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AIR AND MISSILE DEFENSE AT A CROSSROADS

NEW CONCEPTS AND TECHNOLOGIES TO DEFEND AMERICA'S OVERSEAS BASES

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Cover: Background and elements derived from U.S. Air Force and U.S. Navy photos. Photo of the Avenger UAV was provided by General Atomics Aeronautical Systems, Inc.

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Introduction

The Department of Defense (DoD) has invested billions of dollars over the last 30 years to defend against ballistic missile attacks on the United States and its bases and forces overseas. Despite these investments, the U.S. military still lacks the ability to defeat large numbers of ballistic missiles, cruise missiles, unmanned aircraft, and other emerging guided weapons threats. Indeed, tangible progress toward fielding high capacity air and missile defenses has been, to date, barely noticeable.

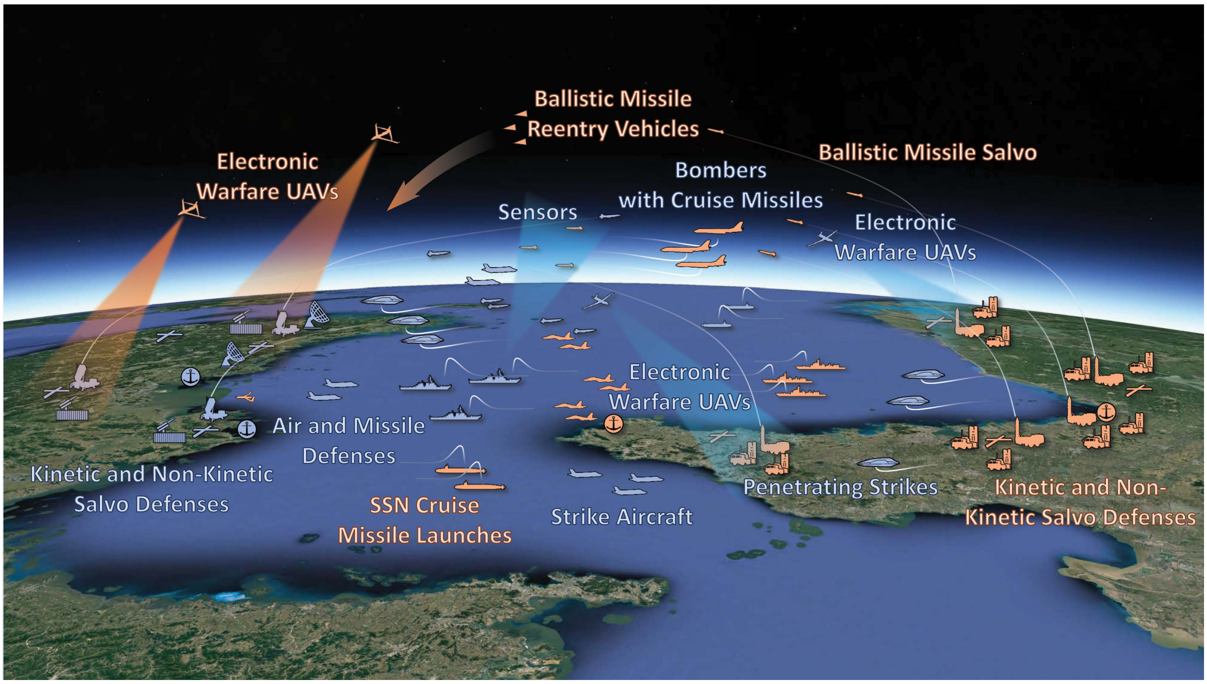
This report addresses how DoD could take advantage of mature and maturing technologies to develop higher capacity and more cost-effective air and missile defenses for its overseas bases, including airbases that currently have few defenses against cruise missile and unmanned aerial vehicle (UAV) attacks. These defenses could include medium-range high energy lasers (HEL), high-power microwave (HPM) systems, guided projectiles launched by rapid-firing guns, and low-cost surface-to-air missiles. Unmanned and manned aircraft carrying extended-range air-to-air missiles and equipped with wide-area surveillance sensors, HELs, and possibly HPM systems could further extend the range and increase the threat engagement capacity of a base salvo defense complex. This layered defense concept would help enable U.S. forces to conduct power-projection operations inside contested areas—and do so at significantly less cost than continuing to rely almost exclusively on expending multimillion-dollar ground-launched surface-to-air missiles against each threat in a salvo.

Understanding the Challenge

Salvo Competitions

In line with previous CSBA assessments, this report uses a salvo competition framework to assess promising concepts and capabilities to defend U.S. bases against guided weapon attacks.[1] This competition is the dynamic between opposing militaries that can each strike and defend with precision against large numbers (or salvos) of air-, ground-, and sea-launched weapons (see Figure 1). In this competition, each combatant seeks to gain advantages by continuously improving the size and survivability of its offensive strikes as well as the lethality and capacity of its defenses.

FIGURE 1: ILLUSTRATIVE SALVO COMPETITION CAPABILITIES



To date, the U.S. military has not been challenged by an enemy capable of launching large salvos of guided weapons against our forces and bases. This reality formed part of DoD's rationale for allocating most of its missile defense resources to the creation of an architecture equipped to defeat a small number of ballistic weapons that could be launched by Iran, North

1 For other CSBA reports that address some of these capabilities, see Mark Gunzinger and Bryan Clark, *Sustaining America's Precision Strike Advantage* (Washington, DC: Center for Strategic and Budgetary Assessments, 2015); and Mark Gunzinger and Bryan Clark, *Winning the Salvo Competition: Rebalancing America's Air and Missile Defenses* (Washington, DC: Center for Strategic and Budgetary Assessments, 2016).

Korea, or other rogue states. In 2010, DoD conducted its first-ever Ballistic Missile Defense Review to evaluate if it should change this focus. The review concluded that DoD should continue to emphasize protecting the U.S. homeland against limited ballistic missile attacks and defeating ballistic missile threats to its forces.[2]

Yet, this bias toward defeating a small number of ballistic weapons may finally be changing, given DoD's strategic shift toward planning for great power competition. Improving defenses against salvos that include not only ballistic missiles, but also cruise missiles, hypersonic glide vehicles (HGV), and UAVs armed with warheads is a key imperative in planning to face more capable great power adversaries.[3] Over the last two decades, China and Russia have invested heavily in advanced military systems to offset the superior conventional capabilities of the United States and its allies. Their so-called anti-access and area-denial (A2/AD) complexes of integrated air defense systems (IADS), long-range precision strike platforms, and other advanced weaponry are designed to raise the cost to the United States and other countries attempting to project military power into their respective regions. Many of China's and Russia's long-range strike systems were designed specifically to attack theater airbases, seaports, and other facilities that are critical to U.S. military operations.[4] These weapon systems undermine security assurances made by the United States to its allies and partners and could incentivize a great power aggressor to strike first in a crisis.

Great Power Salvo Threats: China[5]

China has designed its A2/AD complex to degrade the U.S. military's ability to operate from bases that are located across the Western Pacific. This complex includes overlapping active and passive defenses, early warning and target-tracking sensors, surface-to-air missile (SAM) batteries, increasingly advanced combat aircraft, a growing fleet of UAVs, cruise missiles, and ballistic missiles.[6] Images obtained from commercial satellites show that China has constructed mock targets representing Kadena Air Base in Okinawa—and possibly other U.S., Japanese, and Taiwanese bases and port facilities. China's PLA Rocket Force (PLARF) may be using these mock targets to conduct practice attacks, which is consistent with the PLA's

2 Department of Defense (DoD), Ballistic Missile Defense Review Report (Washington, DC: DoD, February 2010), p. iii, available at https://www.defense.gov/Portals/1/features/defenseReviews/BMDR/BMDR_as_of_26JAN10_0630_for_web.pdf.

3 See Paul Sonne, "Pentagon Looks to Adjust Missile Defense Policy to Include Threats from Russia, China," *Washington Post*, March 2, 2018.

4 Mark Gunzinger, Bryan Clark, David Johnson, and Jesse Sloman, *Force Planning for the Era of Great Power Competition* (Washington, DC: Center for Strategic and Budgetary Assessments, 2017), pp. 32–35, 70–80. Also see David A. Shlapak and Michael Johnson, *Reinforcing Deterrence on NATO's Eastern Flank: Wargaming the Defense of the Baltics* (Santa Monica, CA: RAND Corporation, 2016).

5 This is not an exhaustive analysis of China's salvo threats.

6 China may produce some 41,000 land- and sea-based unmanned systems through 2023. See Thomas R. McCabe, "Keeping A2/AD at Bay: The Imperative for Base Defense in the Western Pacific," *The Mitchell Forum*, no. 17, January 2018, p. 5, available at http://www.mitchellaerospacepower.org/a2ad-release.

Science of Military Strategy that lists the primary mission of the PLARF as "suppressing enemy air force air bases, airfields, and missile defense (air defense) systems."[7]

China's ballistic missile arsenal includes approximately 1,200 short-range ballistic missiles (SRBM) that are mostly postured to attack targets in Taiwan. The PLARF has approximately 200–300 medium-range ballistic missiles (MRBM) such as the DF-21 (CSS-5) and a new DF-16 (CSS-11) that can reach targets along the First Island Chain in the Western Pacific (see Figure 2). China also has an undetermined number of intermediate-range ballistic missiles (IRBM) that can reach the Second Island Chain, including the DF-26 and its expected variants.[8]

FIGURE 2: FIRST AND SECOND ISLAND CHAINS

The First Island Chain follows the Japanese island of Kyushu, down the Ryukyus to the north of Taiwan, west toward Luzon, along Palawan and to Singapore. The Second Island Chain includes the northern Marianas, the Volcano Islands, down to Guam, stretching south to Palau and New Guinea.

