost exchanges against ballistic missiles, cruise missiles, G-RAMM, and even less expensive guided weapons. Developing and fielding this mix, however, will not be easy. Chapter 5 addresses barriers to shifting toward operational concepts and air and missile defense capabilities that could offer the U.S. new advantages in precision strike salvo competitions.

CHAPTER 5

Barriers to Change

Old Assumptions for Defending Theater Bases

Pentagon leaders are quick to point out that none of the seven million U.S. military men and women who have supported contingency operations since the end of the Korean War "died as the result of air attack."[82] While DoD should take great pride in this accomplishment, it doesn't make sense for it to invest billions of dollars to enhance the survivability of its air forces in the air, yet leave U.S. regional bases vulnerable to attack by the panoply of guided weapons that transit the air domain. Since the end of the Cold War, the Pentagon has assumed air and missile attacks on its bases would either not occur or would be within the capacity of the limited defenses it has fielded. Acknowledging this assumption is no longer valid would be a major step toward securing one of the U.S. military's most critical centers of gravity: the overseas installations it depends on to conduct power-projection operations.

A Bias for Long-Range Missile Interceptors

A key barrier to implementing the concepts summarized in this report is cultural in nature. For instance, the Navy prefers to rely on multiple layers of defenses that can engage missile threats multiple times before they reach its surface ships. This approach provides a false confidence, however. A layered missile defense that begins at long ranges (greater than 100 nm) depends on the use of large, expensive interceptors and could consume a ship's VLS capacity much faster without substantially improving AAW effectiveness compared to a single medium-range defensive layer. The alternative defensive AAW scheme proposed by this report would give commanders the ability to rapidly engage a threat, assess the engagement's effectiveness, then if necessary re-engage an incoming missile multiple times using medium and short-range

82 "Squaring the Circle: General Mark Welsh III on American Military Strategy in a Time of Declining Resources," American Enterprise Institute, December 11, 2013, p. 3, available at https://www.aei.org/wp-content/uploads/2013/12/-general-welsh-transcript_141054774567.pdf.

defenses guided by automated decision aids such as Aegis. The challenge is significantly different for DoD's theater land-based air and missile defenses. While they are also biased toward large and expensive long-range interceptors, DoD lacks short- and medium-range capabilities needed to defeat salvo attacks against its bases and forces.

A Strategic Bias Toward Ballistic Missile Defense

DoD has long weighted its missile defense investments toward ballistic missile threats. This bias is reflected in DoD's strategic reviews and the organizations it has created to lead the development of missile defense capabilities.

The 2010 Ballistic Missile Defense Review (BMDR) is one of DoD's most recent strategic assessments of ballistic missile threats that have "significant implications for our ability to project power abroad, to prevent and deter future conflicts, and to prevail should deterrence fail."[83] The review established several key priorities for DoD, including defending "the homeland against the threat of limited ballistic missile attack," and defending "against regional missile threats to U.S. forces, while protecting allies and partners and enabling them to defend themselves."[84] The congressionally-mandated BMDR report did not address cruise missiles and other guided weapons that now threaten U.S. regional bases, forces, and increasingly the U.S. homeland.[85] DoD's 2014 Quadrennial Defense Review (QDR) followed suit by reemphasizing the need to "defend the homeland against a limited ballistic missile attack" and "stay ahead of limited ballistic missile threats from regional actors such as North Korea and Iran." While the QDR made two brief mentions of cruise missile threats, it did not prioritize capabilities needed to defeat large, complex PGM salvos.

This strategic bias is reflected in organizations established by DoD to develop new missile defense capabilities. The Missile Defense Agency's mission is to "provide centralized management [for DoD] to develop and integrate programs of sensors, interceptors, command and control, and battle management into a ballistic missile defense system (BMDS)."[86] The MDA was given the authority to develop a BMDS outside normal Service-centric organization, train, and equip processes due in part to the belief that missile defense priorities within the Services

83 Secretary of Defense Robert M. Gates, *Ballistic Missile Defense Review*, Report (Washington, DC: DoD, February 2010), cover letter.

84 Ibid., p. iii.

85 According to Admiral Winnefeld, "Homeland cruise missile defense is shifting above regional ballistic missile defense," in terms of importance. James Winnefeld, "Remarks at the Center for Strategic and International Studies," May 19, 2015, available at http://www.jcs.mil/Media/Speeches/tabid/3890/Article/589289/adm-winnefelds-remarks-at-the-center-for-strategic-and-international-studies.aspx.

86 The lineage of the MDA can be traced to the Strategic Defense Initiative Organization, which was established in 1984 and renamed the Ballistic Missile Defense Organization (BMDO) in 1992. BMDO became the Missile Defense Agency at the beginning to the George W. Bush administration.

"would not compete well with other Service priorities."[87] While some BMDS capabilities would be effective against threats other than ballistic missiles, defense against large guided weapons salvos is not a primary responsibility of the MDA.

To be fair, other joint organizations do address future defenses against cruise missiles as well as ballistic missiles. For instance, the Joint Integrated Air and Missile Defense Organization (JIAMDO) is a small office embedded within the Joint Staff that is responsible for identifying and coordinating "joint requirements to support efforts to develop air defense, cruise missile defense, and ballistic missile defense for the warfighter."[88] The U.S. Strategic Command (USSTRATCOM) is another joint organization that has a role in integrating DoD air and missile defense priorities. USSTRATCOM established a Joint Functional Component Command for Integrated Missile Defense (JFCC IMD) that "…advocates for missile defense capabilities in support of USSTRATCOM, other Combatant Commands, the Services, and appropriate U.S. Government Agencies, to deter and defend the U.S., deployed forces, and its allies against ballistic missile attacks."[89]

Unfortunately, while "identifying and coordinating" are important functions, JIAMDO lacks authority to initiate and fund new air and missile defense programs. Similar to JIAMDO, the JFCC IMD performs critical supporting functions, but does not have the authority to establish new requirements and create programs for air and missile defense capabilities.