In addition to its many ballistic missiles, China has thousands of cruise missiles and military UAVs. The PLA has developed the CJ-10 ground-launched cruise missile (GLCM), an air-launched version of the CJ-10 called the CJ-20 that has a range of approximately 1,500 km, and numerous other air-launched cruise missile variants.[9] Analysis of prior and ongoing

7 Oriana Skylar Mastro and Ian Easton, *Risk and Resiliency: China's Emerging Air Base Strike Threat* (Arlington, VA: Project 2049, November 8, 2017), p. 3, available at https://project2049.net/2017/11/08/risk-and-resiliency-chinas-emerging-air-base-strike-threat/. Also see Thomas Shugart and Javier Gonzalez, *First Strike: China's Missile Threat to U.S. Bases in Asia* (Washington, DC: Center for a New American Security, June 2017), pp. 4–6, available at https://www.cnas.org/publications/reports/first-strike-chinas-missile-threat-to-u-s-bases-to-asia.

8 Office of the Secretary of Defense (OSD), *Military and Security Developments Involving the People's Republic of China 2018*, Annual Report to Congress (Washington, DC: DoD, May 16, 2018), pp. 59–63, 70–71.

9 Ibid.

PLA activities suggests that cruise missiles may be one of a series of "silver bullet" or "assassin's mace" capabilities that China has sought to develop for years.[10] According to some U.S. defense experts, "Chinese planners have come to regard both anti-ship and land-attack cruise missiles as potentially playing a significant role in determining the outcome of future conflicts."[11] China is also developing multiple UAV variants capable of C3ISR, strike, and many other operations.[12] Although the United States and its regional partners have improved their ballistic missile defenses in the Indo-Pacific region, they have failed to develop the means to counter salvos of large numbers of cruise missiles and UAVs.[13]

FIGURE 3: DF-26 IRBM AND CJ-20 AIR-LAUNCHED CRUISE MISSILES

The DF-26 photo is by IceUnshattered, available via the CC BY-SA 4.0 at https://en.wikipedia.org/wiki/DF-26#/media/File:Dong-Feng_26.JPG. The CJ-20 is available via the Missile Defense Advocacy Alliance at http://missiledefenseadvocacy.org/missile-threat-and-proliferation/missile-proliferation/china/changjian-20-cj-20/.

10 Liu Tonglin, Ni Yonghua, and Liu Yin, eds., *Cruise Missiles—The "Assassin's Mace" in High-Tech Warfare* (Beijing: Military Arts Press, 2002), pp. 1–9. The term assassin's mace is best translated in colloquial English as "silver bullet." Also see Carl Rehberg, review of *A Low Visibility Force Multiplier: Assessing China's Cruise Missile Ambitions*, by Dennis M. Gormley, Andrew S. Erickson, and Jingdong Yuan, *Strategic Studies Quarterly*, Summer 2014, pp. 148–151.

11 Dennis M. Gormley, Andrew S. Erickson, and Jingdong Yuan, *A Low Visibility Force Multiplier: Assessing China's Cruise Missile Ambitions* (Washington, DC: National Defense University Press, 2014), p. 6.

12 McCabe, "Keeping A2/AD at Bay," p. 5. See also Elsa Kania, *The PLA's Unmanned Aerial Systems: New Capabilities for a "New Era" of Chinese Military Power* (Montgomery, AL: China Aerospace Studies Institute, August 8, 2018), available at https://www.airuniversity.af.mil/CASI/Display/Article/1596429/the-plas-unmanned-aerial-systems-new-capabilities-for-a-new-era-of-chinese-mili/.

13 For examples, see David Ochmanek, *Overcoming Anti-Access and Area Denial (A2AD) Threats: Insights from War Games* (Santa Monica, CA: RAND Corporation, Project Air Force, June 9, 2017); Alex Lockie, "The US Has No Good Defense Against Cruise Missiles—And It's a Huge Problem," *Business Insider,* August 9, 2016, available at http://www.businessinsider.com/us-military-lacks-cruise-missiles-defense-2016-8; and McCabe, "Keeping A2/AD at Bay," p. 5.

Great Power Salvo Threats: Russia[14]

Although Russia's arsenal of long-range conventional ballistic missiles is much smaller than China's, it has fielded multiple SRBM variants. SRBMs such as the 9K720 Iskander-M weapon system extend Russia's A2/AD umbrella over much of Europe.[15] By 2020, Russian armed forces are expected to field ten Iskander-M brigades with the combined capacity to launch about 480 missiles, assuming each launcher has a single missile reload. In March 2018, the Russian Air Force announced it had taken delivery of new 2,000-km range Kh-47M2 Kinzhal hypersonic air-launched ballistic missiles, which can be launched by modified MIG-31BM supersonic aircraft. Russian crews from a MIG-31 squadron have already flown some 250 training sorties in support of this mission.[16] It is envisioned that the Kinzhal will be deployed with HGVs that maneuver after separation from their boosters and fly depressed trajectories that make them difficult to intercept.

FIGURE 4: ISKANDER-M LAUNCHER WITH AN SRBM

Photo by Sergey Orlov, © Sputnik, available at https://sputniknews.com/russia/201707241055821430-russia-china-ballistic-missiles/.

Russia has placed a high priority on fielding multiple cruise missile variants that can be launched from its submarines, ships, aircraft, and land batteries. In 2015 and 2017, Russian submarines launched a number of 3M14 Kalibr land-attack cruise missiles (LACM) against

14 Defense Intelligence Agency (DIA), *Russia Military Power: Building A Military to Support Great Power Aspirations* (Washington, DC: DIA, 2017). See also "Russia—Air Force," *IHS Jane's Sentinel Security Assessment, Russia and the CIS,* updated September 27, 2017; and The International Institute for Strategic Studies (IISS), *The Military Balance 2018* (London: IISS, 2018), pp. 169–180, 192–207.

15 Ian Williams, "The Russia–NATO A2AD Environment," *Missile Threat*, Center for Strategic and International Studies, January 3, 2017, updated June 15, 2018, available at https://missilethreat.csis.org/russia-nato-a2ad-environment/. The Iskander-M can launch at least seven different types of missiles, including cruise missiles.

16 Neil Gibson and Nikolai Noichkov, "Russian Aerospace Forces Take Delivery of 'New' Kinzhal Air-launched Ballistic Missile," *Jane's Missiles and Rockets*, March 19, 2018. See also Missile Defense Project, "Kinzhal," *Missile Threat*, Center for Strategic and International Studies, March 27, 2018, updated June 15, 2018, available at https://missilethreat.csis.org/missile/kinzhal/.

targets located in Syria.[17] Air-, ground-, and sea-launched Kh-101, 9M728, and 3M14 LACMs are a significant threat to NATO bases located throughout Europe, including airbases and other military installations in the United Kingdom. LACMs launched by Russia's long-range bombers could reach targets located in North America, which is a major concern given the lack of sufficient cruise missile defenses in the U.S. homeland.[18] Moscow has also developed a land-based GLCM that "violates the spirit and intent" of the 1987 Intermediate-Range Nuclear Forces (INF) Treaty.[19] According to media reports, Russia has deployed one or more battalions of these GLCMs, which are thought to be 9M729 (SSC-8) missiles integrated with Iskander-K launchers.[20] With a reported range of 2,000 km, 9M729s deployed to Russia's Kaliningrad enclave could reach the Royal Air Force's six main operating bases in the United Kingdom and almost all of NATO's continental bases.

In addition to ballistic and cruise missiles, Russia has a large inventory of ground-launched rockets and artillery, and it is developing multiple UAV variants to provide targeting support for its artillery and other strike forces. Due to either resource constraints or other reasons, Russia appears to be focused on fielding smaller UAVs (Group 1 to 4) instead of larger UAVs.[21] DoD classifies UAVs by Group, with Group 1 being the smallest aircraft and Group 5 being the largest. Each Group is defined by the maximum weight, nominal operating altitude, and speed of the UAVs.[22] Russia's smaller UAVs could be used for locating and cueing attacks on NATO's forces.

17 "Game Changer: Russian Sub-launched Cruise Missiles Bring Strategic Effect," *Jane's International Defence Review*, April 27, 2017.

18 "Russia has prioritized the development of advanced cruise missiles capable of holding targets within North America at risk from distances not previously seen. These systems present an increasing threat to North America . . . and the limited indications and warnings likely to be seen prior to a combat launch." General Lori Robinson, Commander U.S. Northern Command and North American Aerospace Defense Command, statement before Senate Armed Services Committee, February 15, 2018, p. 11, available at http://www.northcom.mil/Portals/28/Robinson_02-15-18%20SASC%20Testimony.pdf?ver=2018-02-15-105546-867.

19 General Paul Selva, Vice Chairman of the Joint Chiefs of Staff, testified at a HASC Committee hearing in March 2017 that the U.S. believes Russia has "deployed a land-based cruise missile that violates the spirit and intent" of the 1987 INF Treaty and it poses a threat to NATO. John M. Donnelly, "Hill Wants Answers on Russia's Fielding of New Missiles," *Roll Call*, March 8, 2017, available at https://www.rollcall.com/news/hill-wants-answers-russias-fielding-new-missiles. State Department reports submitted to the U.S. Congress in 2014, 2015, and 2016 cited Russia's violations. See Amy F. Woolf, *Russian Compliance with The Intermediate Range Nuclear Forces (INF) Treaty: Background and Issues for Congress* (Washington, DC: Congressional Research Service, March 15, 2017).

20 Michael R. Gordon, "Russia Deploys Missile, Violating Treaty and Challenging Trump," *New York Times,* February 14, 2017, available at https://www.nytimes.com/2017/02/14/world/europe/russia-cruise-missile-arms-control-treaty.html?mcubz=3.

21 Samuel Bendett, "Russia's Rising Drone Industry," *The National Interest Blog*, July 27, 2016, available at http://nationalinterest.org/blog/the-buzz/russias-rising-drone-industry-17146.

22 Group 1 and 2 UAVs are small aircraft that weigh less than 55 pounds and fly below 3,500 ft above ground level (AGL) at airspeeds of less than 250 knots. Group 3 UAVs have a maximum gross weight of less than 1320 pounds and operate below 18,000 ft mean sea level (MSL) at airspeeds of less than 250 knots . Group 4 UAVs have a maximum gross weight of more than 1320 pounds and operate below 18,000 ft MSL at any airspeed. Group 5 UAVs have a maximum gross weight of more than 1320 pounds and operate above 18,000 ft MSL at any airspeed. Department of Defense, *FY2009–2034 Unmanned Systems Integrated Roadmap* (Washington, DC: DoD, April 6 2009), pp. 96–97, available at https://www.globalsecurity.org/intell/library/reports/2009/dod-unmanned-systems-roadmap_2009-2034.pdf.

U.S. Base Resiliency

A Growing Awareness

Over the last decade, DoD has acknowledged the need to improve the resiliency of its overseas basing posture.[23] The 2018 National Defense Strategy emphasizes transitioning the U.S. military's overseas posture "from large, centralized, unhardened infrastructure to smaller, dispersed, resilient, adaptive basing that include active and passive defenses."[24] The Services are developing concepts to increase the resiliency of their bases and forces operating in areas that could be subject to salvo attacks. For instance, the Air Force is continuing to develop a concept of operations it calls Adaptive Basing to increase the resiliency of its airbases,[25] and the Marine Corps is testing concepts for conducting distributed operations that take advantage of its ability to operate from expeditionary bases. Given the growing threat of great power salvo attacks, these concepts should include affordable high-capacity air and missile defenses that can be quickly deployed and redeployed to support distributed operations.

Current Base Passive Air and Missile Defenses[26]

Despite DoD's concerns over the potential for great power salvos to erode its ability to project power, its main operating bases in the Pacific and Europe are still optimized to conduct efficient operations in peacetime. Given sufficient priority, DoD could begin to address the vulnerability of its overseas bases to salvo attacks in the near term. Technologies are sufficiently mature to field new passive defenses that could shelter or otherwise harden base infrastructure against several classes of munitions, including submunitions that are effective against unfortified, "soft" targets such as aircraft and supporting ground equipment. DoD has developed capabilities to harden airbase infrastructure against penetrating PGMs and is fielding new capabilities and capacity for rapid repair of runways and other facilities following attacks. Although technologies for innovative, cost-effective small shelters are mature and there has been some progress toward fielding them, a critical shortfall of risk-appropriate

23 DoD organizations have used different terms to describe the resiliency of its overseas posture, including "operational resiliency," "joint resiliency," and "posture resiliency." Operational resiliency is an overarching or umbrella term. The 2018 National Defense Strategy (NDS) describes posture resilience as "forces that can deploy, survive, operate, maneuver and regenerate in all domains while under attack." Department of Defense, *Summary of the 2018 National Defense Strategy of The United States of America: Sharpening the American Military's Competitive Edge* (Washington, DC: DoD, January 2018), p. 6, available at https://www.defense.gov/Portals/1/Documents/pubs/2018-National-Defense-Strategy-Summary.pdf. Also see Alan J. Vick, *Air Base Attacks and Defensive Counters: Historical Lessons and Future Challenges* (Santa Monica, CA: RAND Corporation, 2015).

24 DoD, *Summary of the 2018 National Defense Strategy of The United States of America*, p. 6.

25 Headquarters Air Force A5S, "Adaptive Basing: A Concept to Survive, Operate and Project Airpower in a Contested Environment," unclassified PowerPoint briefing, 2016. See also David Dammeier, Meka Toliver, and Logan Smith, "A Power Projection Problem," *CE Online,* U.S. Air Force, Spring 2016, available at http://www.afcec.af.mil/News/CE-Online/Article-Display/Article/1004470/overcoming-a-power-projection-problem/.

26 For a more thorough treatment of the synergy between active and passive salvo defenses, see Gunzinger and Clark, *Winning the Salvo Competition*. The remainder of this report will address concepts and new capabilities for active defenses that have significant potential to counter salvo attacks on U.S. theater bases.

shelter capacity likely remains at U.S. airbases in Japan, Guam, Europe, and other locations that may be subject to large salvo attacks.

Current Base Active Air and Missile Defenses

For most of the post-Cold War era, DoD focused its missile defense priorities on fielding ground-based and sea-based kinetic weapons to intercept ballistic threats.[27] With the exception of the Navy, no other Service has fielded major new capabilities to counter cruise missile salvos.

FIGURE 5: THE U.S. BALLISTIC MISSILE DEFENSE SYSTEM

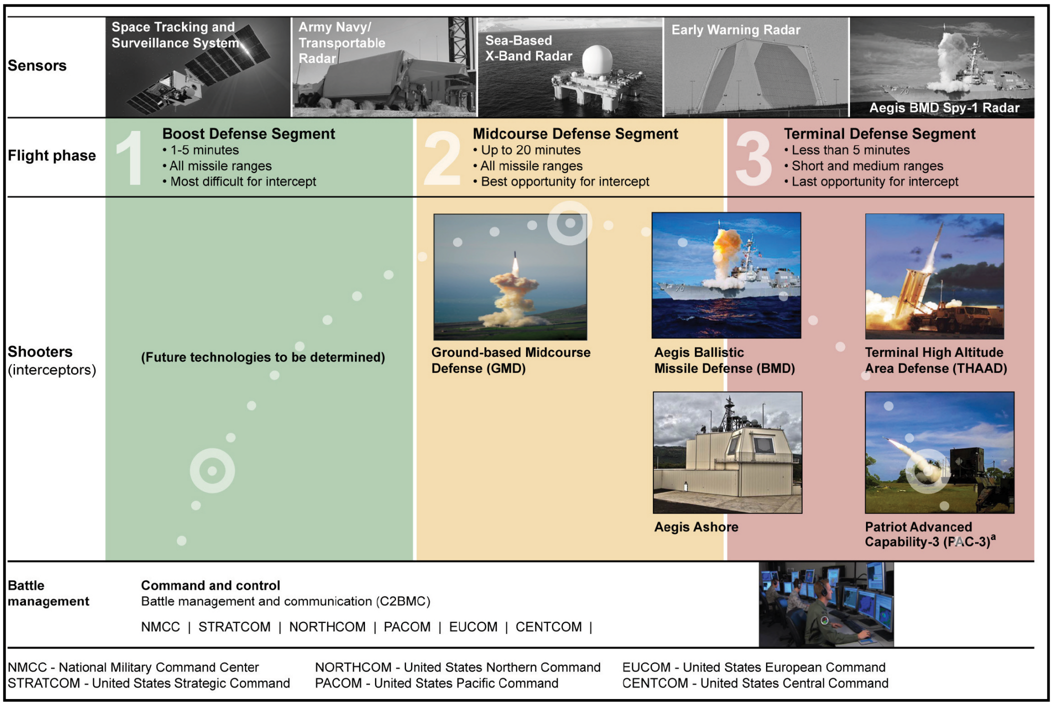


Figure from U.S. Government Accountability Office (GAO), *Missile Defense: Some Progress Delivering Capabilities, but Challenges with Testing Transparency and Requirements Development Need to Be Addressed* (Washington, DC: GAO, May 2017), p. 6, available at https://www.gao.gov/assets/690/684963.pdf.

27 Thomas Karako and Wes Rumbaugh, *Distributed Defense: New Operational Concepts for Integrated Air and Missile Defense* (Washington, DC: Center for Strategic and International Studies, January 25, 2018), pp. 12–13, available at https://www.csis.org/analysis/distributed-defense-0; and Thomas Karako, Ian Williams, and Wes Rumbaugh, *Missile Defense 2020: Next Steps for Defending the Homeland* (Washington, DC: Center for Strategic and International Studies, April 6, 2017), available at https://www.csis.org/analysis/missile-defense-2020.

The Missile Defense Agency. The Missile Defense Agency (MDA) is responsible for developing a layered Ballistic Missile Defense System for DoD that includes capabilities to intercept ballistic missiles in their boost, midcourse, and terminal phases of flight (see Figure 5).[28] The MDA has had a mixed record when it comes to testing and fielding new ballistic missile defenses. Nevertheless, MDA programs have had several recent successes, including the first intercept of an ICBM target by its Ground-based Midcourse Defense (GMD) system and an Aegis SM-3 Block IIA intercept of a medium-range ballistic missile target.

Other, less publicized successes include MDA contributions to Israel's David's Sling and Iron Dome air defense systems.[29] The MDA could soon begin to test an advanced ballistic missile tracking system utilizing a long-endurance variant of the MQ-9 Reaper UAV. Equipped with non-radar sensors, this system could provide a capability against emerging threats that are designed to defeat radar-based tracking systems.[30]

The MDA has not been responsible for leading the development of defenses against cruise missiles or UAVs. According to the director of the MDA, this focus may be about to change:

> We will address the advanced threat by working with Combatant Commands and Services to address emerging threats, to include the growing and highly challenging hypersonic glide vehicle and cruise missile threats by pursuing advanced technologies, such as directed energy, and making prudent and affordable investments in potentially game-changing capabilities.[31]

Although this would be a welcome shift, it is unlikely that the MDA will have the expertise and funding to develop a far more robust system-of-systems with the capacity needed to defend critical infrastructure in the United States and at U.S. military installations overseas against large salvo attacks in the near term.

The Army's airbase salvo defenses. DoD is largely dependent on the Army to organize, train, and equip its forces to provide land-based defenses against theater ballistic missiles and land-attack cruise missiles. The Army's air and missile defense forces include approximately 50 batteries of Patriot Advance Capability (PAC) low-altitude air and missile defense

28 Well over 80 percent of the MDA FY 2018 budget was allocated toward ballistic missile defense. This figure was calculated by comparing the MDA total FY 2018 budget for ballistic missile programs and comparing it with its total budget for non-ballistic threat programs. See Thomas Karako and Wes Rumbaugh, "Analyzing the PB 2018 Missile Defense Agency Budget," *Missile Threat*, Center for Strategic and International Studies, May 24, 2017, updated June 15, 2018, available at https://missilethreat.csis.org/analyzing-pb-2018-missile-defense-agency-budget/.

29 A 2018 GAO report provides an excellent summary of the MDA's 2017 activities. GAO, *Missile Defense: The Warfighter and Decision Makers Would Benefit from Better Communication about the System's Capabilities and Limitations* (Washington, DC: May 30, 2018), available at https://www.gao.gov/assets/700/692136.pdf. See previous GAO reports for accounts of MDA testing successes and failures.