Unclear Responsibilities for Salvo Defense

Considering the missions and authorities of the MDA, JIAMDO, and JFCC IMD, it is evident that DoD lacks a central organization that defines requirements and initiates programs for new capabilities needed to prevail in the defensive dimension of a salvo competition. Rebalancing MDA's mission to include defense against cruise missiles and possibly other PGMs could be one approach to creating such an organization. A 2010 DoD study on MDA's role and missions expressly recommended against this course of action, since:

> there is little convergence between the functional demands of ballistic missile defense and cruise missile defense and only limited opportunities for dual use among host systems (i.e., Patriot and Aegis).[90]

This dynamic could change if DoD pursues operational concepts and capabilities recommended by this report. New systems such as EMRGs, gun-launched HVPs, and DE systems

87 Larry Welch et al., *Study on the Mission, Roles, and Structure of the Missile Defense Agency* (Alexandria, VA: Institute for Defense Analyses, 2010), p. IV-1, available at www.dtic.mil/cgi-bin/GetTRDoc?AD=ada486276.

88 Archer Macy, Rear Admiral USN, Director Joint Integrated Air and Missile Defense Organization, statement before the Strategic Forces Subcommittee of the Senate Armed Services Committee, April 20, 2010, p. 1, available at http://www.dod.mil/dodgc/olc/docs/testArcher04132011.pdf.

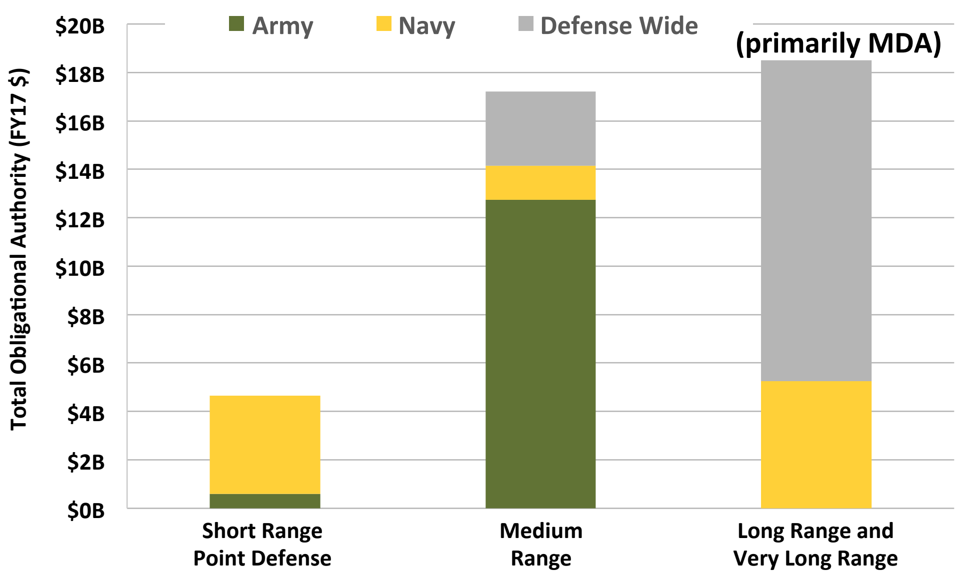
89 U.S. Strategic Command, "JFCC IMD," available at http://www.smdc.army.mil/factsheets/jfcc-imd.pdf.

90 Welch et al., *Study on the Mission, Roles, and Structure of the Missile Defense Agency*, p. VII-I. The same study did determine that there "can be convergence in the command and control and battle management (C2BMC) needs of ballistic missile defense."

could help protect U.S. bases and forces against ballistic missiles, cruise missiles, and other guided weapons. In other words, new concepts and dual-use capabilities could result in a degree of convergence that makes a compelling case to integrate salvo defense within a joint organization with the authority and resources to define requirements and initiate new programs before they are transitioned to the Services.

Another option would be to direct each Service to develop air and missile defenses that have the capacity to protect their regional bases and forces in future salvo competitions. While the Navy is already investing billions in AAW capabilities to protect its surface ships, responsibility for defending U.S. regional airbases against cruise missiles and G-RAMM remains an unresolved issue. The Army has invested billions of dollars in long-range surface-to-air interceptors such as THAADs and Patriots primarily for ballistic missile defense, but it has yet to procure short-range defenses to defeat cruise missile salvos and G-RAMM attacks against U.S. regional bases (see Figure 35). Nor has the Air Force picked up the slack, since it contends that defending its overseas airbases and forces from missile attacks is the Army's responsibility.

FIGURE 35: BREAKOUT OF 1999–2017 TOTAL INTERCEPTOR PROCUREMENT FUNDING BY ORGANIZATION

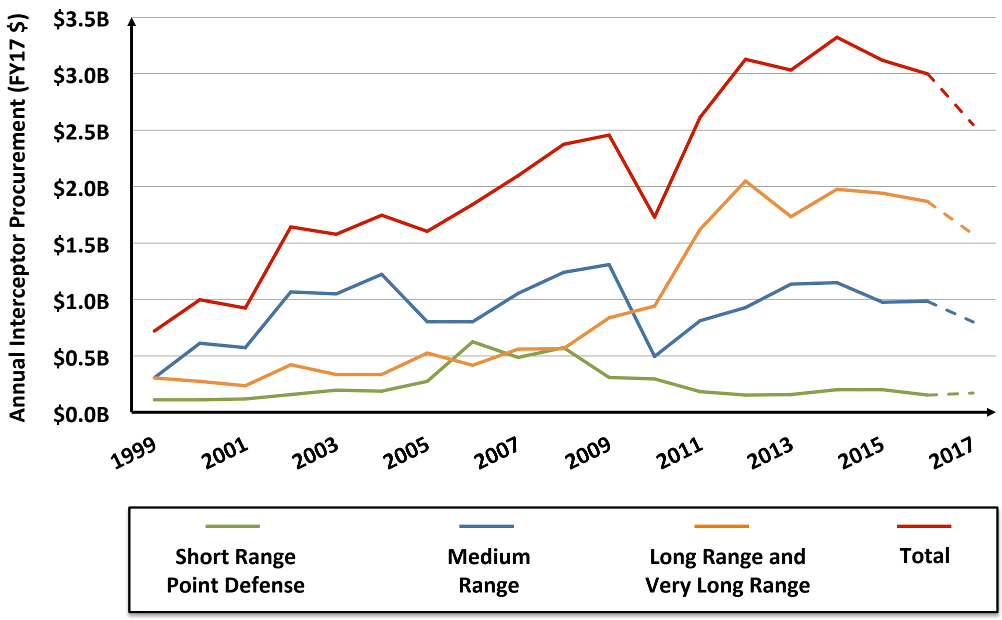


To address this barrier to progress, Congress and DoD could update their guidance on the roles and missions of the Services. A current DoD directive requires all of the Services to provide their unique capabilities for missile defense without elaborating on what these capabilities are. It also directs the Army to organize, train, and equip forces to "conduct air and missile defense to support joint campaigns and assist in achieving air superiority;" the Navy to organize, train, and equip to "conduct ballistic missile defense;" and the Air Force to organize, train, and equip to "conduct offensive and defensive operations, to include appropriate air and missile defense, to gain and maintain air superiority and air supremacy as required."[91] Working with the Congress, DoD could change guidance to clarify that each Service should prepare to defend their bases and forces against cruise missiles and other PGM threats. Alternatively, the Army could be directed to organize, train, and equip forces to protect all U.S. regional bases against guided weapon salvos.

Insufficient Resources

DoD's enduring focus on preparing for contingency operations against enemies that lack the ability to launch guided weapon salvos may be reflected in its overall allocation of resources to procure missile defense interceptors.

FIGURE 36: ANNUAL INTERCEPTOR PROCUREMENT FUNDING SINCE 1999



Overall, DoD's annual budget proposals over the last eighteen years have shown an upward trend in funding requested to procure air and missile defense interceptors (see Figure 36). In context, however, total annual funding (red line) requested for interceptors of all classes has averaged well below $3 billion dollars, which is about half the amount DoD requested to procure a single variant of the F-35 fighter in FY 2016.[92] Figure 36 also indicates funding requested for mid-range ballistic missile defense interceptors has shown the most growth over

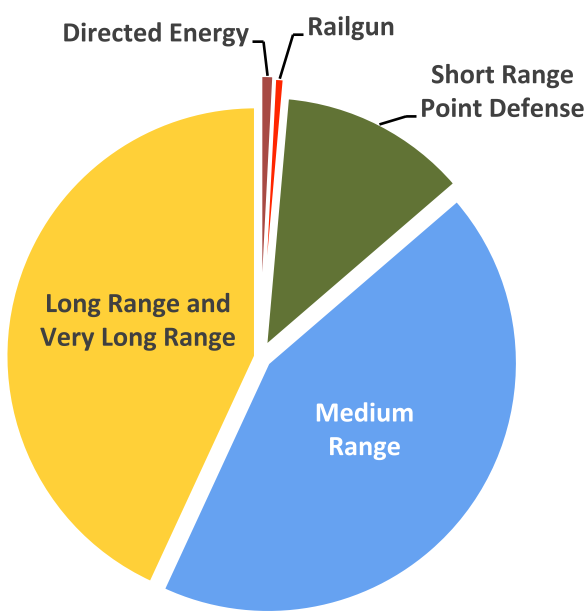
91 DoD, *Functions of the Department of Defense and Its Major Components* (Washington, DC: DoD, December 21, 2010), pp. 28–34, available at http://www.dtic.mil/whs/directives/corres/pdf/510001p.pdf.

92 The Air Force budget proposal for FY 2016 requested $6.029 billion to buy forty-four F-35A fighters. Jim Martin, "United States Air Force Fiscal Year 2016 Budget Overview," February 2015, pp.12–13.

the last five years, while funding for short-range interceptors remained relatively flat. These trends reflect a continued bias toward procuring long-range interceptors capable of defeating ballistic missiles. More troubling, they may also indicate that DoD's resource priorities have yet to catch up with its own rhetoric regarding the growing air and missile threat to America's interests at home and abroad.

Figure 36 does not include DoD's proposed funding for electric weapons such as DE defenses and EM railguns. This reflects the fact that DoD has yet to establish any acquisition programs to develop and buy high power SSLs, HPM defenses, and railguns. Furthermore, total funding to develop these technologies remains a fraction of the amount DoD spends to buy kinetic interceptor missiles (see Figure 37).