30 Rachel Karas, "MQ-9 Missile Defense Efforts Moving Toward Flight Tests," *Inside Defense*, August 23, 2018, available at https://insidedefense.com/insider/mq-9-missile-defense-efforts-moving-toward-flight-tests.

31 Lieutenant General Samuel Greaves, Director MDA, statement before Senate Appropriations Committee Subcommittee on Defense, April 17, 2018, pp. 3–4, available at https://www.appropriations.senate.gov/imo/media/doc/041118%20-%20FY19%20MDA%20Greaves%20Testimony1.pdf.

systems. Army Patriot battalions are equipped with PAC-3 and PAC-3 MSE weapon systems or earlier-generation PAC-2 GEM and PAC-2 GEM-T missiles.[32] Approximately 15 Army Patriot battalions operate 50 batteries with 480 launchers and more than 1,200 interceptors in total.[33] Although Patriots are an effective element of the air and missile defense architectures of the United States and many of its allies, they are expensive and their combined capacity would be insufficient to protect airbases and other military infrastructure that U.S. and allied forces would depend on during a major conflict with a great power. Annual operations and support (O&S) costs for the Army's 15 Patriot battalions is approximately $800 million,[34] which does not include modernization costs or the cost of replacing missiles expended during operations.[35] The Army is upgrading its Patriots and developing a new Integrated Air and Missile Defense Battle Command System (IBCS) to integrate all of its air and missile defense sensors, launchers, and command and control (C2) networks. A new Sentinel radar system will provide 360-degree coverage of the battlespace and improve the ability of the Army's short-range air defenses (SHORAD) to identify cruise missiles, UAVs, and other threats.

The Army also has seven batteries of Terminal High Altitude Air Defense (THAAD) ballistic missile defense systems with 42 launchers and more than 500 interceptors altogether. THAAD is capable of intercepting ballistic missiles at endo- and exo-atmospheric altitudes during their last stage of flight.[36] The Army has said it has a requirement for nine THAAD batteries, but it is unclear if DoD will request an estimated $7.5 billion for two additional batteries.[37] The United States has deployed THAADs to Guam and South Korea.

The Army has named air and missile defense as one of its Big Six modernization priorities and requested approximately $6.8 billion over and above its baseline FY 2019 budget submission for new systems between FY 2020–2024 (see Table 1).[38] The Army's SHORAD forces consist of seven battalions in the Army National Guard equipped with small, short-range Stinger surface-to-air missiles mounted on ground vehicles and two Army active component battalions equipped with Stingers and short-range Land-based Phalanx Weapon Systems (LPWS) to

32 Patriot systems have been sold to over 13 countries and will soon be acquired by Poland, Romania, and Sweden. MSE stands for Missile Segment Enhancement; GEM stands for Guidance Enhanced Missile; and in GEM-T, the T is short for TBM, or tactical ballistic missile.

33 IISS, *The Military Balance 2018* (London: IISS, 2018), p. 49.

34 National Research Council, *Making Sense of Ballistic Missile Defense: An Assessment of Concepts and Systems for U.S. Boost-Phase Missile Defense in Comparison to Other Alternatives* (Washington, DC: The National Academies Press, 2012), pp. 266–273, available at https://www.nap.edu/catalog/13189/making-sense-of-ballistic-missile-defense-an-assessment-of-concepts. According to this report, O&S for each battalion is about $54 million in FY 2010 dollars.

35 GAO, *Weapon Systems Annual Assessment: Knowledge Gaps Pose Risks to Sustaining Recent Positive Trends* (Washington, DC: GAO, April 2018), pp. 72–73, available at https://www.gao.gov/assets/700/691473.pdf. Patriot MSEs cost about $5.8 million each.

36 GAO, *Missile Defense*, pp. 85–90.

37 Ibid., p. 89.

38 Sydney J. Freedberg Jr., "Army Says It Needs $2B More Per Year For Big Six: Over Half For Air & Missile Defense," *Breaking Defense,* May 8, 2018, available at https://breakingdefense.com/2018/05/army-needs-2b-a-year-more-for-big-six-52-for-air-missile-defense/.

counter rockets, artillery shells, and mortar rounds. The Army would like to replace most of its Stingers, which are not effective against modern cruise missile threats, with the Indirect Fire Protection Capability Increment (IFPC) 2—Intercept Block 1 system. Based on the Sentinel radar, a new Multi-Mission Launcher (MML), and lower-cost AIM-9XB2 missiles, the IFPC Increment 2-I should significantly improve the Army's ability to defeat cruise missiles and UAVs.[39]

TABLE 1: ADDITIONAL REQUESTED AIR AND MISSILE DEFENSE FUNDING

System	Brief Description	FY20–24 Additional Cost ($B)
Stryker-mounted M-SHORAD	Very limited range, may not have cruise missile defense capability, primarily defend Army maneuver forces	3.2
IBCS	Netcentric command, control, and targeting system for PAC-3, THAAD, and IFPC 2-I	2.0
Sentinel Radar improvements	All Army M-SHORAD units, including its IFPC units, will receive Sentinel Radars to improve their threat detection and warning capability	1.2
Ground-based lasers	Mostly RDT&E investment, fielding is uncertain	0.415
		Total $6.8 billion

Freedberg, "Army Says It Needs $2B More Per Year For Big Six." M-SHORAD stands for Maneuver Short-Range Air Defense, and IBCS is the Integrated Air and Missile Defense Battle Command System.

Regrettably, IFPC Increment 2-I Block 1[40] has experienced a number of challenges that have led to delays in its fielding, including issues with integrating it with the Army's future Integrated Air and Missile Defense Battle Command System (IBCS) and the development of the MML.[41] The *National Defense Authorization Act for Fiscal Year 2019 Report* noted that this will extend the period of time that the Army will lack the capability to defend fixed stations against cruise missile attacks.[42] As a consequence, the FY 2019 NDAA requires the Army to field at least two batteries of cruise missile defenses by 2020 and two additional batteries by September 2023 "if the Secretary of Defense certifies that there is a need for the Army to deploy an interim missile defense capability."[43]

39 See Randall McIntire, "The Return of Army Short-Range Air Defense in a Changing Environment," *Fires*, November–December 2017, pp. 5–8, available at http://sill-www.army.mil/firesbulletin/archives/2017/nov-dec/articles/1_McIntire.pdf.

40 Sydney J. Freedberg Jr., "SASC NDAA Would Add $500M for Cruise Missile Defense," *Breaking Defense*, June 7, 2018, available at https://breakingdefense.com/2018/06/sasc-ndaa-would-add-500m-for-cruise-missile-defense/.

41 GAO, *Weapon Systems Annual Assessment*, pp. 66–67.

42 "While the Army continues to deprioritize IFPC, critical capabilities, such as cruise missile defense of fixed stations, are nonexistent." *National Defense Authorization Act for Fiscal Year 2019 Report,* 115th Congress, 2nd Session, Report 115-262, p. 73, available at https://www.govinfo.gov/content/pkg/CRPT-115srpt262/pdf/CRPT-115srpt262.pdf.

43 *The John S. McCain National Defense Authorization Act for Fiscal Year 2019*, 115th Congress, 2nd Session, pp. 25–26, available at https://www.govtrack.us/congress/bills/115/hr5515/text.

To be fair, the Army is considering a number of novel and less costly means to defend against salvos as part of a "raid breaking" strategy, such as lower-cost surface-to-air interceptors, vehicle-mounted lasers, and electromagnetic rail guns, as well as command-guided hypervelocity projectiles (HVP) that can be fired from 155-mm Paladin self-propelled howitzers.[44] Whether or not the Army will be able to afford these new systems, given its other modernization priorities, or procure a sufficient number of systems to defend U.S. theater bases in the Indo-Pacific and Europe against salvo attacks are major unknowns. Another important question is whether the other Services should begin to invest in capabilities to defend their own theater bases against salvo attacks or continue to rely solely on the Army to perform this mission. This does not mean the Air Force, for example, should "go it alone" and field all systems needed to defend its airbases against salvo threats or procure the same kinds of defenses as the Army. The remaining sections of this report propose an alternative concept that includes armed UAVs, air-launched extended-range interceptors, and other potential cutting-edge base defenses that could be developed and procured by the Air Force, Army, and possibly the Marine Corps.

TABLE 2: ACTIVE SALVO DEFENSE SHORTFALLS AT U.S. BASES IN THE PACIFIC AND EUROPE

	Indo-Pacific Region	European Region
Salvo detection, warning, and integrated fire control	• Limited for PLA ballistic missile salvos, almost non-existent for cruise missile and UAV salvos	• Very limited for Russian ballistic missile, cruise missile, and UAV salvos
Salvo defense C2	• DoD lacks a central authority responsible for developing integrated C2 systems for theater salvo defenses • The Army's IAMD Battle Command System is delayed	
Defenses against ballistic missiles	• Most U.S. air and missile defenses are focused on North Korean ballistic missile threats	• Most NATO air and missile defenses are geared toward Iran's ballistic missiles
Defenses against cruise missiles	• DoD has allocated insufficient resources toward defending its bases against cruise missile salvos • The Army's IFPC Program is delayed	
Defenses against UAVs	• DoD is developing technologies to counter UAVs; programs to acquire them are still needed	• The Army is investing in M-SHORADs primarily to defend its brigade combat teams
Theater base defense force posture	• Insufficient for great power salvos, especially large salvos of cruise missiles and UAVs	

Sources for Table 2 include GAO, *Missile Defense*; previous GAO reports; and CSBA interviews with government and non-government experts. Table 2 addresses salvo defenses at U.S. bases only and assumes the Navy will not provide significant capacity to defend U.S. land bases against salvo attacks.

44 Joseph Trevithick, "The Army Now Wants Hypersonic Cannons, Loitering Missiles, and a Massive Supergun," *The Warzone,* April 3, 2018, available at http://www.thedrive.com/the-war-zone/19847/the-army-now-wants-hypersonic-cannons-loitering-missiles-and-a-massive-supergun.