FIGURE 37: COMPARISON OF FY 2015 PROCUREMENT FUNDING FOR KINETIC INTERCEPTORS AND S&T FOR ELECTRIC WEAPON TECHNOLOGIES DEVELOPMENT



A 2012 CSBA report, *Changing the Game: The Promise of Directed Energy Weapons,* assessed that the lack of resources, not technological maturity, may now be the greater barrier to developing major new DE capabilities over the next decade. This appears to remain the case today. The first step toward overcoming institutional resistance to transitioning electric weapon science and technology development initiatives to acquisition programs may be an acknowledgement that kinetic interceptors alone will not meet the growing missile threat to DoD's forces, bases, and the U.S. homeland. Rather, kinetic and non-kinetic capabilities—in combination—could create a defensive architecture that is far more capable against the full range of air and missile threats.

Conclusion and Recommendations

The Department of Defense has established defeating ballistic missile threats to its forces, bases, and the U.S. homeland as one of its top priorities. Yet despite the billions of dollars it has spent to create layered ballistic missile defenses, it has fallen short of creating an architecture capable of countering large salvos of guided weapons that include cruise missiles, G-RAMM, and other PGMs that will threaten future U.S. power-projection operations.

A first step toward addressing this shortfall may be to frame the problem as a salvo competition, where the U.S. military and its adversaries continually seek to gain advantages by improving their capabilities to attack with precision and defend against an opponent's precision strike weapons. Prevailing in salvo competitions with enemies that are capable of launching hundreds and possibly thousands of guided weapons will require more than a relative handful of long-range, expensive surface-to-air interceptors. Instead of continuing on its current course, DoD should rebalance its air and missile defenses toward short- and medium-range kinetic and non-kinetic capabilities. This rebalancing could increase the density of DoD's defenses against PGM salvos as well as create more favorable cost exchanges.

Some of these medium-range defenses, such as the ESSM, exist or are in the latter stages of development but have not been fielded. Technologies for other kinetic and non-kinetic defenses, including gun-launched HVPs, SSLs, and HPM weapons, are mature or rapidly maturing. Transitioning these technologies will require DoD to define requirements and request funding from Congress for new acquisition programs. This may first require DoD to determine how and what organizations should be responsible for championing the development and acquisition of its future air and missile defense architecture.

In summary, this report makes the following recommendations:

Change operational concepts

A shift toward a different mix of operational concepts could help create advantages for U.S. power-projection forces in future salvo competitions.

Place a greater emphasis on operating from range. The U.S. military could reduce the size and effectiveness of enemy PGM salvos by operating from locations that exceed the range of most land-based air and missile threats. U.S. forces operating from outside air and missile threat rings could compel enemies to invest in more expensive, longer-range surveillance and strike systems. In addition to imposing costs on an enemy, this would create opportunities for U.S. forces to attack long-range C3ISR networks and other kill chain capabilities used by enemy forces for precision targeting and bomb damage assessment.

Operate from dispersed theater postures. To the maximum extent possible, DoD should plan to disperse forces that must operate within A2/AD areas. Frequently moving forces across a network of distributed bases in contested areas would complicate an enemy's precision targeting and induce it to waste PGMs on unnecessary restrikes.

Prepare to operate from base clusters. DoD should take advantage of "clusters" of theater bases and expeditionary operating locations to disperse its forces within A2/AD areas. Cluster basing could induce enemies to dilute their strikes over more targets and allow U.S. forces to increase their defense capacity by taking advantage of mutually supporting air and missile defenses located within each cluster.

Increase base resiliency. Measures such as dispersing U.S. forces and critical facilities within individual bases, CCD, and hardening/deeply burying potential high-value targets would complicate an enemy's precision targeting, force it to use more expensive penetrating weapons, and cause it to waste PGMs against unproductive targets.

Conduct left-of-launch operations. DoD could reduce the size and frequency of an enemy's precision strikes by conducting offensive operations against its airbases and intercepting its strike platforms before they launch their weapons. Operations to suppress enemy strike systems will require manned and unmanned platforms capable of penetrating and enduring in contested areas, as well as a supporting network of C3ISR capabilities.

Shift toward short-to-medium-range air and missile defense operations. In lieu of its current emphasis on a layered architecture designed to progressively intercept missile threats at long ranges, medium ranges, then short ranges, the Navy could shift toward a defensive AAW scheme that preferentially uses medium-range interceptors and short-range kinetic and non-kinetic defenses. DoD could adopt a similar operational concept to defend its theater bases and forces against salvos that include cruise missiles, G-RAMM, and other PGMs. A shift toward these concepts could increase the density of the U.S. military's air and missile defenses as well as create more advantageous cost exchanges.

Development and procurement priorities

Kinetic interceptors. DoD should take advantage of mature technologies to develop and acquire lower cost short- and medium-range interceptors that increase the defense capacity of its ships and theater bases. These interceptors should incorporate active seekers and other technologies that could increase the tempo of engagements against enemy salvos and reduce the need for U.S. fire control systems to provide target updates after launch.

Hypervelocity projectile weapons. DoD should develop and field as soon as possible EMRGs and powder guns that can launch GPS- and command-guided HVPs at high rates of fire. HVPs should be capable of compensating for air and missile threats that maneuver during their terminal stages of flight.

Directed energy weapons. DoD should augment its kinetic defenses with non-kinetic SSLs and HPM weapons that can engage threats as long as they are provided with power and cooling. Given adequate resources, DoD should field land- and sea-based SSLs with sufficient power (150–300 kW) to counter unmanned aircraft, G-RAMM, and some cruise missiles within five to ten years. While it may require more time, the Services should prioritize development of land- and sea-based broadband HPM systems capable of countering multiple threats in a salvo.

Electronic warfare countermeasures. The Services should develop complexes of LPI/LPD jammers, decoys, and other counter-salvo EW capabilities. These complexes should be networked, agile, multifunctional, small, and autonomously adaptable to changes in the operational environment and to adversary actions.

Battle management and fire control systems. DoD should pursue battle management systems that are able to evaluate enemy air and missile salvo threats, determine which threats should be engaged, assign kinetic and non-kinetic defenses to appropriate targets, and continuously reevaluate the operational picture to respond to new threats or determine when current threats have been negated.

Capabilities for left-of-launch salvo suppression operations. DoD should increase its capacity to suppress enemy ground-based, sea-based, and airborne PGM launchers. Defeating enemy strike systems before they can launch their weapons will impose costs and help reduce the size of salvos to within the capacity of U.S. defenses. Missile suppression operations against land-based missile launchers will require sufficient long-range, penetrating ISR and strike platforms capable of enduring in contested and denied areas. In addition to advanced SAMs, DoD should pursue long-endurance, large-payload manned and unmanned aircraft that can sustain counter-air CAPs—potentially including platforms with high energy lasers—at long ranges.

Organizing, training, and equipping forces for salvo competitions

Allocate sufficient resources. The Congress and DoD should allocate sufficient resources to create an air and missile defense architecture at sea and on land that will help America's military to prevail in future salvo competitions. The FY 2017 President's Budget requested $524 billion for DoD's base budget. This request included less than $3 billion, or less than half of a percent of the proposed budget, to procure missile interceptors of all types. This may prove insufficient to develop effective defenses against ballistic missiles, cruise missiles, and other guided weapons that threaten vital U.S. interests abroad and at home.

Clarify responsibilities within DoD. Working with Congress, DoD should develop guidance that will clarify the responsibilities of its major components, including MDA and the Services, to establish requirements and fund acquisition programs for systems that will defend U.S. bases and forces against salvos comprising ballistic missiles, cruise missiles, and G-RAMM.

In conclusion, over the last twenty-five years DoD has heavily weighted its air and missile defense investments toward defeating a small number of ballistic missiles. As a result, it is inadequately prepared for salvo competitions with enemies that have developed their own sophisticated precision strike complexes. DoD has the opportunity to adopt operational concepts and rebalance its capabilities to defend against a wider range of guided weapons. This would require congressional support for new programs and an allocation of resources commensurate with this growing threat. Continuing to adhere to traditional concepts and capabilities for ballistic missile defense, however, could invite America's adversaries to continue, if not accelerate, their investments in guided weapons, further eroding the U.S. military's ability to project power.

APPENDIX 1. CHINA'S CRUISE MISSILES

Anti-Ship Cruise Missiles	Launch Mode	Range (km)	Payload (kg)	Guidance Systems	Speed
YJ-7	ground, ship, air	25	30	INS, active radar	subsonic
HY-2	ship	95	454	INS, active radar, IR	subsonic
YJ-62	air, ship, sub, ground	280	300	INS, satellite, active terminal	subsonic
YJ-82	sub	33	165	INS, active radar	subsonic
YJ-8A	ship, ground	42	165	INS, active radar	subsonic
YJ-81	air	70	165	INS, active radar	subsonic
YJ-82K	air	120	165	INS, active radar	subsonic
YJ-83	ship	180	165–190	INS, TV, satellite, IIR	supersonic (terminal only)
YJ-83K	air	200	165–190	INS, TV, satellite, IIR	supersonic (terminal only)
YJ-83KH	air	230	285	INS, TV, satellite, IIR terminal datalink	supersonic (termi-nal only)
YJ-91A/Kh-31A	air	70	94	INS, active radar	supersonic
SS-N-22 Sunburn					
3M8OE	ship	120	300	INS, active and passive	supersonic
3M8OMVE	ship	120 (est.)	300	INS, active and passive	supersonic
SS-N-27B Sizzler	submarine	220	200	INS, active radar	supersonic (terminal only)
AS-13 Kingbolt (Kh-59MK)	air	285	320	INS, active radar, satellite	subsonic
YJ-12 (developmental)	air, ship	250–500		INS, satellite, datalink, active radar	supersonic
YJ-18 (KLUB-copy)	ship, submarine	220	200	INS, active radar	supersonic (terminal only)

Land-Attack Cruise Missiles	Launch Mode	Range (km)	Payload (kg)	Guidance Systems	Speed
KD-88 KD-88 “cargo”	air air	100 300	100 250	INS, TV INS, TV, IIR, active/ passive radar	subsonic subsonic
YJ-91/Kh-31P	air	120	87	INS, passive radar	supersonic
YJ-63/AKD-63	air	200	500	INS, satellite, passive, EO terminal, datalink	subsonic
YJ-83KH	air	230	285	INS, TV, satellite, IIR terminal, datalink	subsonic
DH-10/CJ-10	ground, air	>1,500		INS, satellite, TERCOM, probably DSMAC for terminal guidance	subsonic
KD-20	air	2,200		INS, satellite, TERCOM	subsonic
HN-3	air, ship, sub, ground	up to 3,000		INS, satellite, TERCOM	subsonic

DSMAC: Digital Scene Matching Area Correlator; IIR: Imaging Infrared; TERCOM: Terrain Contour Matching; TV: television (guidance).