Air and Missile Defense at a Crossroads

Table 2 summarizes the status of active salvo defenses now at U.S. bases located in the Indo-Pacific and European regions. Overall, existing capacity to defeat large numbers of guided weapons is lacking, especially capabilities to counter non-ballistic threats.

Given the continued proliferation of advanced munitions and the limitations of current U.S. defenses against guided weapon salvos, DoD should assess the need to create new operating concepts to defend its bases and other vulnerable installations overseas. It is technologically feasible to develop and deploy higher capacity air and missile defenses at U.S. bases in the Indo-Pacific region and Europe within the next decade. A major objective for a future base defense architecture should be to increase the level of effort needed to attack U.S. bases to the point where an adversary may conclude the cost would be prohibitive. Another objective should be to incorporate a mix of kinetic and non-kinetic defenses that are complementary and could, in combination, counter an enemy's salvos at a cost that is advantageous to the United States. In contrast, simply buying more of the same kinds of legacy kinetic defenses currently in the U.S. inventory would not create a significant advantage in a salvo competition with a great power. These defenses were not designed to counter emerging threats such as HGVs, and using very large numbers of them in a major conflict would impose costs on the United States.

The next section summarizes a notional operating concept for an outer defense that begins to attrite salvos at range from a base and an inner base defense that includes high-capacity, short- and medium-range defenses that are located on or close to a base.[45] A follow-on section addresses the technological maturity of capabilities included in this concept.

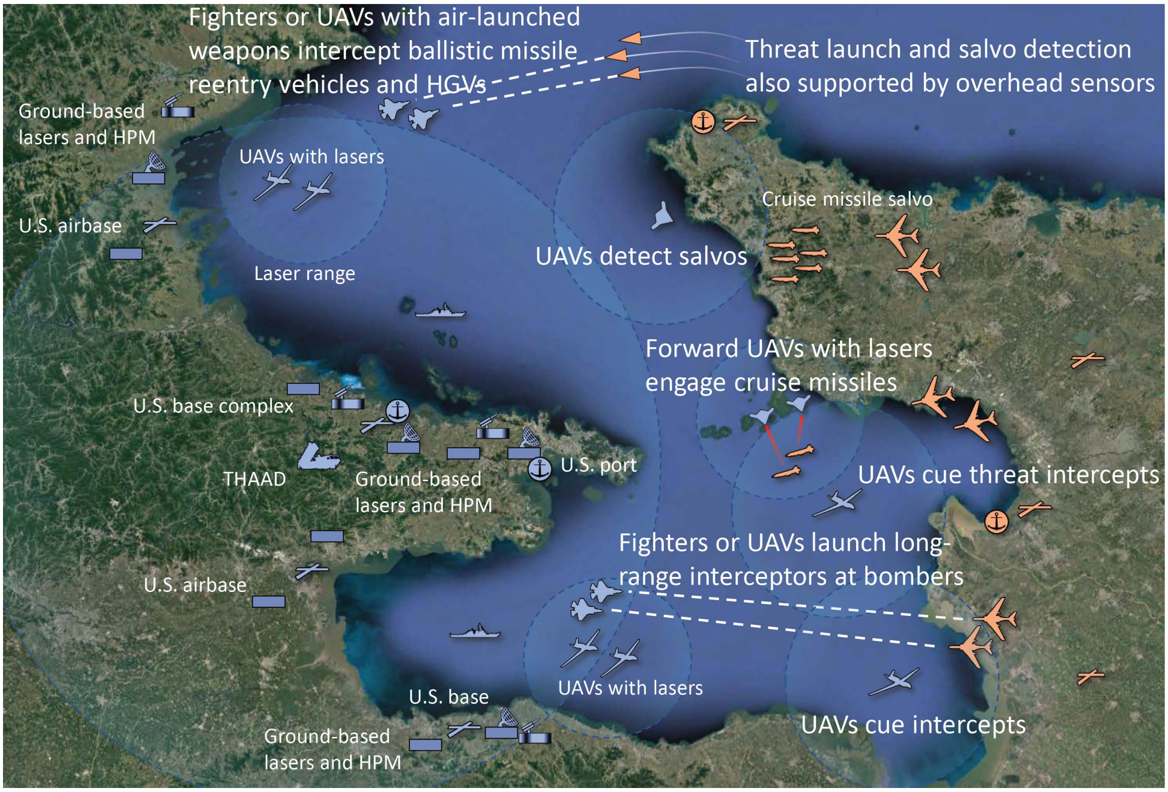
45 This concept would also include a variety of electronic warfare systems. For additional information on these capabilities and concepts, see Bryan Clark, Mark Gunzinger, and Jesse Sloman, *Winning in the Gray Zone: Using Electromagnetic Warfare to Regain Escalation Dominance* (Washington, DC: Center for Strategic and Budgetary Assessments, 2017); and Bryan Clark and Mark Gunzinger, *Winning the Airwaves: Regaining America's Dominance in The Electromagnetic Spectrum* (Washington, DC: Center for Strategic and Budgetary Assessments, 2015).

A Future Salvo Defense Concept for Theater Bases

A Notional Outer Salvo Defense System

Figure 6 illustrates an outer network of defenses that would begin to reduce the size of salvos launched against one or more U.S. bases.

FIGURE 6: POTENTIAL OUTER SALVO DEFENSE FOR U.S. BASES



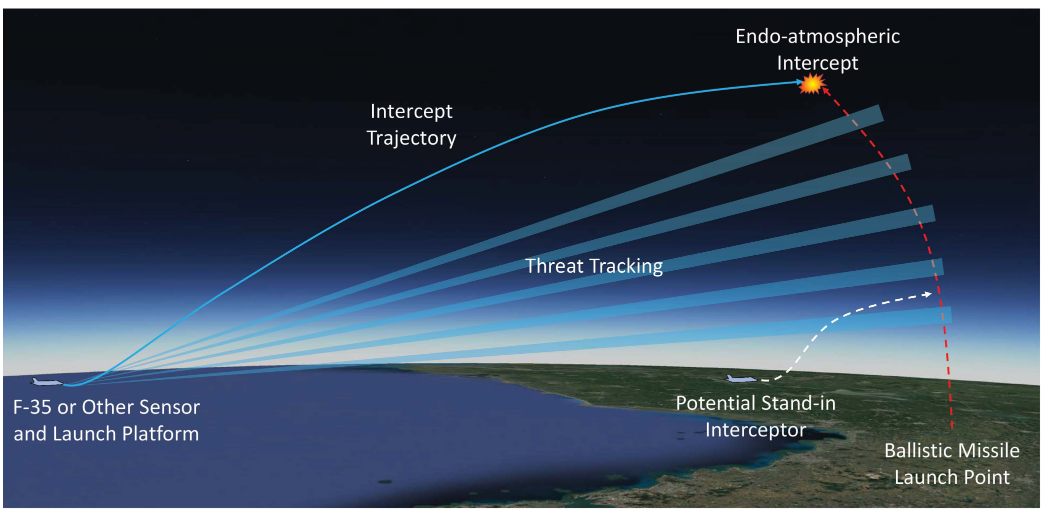
Sensor network. As depicted in Figure 6, a network to provide early detection and warning of salvos could consist of space-based systems, UAVs, and possibly manned aircraft with active and passive sensors to provide early warning of a salvo attack. Such sensors have already been demonstrated by the MDA Airborne Discrimination Sensor Technology program.[46] A battle management system that integrates information from multiple airborne and space-, land-, and sea-based sensors would increase the probability of detecting salvos in time to

46 Karas, "MQ-9 Missile Defense Efforts Moving Toward Flight Tests."

cue a distributed network of interceptors. This extended sensor network should have enough depth to detect ballistic missile launches and flights of enemy strike aircraft before they reach their weapons launch points. Secure datalinks should link this network with the Navy's Naval Integrated Fire Control-Counter Air (NIFC-CA) and its sensor networks to share information rapidly with sensors and shooters across the outer and inner ring of base defenses. NIFC-CA integrates counter-air operations between the Navy's Aegis ships, E-2D early warning aircraft, and other airborne and sea-based sensors.

Capabilities to intercept ballistic missiles. Distant orbits of future unmanned and manned aircraft carrying payloads of extended-range air-launched kinetic interceptors could form the first layer of active defenses against ballistic missile salvos. Fighter-sized manned and unmanned aircraft may be capable of carrying between two and four of these interceptors internally or externally, depending on the physical dimensions of the weapon. As illustrated by Figure 7, air-launched weapons with sufficient range, kinematics, and appropriate guidance systems could intercept ballistic missiles during their ascent phase of flight. These intercepts would help thin the size of an enemy's missile salvos and increase the potential for follow-on defenses to have enough capacity to engage surviving threats. Assuming on-board or off-board target cueing is available, unmanned and manned aircraft with extended-range interceptors could also attack enemy bombers before they launch their weapons and disrupt or eliminate their high value airborne assets such as battle management, command, control, and communications (BMC3) aircraft and air refueling tankers. As depicted in Figure 6, the outer defense complex should also include THAADs that are linked with other outer and inner salvo defense capabilities.