APPENDIX 1 NOTES:

The 2nd Artillery Force has approximately 500 cruise missiles on 40–50 road-mobile tri-canister launchers.

H-6M bombers can carry ASCMs.

H-6K bombers with LACMs may be able to range Guam, possibly carry 6 LACMs.

The data in Appendix 1 was compiled and cross-verified using various unclassified sources including:

Jane’s Strategic Weapon Systems, IHS Jane’s, 2014, 2015.

Jane’s Air-Launched Weapons, IHS Jane’s, 2014.

Weapons: Naval, IHS Jane’s, 2014.

Chinese Military Review, available at: http://chinesemilitaryreview.blogspot.com.

Defense Media Network, available at: http://www.defensemedianetwork.com.

OSD, *Military and Security Developments Involving the People’s Republic of China 2014*, Annual Report to Congress (Washington, DC: DoD, 2014).

APPENDIX 2. CHINA'S BALLISTIC MISSILES

SRBMs	Estimated Range (km)	Estimated Payload (kg)	Guidance Systems	Estimated CEP (meters)
B-611	150	480 HE, cluster	INS, satellite	75–150
B-611M	260	480 HE, cluster, or fuel air explosive	INS, satellite	50
DF-11	280	800	INS, terminal	600
DF-11A	400–600	500–600	INS, satellite, terminal	200
DF-15	600	500	INS, terminal guidance	300
DF-15A	900	600	INS, terminal guidance	30–45
DF-15B	800	?	INS, terminal guidance	5–10
DF-15C	?	?	INS, terminal guidance	?
DF-16 developmental	800–1,000	?	INS, satellite, mid-course update	?
MRBMs				
DF-21	1,750–2,150	600	INS, satellite	700
DF-21A	1,800–2,500	600	INS, satellite, radar	50
DF-21B	2,500	?	INS, satellite, radar	10
DF-21C	1,750	2,000	INS, satellite, radar	40–50
DF-21D	1,550–2,000	?	INS, satellite, radar	20
IRBMs				
DF-25	3,200	1,200	INS, satellite, active and passive radar, imaging IR	10
DF-26	3,000–4,000	Conventional and nuclear; ASBM and fixed targets		150

HE: high explosive; CEP: circular error probable.

APPENDIX 2 NOTES:

By November 2013, China had more than 1,000 SRBMs in its inventory and more than 200 SRBM launchers (NASIC 2013 report).

Some sources suggest the DF-26 could reach out to 5,000 km.

The data in Appendix 2 was compiled and cross-verified using various unclassified sources including:

Jane's Strategic Weapon Systems, IHS Jane's, 2013, 2014.

OSD, *Military and Security Developments Involving the People's Republic of China 2014*, Annual Report to Congress (Washington, DC: DoD, 2014).

National Air and Space Intelligence Center (NASIC), *Ballistic and Cruise Missile Threat* (Wright-Patterson AFB, OH: NASIC, 2013).

Dennis Gormley, Andrew Erickson, and Jingdong Yuan, "A Potent Vector: Assessing Chinese Cruise Missile Developments," *Joint Force Quarterly*, 75, September 30, 2014.

The Nuclear Threat Initiative online, updated 2014.

APPENDIX 3. IRAN'S CRUISE MISSILES

ASCMs	Launch Mode	Range (km)	Payload (kg)	Guidance Systems	Speed	Notes
Kosar Kosar-1 Kosar-3	ship, ground ship, ground air	15 15 25	30	INS, TV INS, active radar	subsonic	C-701
Fajr-e-Darya	air, ship. ground	25	70	INS, TV, active radar	subsonic	FL-6 and/or Oto Melara Sea Killer
Zafar	air, ship. ground	25	30	INS, MMW, active radar	subsonic	Possible C-701AR derivative
Nasr-1 Nasr-2	ship, ground air	35 50	130	INS, active radar INS, active radar, TV, IR	subsonic	C-704
Karus	ship, ground air	40 50	165	INS, active radar	subsonic	C-801
Tondar	ship, ground air	120 130	165	INS, active radar	subsonic	C-802
Noor	ship air	180 250	165	INS, satellite, active radar	subsonic	upgraded C-802
Qader/ Ghader	ship, ground air	300 ?	165	INS, active radar	subsonic	upgraded C-802
Ra'ad	ground	350	500	INS, IIR, active radar	subsonic	HY-2 derivative
LACMs						
Soumar	ground, ship, air	3,000	400	INS, TERCOM	subsonic	Kh-55 based
Ya Ali	air	700	200	INS, Satellite	subsonic	ground- and sea-launched versions under development

MMW: millimeter wave.

APPENDIX 3 NOTES:

The data in Appendix 3 was compiled and cross-verified using various unclassified sources including:

Jane's Strategic Weapon Systems, IHS Jane's, 2014.

Jane's Air-Launched Weapons, IHS Jane's, 2014.

Weapons: Naval, IHS Jane's, 2014, 2015.

Jane's Missiles & Rockets, IHS Jane's, 2011, 2014.

Jane's Defence Weekly, IHS Jane's, 2012.