FIGURE 7: EXTENDED-RANGE AIR-TO-AIR MISSILE INTERCEPTING A BALLISTIC MISSILE

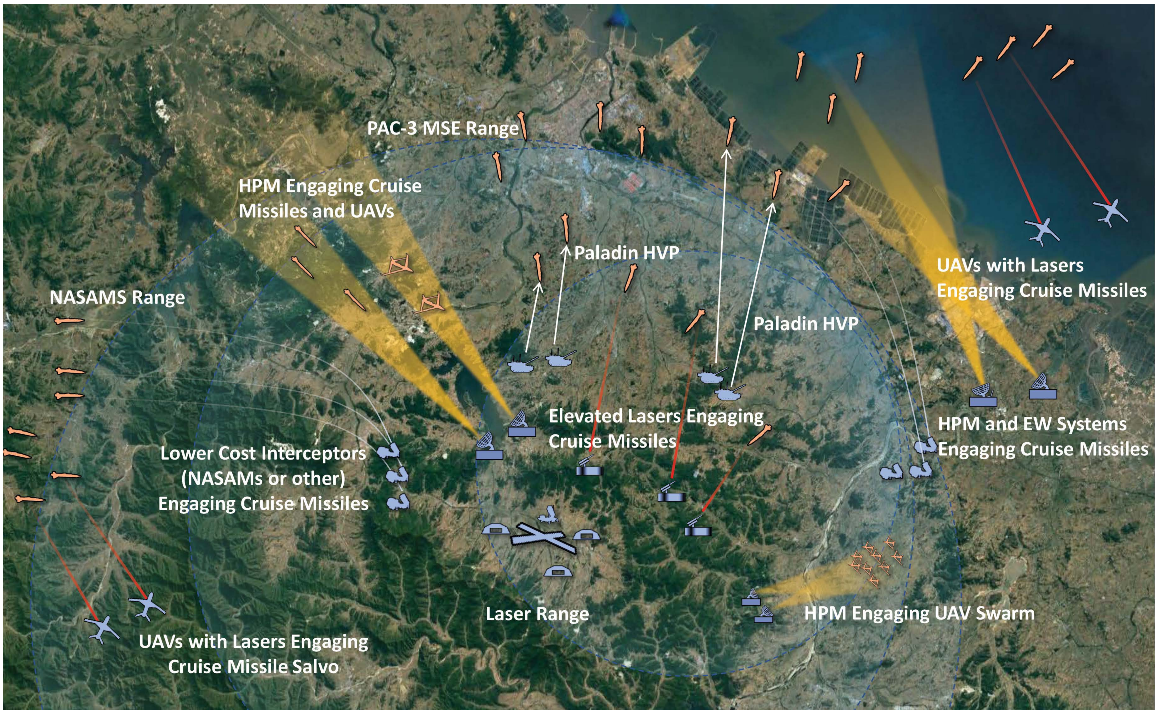


Other UAVs equipped with HELs could fly forward combat air patrols (CAP) to defend against salvos of cruise missiles and other weapons vulnerable to the effects of a laser. As addressed in the next section, UAVs capable of long-duration flight outfitted with solid-state lasers (SSL) would help deployed U.S. air forces to sustain salvo defense CAPs at range from their airbases.

A Notional Inner Salvo Defense System

A future inner ring of airborne and ground-based defenses protecting U.S. bases (see example in Figure 8) should be fully integrated with outer-ring weapon systems.

FIGURE 8: POTENTIAL INNER SALVO DEFENSE FOR U.S. BASES



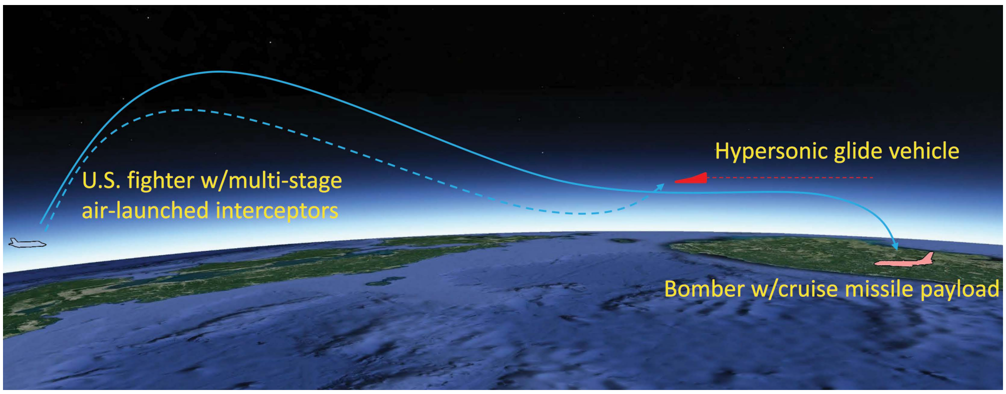
<u>Threat detection, warning, and fire control.</u> Similar to the outer defense concept, an inner base defense would require a sensor and communications network capable of detecting multiple threats and sharing a common picture of the battlespace across the complex. This network should include DoD's existing and planned space-based sensors, airborne sensors, long-range ground-based radars to detect and provide early warning of incoming raids and salvos, and fire control radars. Inner and outer base defenses should be linked by a BMC3 system that is capable of coordinating sensor and shooter operations.

<u>UAVs with high energy lasers</u>. Figure 8 illustrates how orbits of UAVs equipped with 150 kW-class HELs could support an inner ring salvo defense. CAPs of UAVs with HELs could deploy on different axes from a base to counter incoming salvos of UAVs, cruise missiles, and other air-launched PGMs. UAV HELs would have several advantages compared to ground-based laser defenses that are located on or close to a base. Compared to ground-based lasers with similar design characteristics, airborne HELs would have both increased slant ranges

to targets due to their altitudes and the advantage of operating in less dense and particulate-laden atmospheres. Moreover, if the geometry is favorable, a UAV HEL could attack the thin sides of cruise missiles as depicted in Figure 8 instead of their hardened nose sections.

UAVs or fighters with multi-stage, extended-range interceptors. The airborne segment of the inner ring could include CAPs of unmanned or manned aircraft carrying two to four multi-stage, extended-range air-to-air interceptors each. These CAPs could provide a significant new capability against very challenging threats such as ballistic missile reentry vehicles, hypersonic glide vehicles, and enemy bombers (see Figure 9). Given interceptors with sufficient range and target cueing from forward sensors, salvo defense CAPs may not need to be located far from the airfields and other bases they are defending. This would reduce turn times between aircraft sorties and possibly free some combat aircraft to conduct offensive operations.

FIGURE 9: FUTURE AIR-LAUNCHED EXTENDED-RANGE AIR-TO-AIR MISSILES INTERCEPTING HGV THREATS AND BOMBERS CARRYING CRUISE MISSILES



Ground-based high-power microwaves.[47] HPM weapons use electromagnetic energy to damage or disrupt sensors, guidance systems, and other electronic systems by inducing currents that exceed the tolerances of targeted subcomponents. Future HPM defenses could have longer ranges than short-to-medium-range (up to 30 nm) kinetic air and missile defenses. A single high-power microwave weapon integrated with a ground vehicle or modified transportable container similar to Conex boxes could counter multiple cruise missiles, swarms of UAVs, and other threats in a single enemy salvo. Unlike kinetic weapons and lasers, HPM defenses can target multiple threats located within its beamwidth simultaneously. HPM emitters could be located around a base to provide 360-degree threat coverage while minimizing the potential that an HPM beam would create collateral damage to a friendly electronic system.

47 HPM weapons could be capable of achieving a larger number, and possibly a more effective range, of effects on targets if details are known about the targets' designs and vulnerabilities. See Air Force, "High-Power Microwaves," factsheet, September 2002, available at http://armes.silencieuses.free.fr/doc/AFD-070404-036.pdf; and Tamir Eshel, "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.

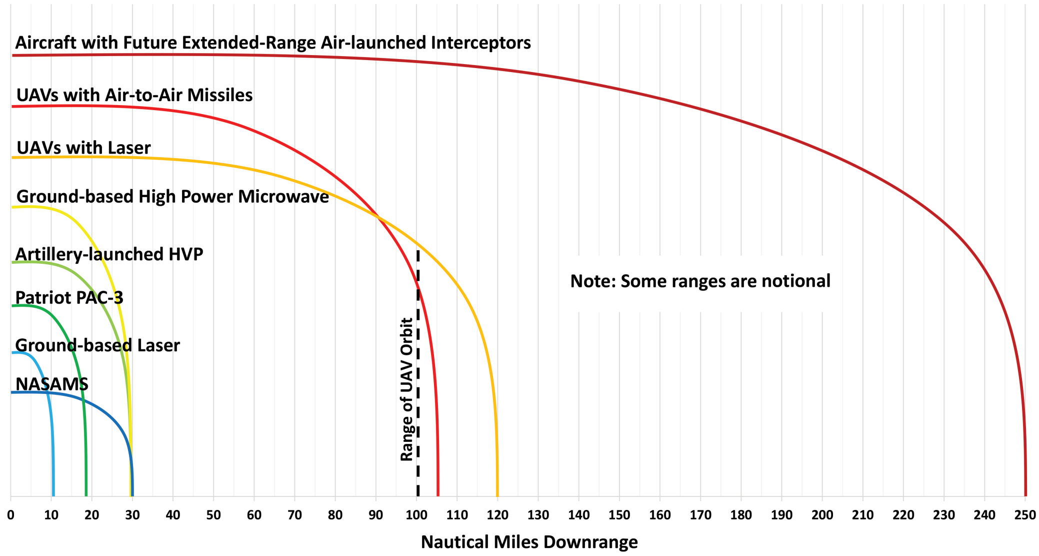
Ground-based SSLs. Future laser systems capable of generating 300 kW output power or greater integrated into modified transportable container boxes or mobile platforms could be postured around U.S. bases to defend against salvo threats. Lasers can damage enemy weapons by rapidly heating their external casings, aerodynamic features, or susceptible seekers. Because they cannot engage targets over the horizon and are affected by some atmospheric phenomena, ground-based lasers would be most effective if employed over short-to-medium ranges against cruise missiles; some types of UAVs; and guided-rockets, artillery, mortars, and missiles (G-RAMM). These limitations could be partially offset by increasing laser power outputs. It is highly likely that ground-based HELs will be capable of generating beams with much greater output power than lasers carried by fighter-sized aircraft with more constrained payload, power, and cooling capacities. Since electricity-based SSLs do not consume a chemical fuel or expend a missile or projectile to generate their beams, they will require significantly less logistics support to deploy and operate compared to most of DoD's current ground-based kinetic air and missile defenses.