APPENDIX 4. IRAN'S BALLISTIC MISSILES

Rocket Artillery	Range (km)	Payload (kg)	Guidance Systems	Estimated CEP (meters)
Nazeat N5	105	105		
Nazeat N6-H	?	150		
Nazeat N8	100	300	unguided	700
Nazeat N10	125	240		
Nazeat N10-H	140	?		
Fajr-5	80	175	unguided	
Two-stage Fajr-5	180			
Zelzal-1	125			
Zelzal-2	200	600	unguided	
Zelzal-3	200–300			
SRBM				
Scud-B/ Hwasong-5	300	985	INS	450
Tondar-69	150	250	INS, command update	100
Fateh-110	200	650	INS, satellite	100
Fateh-110 2nd generation	250	450	INS, satellite	100
Fateh-110 3rd generation	300	650	INS, satellite	100
Fateh-110-D1	300	650	INS, satellite	<100
Khalij Fars ASBM	300	650	INS, EO/IR	-
Fateh-313	500	<650	INS, satellite	-
Hormuz-1 anti-radar	300	-	passive radar	-
Hormuz-2 ASBM	300	-	INS, EO/IR	-
Shahab-1	300	985	INS	450
Shahab-2	500	770		700
Qiam-1	800	750	INS	500

MRBM	Range (km)	Payload (kg)	Guidance Systems	Estimated CEP (meters)
Shahab-3	1,300–1,500	500–800	INS	2,500
Shahab-3A	1,500–1,800	500		?
Shahab-3B	2,000–2,500	800		?
Shahab-4	2,000	?		2,500+
Ghadr-1	1,950	?	INS	300
Sejil/Sejil-2/Ashoura	2,000	500–1500	INS, satellite	?
Sejil-3	4,000	?	?	?
IRBM				
Musudan (BM-25)	4,000	1,200	INS	1,600

APPENDIX 4 NOTES:

The data in Appendix 4 was compiled and cross-verified using various unclassified sources including:

Jane's Strategic Weapon Systems, IHS Jane's, 2013, 2014, 2015.

Jane's Defence Weekly, IHS Jane's, 2014, 2015.

Anthony Cordesman, *Iran's Rocket and Missile Forces and Strategic Options* (Washington, DC: Center for Strategic and International Studies, October 7, 2014).

APPENDIX 5. GROSS WEAPON SYSTEM UNIT COSTS FOR INTERCEPTORS IN PRODUCTION FOR THE U.S. MILITARY

Point Defense (Short Range)	Service	Description	Warhead	Guidance	Unit Cost (FY17 $K)
RIM-119 RAM	Navy	Short-range defense against anti-ship missiles and asymmetric air and surface threats.	3.58 kg	INS, radar (or EO terminal)	$795
Phalanx CIWS	Navy	A Gatling gun-like weapon to counter anti-ship missiles, aircraft, other threats.	20 mm	Computer-controlled, radar-guided	Upgrades only
SeaRAM	Navy	Combines RAM with the computer-controlled, radar-guided Phalanx system to counter anti-ship missiles and other air and surface threats.		INS, radar, EO/IR terminal	$795
Counter-Rocket, Artillery, Mortar Intercept Land-Based Phalanx Weapon System	Army	A truck mounted variant of the Navy Phalanx system to counter rockets, artillery, and mortars.	20 mm	Computer-controlled, radar-guided gun system	Upgrades only
Area/Terminal Air and Missile Defense (Medium Range to Long Range)					
RIM-162 ESSM	Navy	A medium-range missile designed to intercept anti-ship missiles and asymmetric threats.	40.5 kg	Semi-active radar	$1,432 (VLS variant)
SM-2	Navy	The Navy's primary surface-to-air interceptor, launched from VLS.	115 kg	Semi-active radar homing; IR (Block IIIB)	$1,372
SM-6	Navy	SM-6 will replace the SM-2 for anti-air warfare. It combines the AMRAAM active seeker with the existing SM airframe.	115 kg	dual-mode seeker (active and semi-active	$4,010
THAAD	Defense Wide	Uses a hit-to-kill interceptor to destroy short-, medium-, and intermediate-range ballistic missiles in their terminal phase.	hit-to-kill	GPS/INS	$15,400
PAC-3	Defense Wide, Army	Designed to intercept short-range ballistic missiles, aircraft, air-to-surface, surface-to-surface, and cruise missiles.	hit-to-kill	INS and active radar	PAC-3 MSE: $4,979

Mid-Course BMD (Very Long Range)	Service	Description	Warhead	Guidance	Unit Cost (FY17 $K)
SM-3	Defense Wide	Theater-wide defense capability against medium-to-long-range ballistic missiles. Launched from VLS cells either on BMD equipped ships or AEGIS ashore facilities.	23 kg	INS, GPS, IIR	SM-3 IB: $13,251
GBI	Defense Wide	GBI are designed to intercept ballistic missiles in the mid-course flight phase after incoming warheads have separated from the booster.	hit-to-kill	INS with ground based radar, satellite command updates, IIR, and visual	$86,296

AMRAAM: Advanced Medium-Range Air-to-Air Missile; GPS: Global Positioning System.