Short-to-medium-range guided kinetic defenses. HVPs fired by Paladins and other powder guns could have effective ranges of 10–40 nm or more against airborne targets.[48] DoD envisions using these weapons to defend against some ballistic missiles, cruise missiles, and possibly some types of submunitions. Future artillery may be able to launch HVPs at velocities needed to defeat very fast-moving targets such as supersonic cruise missiles and HGVs. Developmental command-guided HVP designs have control surfaces and other features to allow a fire control system to direct them toward maneuvering targets and compensate for small target location errors. Since HVPs with small warheads will need to be detonated very close to their targets, the projectiles and their intended targets will need to be tracked by highly accurate sensors such as interferometric radars or upgraded versions of contemporary fire control radars. The Army is also developing lower-cost surface-to-air interceptors that could be launched by future increments of its IFPC. Another alternative would be to procure the mature National Advanced Surface-to-Air Missile System (NASAMS) that is in service with seven countries and is part of the U.S. National Capital Region's air defenses. Very short-range (up to 5 nm) point defenses could constitute a last line of defenses against "leaker" salvo threats. These systems could be modified versions of Iron Dome, the Land Phalanx Weapon System, or other developmental guided projectile launchers.

Figure 10 illustrates the ranges of defensive weapons that could constitute part of a future inner salvo defense complex for U.S. theater bases and other critical military facilities.

48 For additional analysis of HVPs launched by power guns, see Gunzinger and Clark, *Winning the Salvo Competition*, pp. 22, 34–35. According to a BAE Systems datasheet, the range of an HVP launched by a 5" naval gun could exceed 40 nm, and an HVP launched by a 155-mm gun could have a range greater than 43 nm. See "HVP Hypervelocity Projectile," BAE Systems, March 2015, available at https://www.baesystems.com/en/product/hyper-velocity-projectile-hvp.

FIGURE 10: RANGE COMPARISONS



These numbers are based on open-source information and estimates from Gunzinger and Clark, *Winning the Salvo Competition: Rebalancing America's Air and Missile Defenses.*

Advances in Supporting Technologies

High Energy Lasers[49]

DoD has made a great deal of progress over the last 15 years toward developing technologies for electrically powered HELs that could support the weapon systems described in this report's base defense concept.

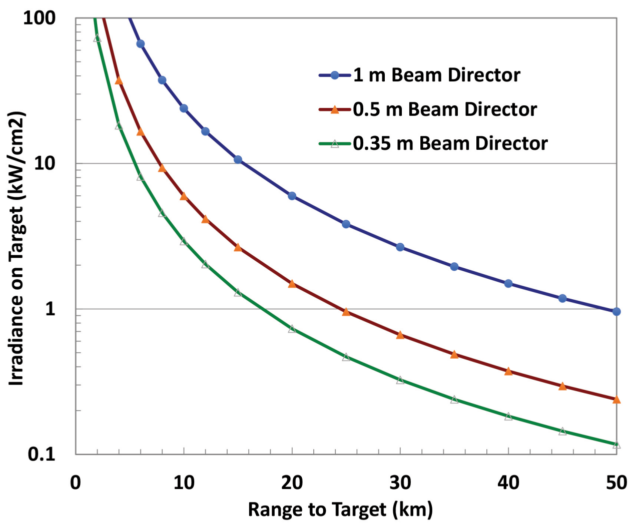
Although a variety of lasing media have been used since lasers were first designed, they can generally be separated into three basic categories: free-electron, chemical/gas, and solid-state lasers. Due to the large size and weight of high-power free-electron lasers and gas lasers, the U.S. military have discounted their procurement in the near term. Electrically pumped SSLs generate high-energy beams of electromagnetic energy by using photons from banks of laser diodes to "pump" a lasing medium that emits intense light in a very narrow wavelength range.[50] SSLs can produce more than 100 times the power density of gas or free-electron lasers, which enables them to be smaller and less complex than lasers that require liquid or

49 In addition to the sources listed in this section, the authors talked to experts inside the U.S. Government and defense industry. For an overview of the general status of directed energy weapons, see Howard R. Meyer Jr., "The Role of Directed Energy Weapons in Modern Warfare," *Defense Dossier*, American Foreign Policy Council, issue 20, November 2017, pp. 16–23, available at http://www.afpc.org/files/defense_dossier_issue_20.pdf.

50 Laser diodes are more than 1,000 times brighter than common light emitting diodes.

gas media to generate their beams.[51] Various SSL designs use solid lasing medium in the form of fiber optic cables, a slab, or a thin disk. Fiber lasers combine light from many individual fibers to form a single high-energy output beam, and bulk lasers emit a single coherent beam. The innovative SSL concept of Distributed Gain spreads the heat out among many elements (like a fiber laser) but the elements themselves form the bulk of laser media producing a single coherent beam. Future laser weapons that generate sufficient power will be able to destroy threats such as cruise missiles, UAVs, manned aircraft, PGMs, and G-RAMM or degrade them to the point where they miss their intended targets.[52]

FIGURE 11: ILLUSTRATIVE AVERAGE IRRADIANCE ON A TARGET FOR A 100 KW-CLASS LASER



Representative diffraction-limited irradiance.

Laser lethality. The objective for a laser weapon "shot" is to place enough energy on a susceptible spot on a target to achieve a desired effect such as blinding or burning out a PGM's sensor or burning through a vulnerable area such as the thin side of a cruise missile. The amount of energy a laser can place on a target per unit area (fluence) is determined by the laser's power, the size of the laser's beam director, the laser's beam quality, and the total time a laser continuously illuminates a target.[53] In the absence of atmospheric distortion and laser aberrations,

51 Mark Gunzinger and Chris Dougherty, *Changing the Game: The Promise of Directed Energy Weapons* (Washington, DC: Center for Strategic and Budgetary Assessments, 2012). The Airborne Laser used a megawatt-class chemical oxygen iodine laser (COIL) that depleted its chemical fuel after several laser shots. See also David Szondy, "Is This the Dawn of the Death Ray?" *New Atlas,* March 21, 2018, available at https://newatlas.com/laser-weapons-future-warfare/52801/.

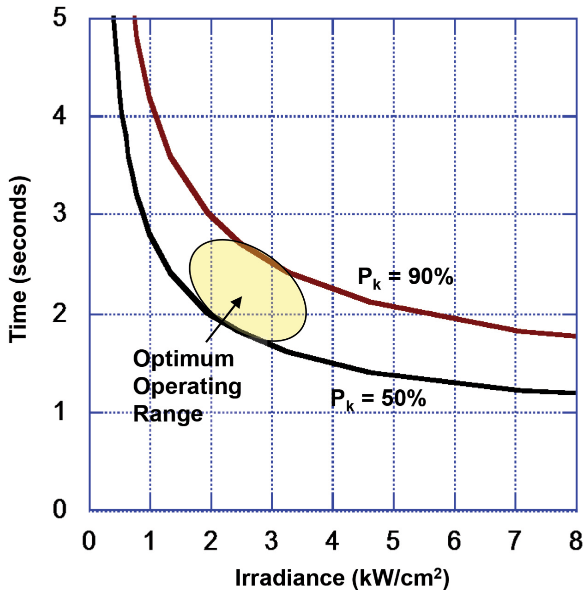
52 Gunzinger and Clark, *Winning the Salvo Competition.*

53 Fluence is measured in joules per square centimeter, or J/cm^2. The total time a laser continuously illuminates a target is its dwell time.

a laser's irradiance[54] on a target is a function of the range to a target and the size of the laser's beam director (see Figure 11).

Target characteristics. Because overheating is a primary target damage mechanism for HEL weapons, the material and design of a target's surface can impact the laser's effectiveness. For instance, it may require only a few seconds for a high-power laser beam to penetrate the thin sides of small boats, UAVs, and most missiles. Targets such as ballistic missile reentry vehicles and supersonic cruise missile nosecones that are hardened against the heat associated with high-speed travel through the atmosphere are less susceptible to lasers. A very high-power laser (multi-megawatt class) may have to illuminate such targets for longer periods of time to achieve desired effects. Figure 12 helps illustrate ranges of irradiance and dwell times needed to achieve a desired effect on a target. It is based on representative data for a laser's dwell time and irradiance to achieve a target probability of kill (Pk) of 50 percent (black line) and 90 percent (red line).

FIGURE 12: ILLUSTRATIVE RELATIONSHIPS BETWEEN LASER IRRADIANCE, BEAM DWELL TIMES, AND Pk



Meteorological (moisture and turbulence) conditions. Atmospheric particulates and water vapor absorb and scatter laser energy at distinct wavelengths of the electromagnetic spectrum. At low altitudes, especially in maritime environments and during inclement weather, atmospheric absorption, scattering, and turbulence can significantly affect laser transmission. Lasers mounted on ground- or ship-based platforms will require more power to overcome atmospheric degradation. Moreover, ground-based lasers located on or close to a defended

54 Irradiance is measured in kilowatts per square centimeter, or kW/cm^2.

base may have to shoot at the front ends of incoming airborne threats. Since these areas are usually well protected, ground-based SSLs will need longer dwell times, higher power levels, or both to achieve the necessary fluence to kill or damage incoming targets. Since longer lasing times reduce the number of targets that a single laser can engage within a salvo, it will be important to quickly determine when a laser shot has been successful before engaging a new target.

Scattering and absorption effects can be mitigated by reducing the distance (or path length) a laser beam must travel through dense atmospheres laden with water vapor and particulates. In general, atmospheric turbulence, laser beam absorption, and beam scattering decrease at higher altitudes. This decrease is dramatic above an altitude of approximately 3,200 ft. This is why airborne lasers could have increased ranges and effectiveness against targets compared to ground-based lasers with similar design characteristics.

DoD's laser weapon programs have made significant progress. DoD has made dramatic advances in laser technologies since it shifted its focus toward developing SSLs about 18 years ago.[55] Multiple developmental SSLs are approaching the point where they will be sufficiently mature for operational applications.