APPENDIX 5 NOTES:

Weapon unit costs in Appendix 5 are the Gross Weapon System Unit Costs reported in the President's Budget for FY 2017 except in the case of the SM-2 and the GBI. The Gross Weapon System Unit Cost of a weapon is higher than its Flyaway Unit Cost since it includes the expenditures necessary for the production and use of a new missile in addition to the missile itself. For example, the Gross Weapon System Unit Cost for an SM-6 is $4.01 million and covers additional costs such as the FE002 canister and checkout and documentation costs. In contrast, the Flyaway Unit Cost of an SM-6 is $2.63 million, which includes only the cost of the missile itself. Since DoD is no longer procuring the SM-2, its unit cost was derived from DoD's FY 2012 budget submission, the last year it was reported, and inflated to 2017 dollars. Additionally, DoD does not report a gross weapon unit cost for the GBI. The entire program is funded out of the RDT&E budget. Instead, the table includes the average procurement unit cost (APUC) from 2013, the last year where a multi-interceptor procurement was linked to funding, inflated to 2017 dollars. Since APUC includes additional cost elements not covered in the gross weapon system unit cost, it is not completely comparable to other defensive munitions in Appendix 5. However, GBI's significantly larger APUC is suggestive that its gross weapon system unit cost would also be substantially larger than other interceptors.

*Data in Appendices 1–5 updated as of April 2016. All foreign munitions specifications are subject to change as a result of new technologies, improved design, and better intelligence. U.S. weapon systems cost subject to change as procurement programs evolve.

LIST OF ACRONYMS

A2/AD	anti-access/area denial
AAW	anti-air warfare
ABL	Airborne Laser
AI3	Accelerated Improved Interceptor Initiative
AMRDEC	Aviation and Missile Research, Development, and Engineering Center
APUC	average procurement unit cost
ASBM	anti-ship ballistic missile
ASCM	anti-ship cruise missile
BMD	ballistic missile defense
BMDO	Ballistic Missile Defense Organization
BMDR	Ballistic Missile Defense Review
BMDS	ballistic missile defense system
C3ISR	command, control, communications, intelligence, surveillance, and reconnaissance
CAP	combat air patrol
CCD	camouflage, concealment and deception
CEP	circular error probable
CG	guided missile cruiser
CHAMP	Counter-Electronics High Power Microwave Advanced Missile Project
CIWS	Close in Weapon System
COIL	chemical oxygen iodine laser
CSBA	Center for Strategic and Budgetary Assessments
CSG	carrier strike group
DARPA	Defense Advanced Research Projects Agency
DCA	defensive counter-air
DDG	guided missile destroyer
DE	directed energy
DIA	Defense Intelligence Agency
DoD	Department of Defense
DSMAC	digital scene matching area correlation
EM	electromagnetic
EMRG	electromagnetic railguns
EPAA	European Phased Adaptive Approach
EPF	Expeditionary Fast Transport

LIST OF ACRONYMS

ESSM	Evolved Sea Sparrow Missile
EW	electronic warfare
GAO	General Accounting Office
G-RAMM	guided rockets, artillery, mortars, and missiles
GBI	Ground Based Interceptors
GPS	Global Positioning System
HE	high explosive
HELLADS	High Energy Liquid Laser Area Defense System
HGV	hypersonic glide vehicles
HPM	high power microwave
HVP	hypervelocity projectiles
IBCS	Integrated Air and Missile Defense Battle Control System
ICBM	intercontinental ballistic missiles
IFPC	Indirect Fire Protection Capability
IIR	imaging infrared
Inc 2	Increment 2 (of the IFPC)
INS	inertial navigation system
IOC	initial operating capability
IR	infrared
IRBM	intermediate-range ballistic missile
ISR	intelligence, surveillance, and reconnaissance
JFCC IMD	Joint Functional Component Command for Integrated Missile Defense
JIAMDO	Joint Integrated Air and Missile Defense Organization
km	kilometer
kW	kilowatt
LACM	land-attack cruise missiles
LaWS	laser weapon system
LED	light-emitting diode
Lower-AD	Lower Cost Extended-Range Air Defense Interceptor
LPD	low probability of detection
LPI	low probability of intercept
LRASM	Long-Range Anti-Ship Cruise Missile
MAD-FIRES	Multi-Azimuth Defense Fast Intercept Round Engagement System
MaRV	maneuverable reentry vehicle

LIST OF ACRONYMS

MDA	Missile Defense Agency
MIRACL	Mid-Infrared Advanced Chemical Laser
MJ	megajoule
MML	Multi-Mission Launcher
MMW	millimeter wave
MRBM	medium-range ballistic missiles
MSE	Missile Segment Enhancement
MW	megawatt
NIFC-CA	Naval Integrated Fire Control-Counter Air
OAB	Outer Air Battle
ONR	Office of Naval Research
OSD	Office of the Secretary of Defense
OTH	over the horizon
PAC	Patriot Advanced Capability
PES	probability of engagement success
PGM	precision-guided munition
P_k	probability of kill
PLA	People’s Liberation Army
PLAAF	People’s Liberation Army Air Force
QDR	Quadrennial Defense Review
RAM	Rolling Airframe Missile
RAMM	rockets, artillery, mortars, and missiles
RDT&E	Research Development Test and Evaluation
RF	radio frequency
SAM	surface-to-air missile
SEWIP	Surface Electronic Warfare Improvement Program
SHiELD	Self-protect High Energy Laser Demonstrator
SM	Standard Missile
SRBM	short-range ballistic missiles
SSL	solid state lasers
SSL-TM	Solid State Laser-Tech Maturation
USSTRATCOM	U.S. Strategic Command
TEL	transporter erector launcher
TERCOM	terrain contour matching

LIST OF ACRONYMS

THAAD	Terminal High-Altitude Area Defense
TTP	tactics, techniques, procedures
TV	television
UAV	unmanned aerial vehicle
UCAV	unmanned combat aerial vehicle
VLS	vertical launching system

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