The first U.S. 100 kW-class SSLs were bulk systems such as the High Energy Liquid Laser Area Defense System (HELLADS) and the Joint High-Power Solid-State Laser (JHPSSL).[56] HELLADS is an electrically pumped, liquid-cooled Distributed Gain Laser funded by the Defense Advanced Research Projects Agency (DARPA). One of the HELLADS program's objectives was to develop a 150 kW-class laser that would weigh less than 5 kilograms per kW.[57] Developed in progressive stages, the final HELLADS system achieved a 150 kW-class output and was the first to be developed as a complete laser weapon with an integrated Lithium-ion battery and tactical cooling system. A separate DoD program developed the JHPSSL, which achieved a 100 kW-class output for short run times. A follow-on to the JHPSSL called the Robust Electric Laser Initiative (RELI) developed a 2nd generation distributed-gain laser and spectral beam combined fiber laser technologies to further reduce the weight and increase the efficiency of SSLs.[58]

The Services are also developing solid-state laser technologies. The Army's HEL Mobile Demonstrator program has demonstrated a 60 kW-class spectral beam combined fiber laser.

55 DoD, *High Energy Laser Review Panel: Department of Defense Laser Master Plan* (Washington, DC: DoD, March 24, 2000), available at http://www.wslfweb.org/docs/MasterLaserPlan.pdf.

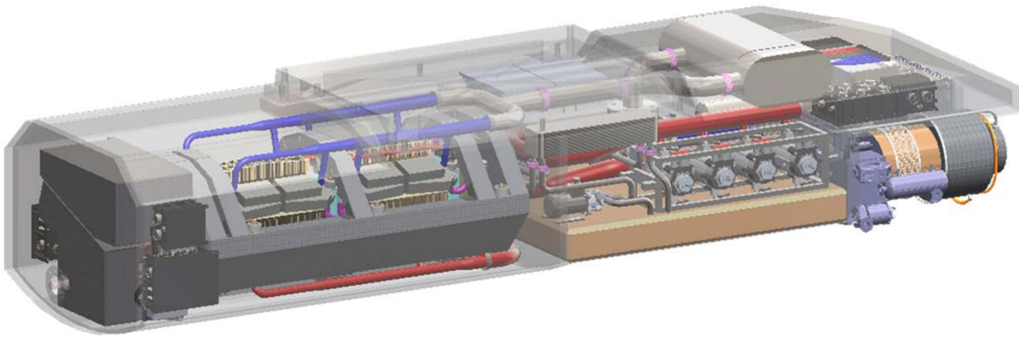
56 J.R. Wilson, "Smaller, Deadlier: Directed Energy Weapons Progress," *Defense Media Network,* November 30, 2009, available at https://www.defensemedianetwork.com/stories/smaller-deadlier-directed-energy-weapons-progress/.

57 Ben Goodland, "Star Wars: High Energy Laser Weapons Awakening," *Jane's Intelligence Briefings*, April 21, 2016.

58 Graham Warwick, "RELI Program to Drive Down Laser Weapon Size, Weight," *Aerospace Daily & Defense Report*, August 9, 2010, available at http://aviationweek.com/awin/reli-program-drive-down-laser-weapon-size-weight; and Graham Warwick, "RELI Program Aims to Improve Laser Weapon Efficiency," *Aviation Week & Space Technology*, August 16, 2010, available at http://aviationweek.com/awin/reli-program-aims-improve-laser-weapon-efficiency.

The Navy is developing a 100 kW-class fiber laser under its SSL Technology Maturation (SSL-TM) program and a 150 kW-class distributed-gain laser (3rd generation) under its Ruggedized High Energy Laser (RHEL) program.[59] The Navy's High Energy Laser and Integrated Optical-dazzler with Surveillance (HELIOS) program will field DoD's first operational ship-based laser weapon.

FIGURE 13: DEVELOPMENTAL 100 KW-CLASS LASER CONFIGURED TO INTEGRATE WITH A UAV



Figures courtesy of General Atomics. These images depict a 100 kW-class Distributed Gain Laser weapon system for integration on a UAV.

59 Jessica L. Tozer, "Laser Weapons for Navy Ships," *DoD Science Blog*, May 14, 2012, available at http://science.dodlive.mil/2012/05/14/laser-weapons-for-navy-ships/.

Near-term potential to field airborne lasers. Investments by DoD and the U.S. defense industry have dramatically accelerated the development of electrically powered SSL weapons with power density, weight, volume, and other characteristics suitable to integrate them with military aircraft. Although the Air Force's developmental Airborne Laser successfully demonstrated the ability of a chemical laser to destroy ballistic missiles in their boost phase, a Boeing 747-class aircraft was required to carry the system's multiple laser modules, expendable chemicals, and other components. Large non-stealthy aircraft such as the Airborne Laser (ABL) YAL-1A would not be capable of penetrating and loitering for long periods of time in areas that are defended by advanced IADS. As a result, the ABL was not operationally practical.

Dramatic reductions in the size and weight of electrically pumped SSLs will allow them to be integrated into manned and unmanned combat aircraft that are better capable of penetrating and persisting in contested airspace. Lighter and more compact SSLs could also increase the survivability of some high-value non-stealthy aircraft, such as air refueling tankers, without using up most of their useful payloads. The MDA and the Air Force are now developing compact, high density electric power, integrated thermal management, and beam control/beam director subsystems that will be critical elements of future aircraft laser weapons. The Air Force's Self-Protect High Energy Laser Demonstrator (SHiELD) program is developing a 50 kW-class laser pod for small aircraft,[60] and the MDA Low Power Laser Demonstrator program will demonstrate a high-altitude long-endurance (HALE) UAV carrying a 100 kW-class laser weapon with the precision beam control needed to engage ballistic missiles in their boost phase.[61] Given this progress, it is highly likely that operationally effective 100 to 150 kW-class laser weapons can be demonstrated on U.S. military aircraft within the next few years.

Lasers for ground-based short-range air defense. Employing lasers against air and missile threats has been contemplated by the United States and its competitors for decades. Technological advances will finally enable the Pentagon to field ground-based SSL SHORADs in the near term. The Marine Corps' Ground-Based Air Defense (GBAD) program is demonstrating a small-scale laser to provide a defense against small UAVs, rockets, and artillery. Lasers with 300 kW or greater power will likely be needed to defeat more challenging targets such as cruise missiles. An initial 300 kW-class laser weapon could combine two 150 kW-class lasers that already exist. Combining SSLs to achieve a cumulative increase in power is a proven technique.

60 Kyle Mizokami, "The U.S. Navy Is Funding Lasers and Killing the Railgun (corrected)," *Popular Mechanics*, February 15, 2018, available at https://www.popularmechanics.com/military/research/a17764166/navy-four-laser-weapons/.

61 Katherine Owens, "New Drone Laser Weapon Could Stop Enemy Missiles in Boost Phase," *Defense Systems*, June 19, 2017, available at https://defensesystems.com/articles/2017/06/19/mda-pentagon-lasers.aspx. General Atomics, Lockheed Martin, and Boeing are developing designs for such a laser system. It is assumed that the General Atomics system will be capable of fitting within the weapons bay of the Avenger ER UAV or a variant. 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. This 100 kW-class laser system has been developed and is operating in the laboratory.

In summary, advances in laser output power, laser beam quality, and other laser technologies have reduced system sizes, increased the potential irradiance lasers can generate on a target, and improved laser weapons to the point where they could soon be deployed to defend bases against salvo attacks. Multiple DoD organizations are on the cusp of transitioning from years of pursuing laser "science projects" to creating programs that will develop and acquire operational SSLs for U.S. warfighters.[62]

High-Power Microwave Weapons

HPM weapons generate very short-duration high-power pulses of electromagnetic energy using waveforms that are designed to damage sensitive electronic components such as PGM seekers, guidance systems, and control systems. HPM pulses can upset 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.[63] Because HPM beams attack specific elements such as input/output boards or amplifiers that are located inside targeted systems, they are less affected by heat shielding on a target's exterior. Since most semiconductor circuits are very sensitive, they can become over-biased or damaged by very small increases in current. A future HPM defense system may need a very short period of time—perhaps microseconds—to create desired effects on incoming threats. These effects may range from creating damage that causes an airborne threat to crash, to degrading components that prevent threats from reaching or killing their intended target.[64] HPM weapons can create disruptive or destructive effects on appropriate airborne threats over longer ranges than lasers that have much higher average power levels.[65] Consequently, HPM defenses could engage more threats in a single salvo than lasers, which require much longer dwell times on targets.

<u>Near-term potential for HPM base defenses.</u> DoD and the U.S. defense industry have already developed some HPM weapon prototypes for offensive purposes, most notably the Counter-electronics High-powered Microwave Advanced Missile Project (CHAMP) which combined a mature cruise missile with an HPM transmitter payload.[66] As a proof of concept, CHAMP missiles used a short HPM pulse to damage or cause a variety of electronic systems to lock-up.

62 "HELLADS Laser Achieves Acceptance for Field Testing: High-power Laser Marks a Significant Technological Advance," DARPA Press Release, May 21, 2015, available at https://www.darpa.mil/news-events/2015-05-21-2.

63 Air Force, "High-Power Microwaves." For a detailed explanation of the generic effects of HPMs, see Philip E. Nielsen, *Effects of Directed Energy Weapons* (Albuquerque, NM: Directed Energy Professional Society, 2009).

64 H. Z. Guo et al., "Analysis of Damage Efficiency of HPMW on Typical Active Radar Guided Missile," *Applied Mechanics and Materials* 263–266, pp. 85–89, 2013.

65 Nielsen, *Effects of Directed Energy Weapons*. Typical peak power for an HPM may be up to approximately 1 GW, but the average power radiated is about 1 kW. The actual effects of HPM pulses is also a topic of significance with academicians. See, for example, Ji-Eun Baek, Young-Maan Cho, and Kwang-Cheol Ko, "Analysis of Design Parameters Reducing the Damage Rate of Low-Noise Amplifiers Affected by High-Power Electromagnetic Pulses" *IEEE Transactions on Plasma Science* 46, no. 3, March 2018. One article sums up an important insight: "We can arrive at the conclusion that hit probability is affected by HPM obviously, and the hit probability decreases rapidly while HPM power [is] increasing." Guo et al., "Analysis of Damage Efficiency of HPMW on Typical Active Radar Guided Missile."

66 Eshel, "US Air Force Moves Forward with High-Power Microwave Weapon."

Although DoD chose not to begin an HPM cruise missile acquisition program following CHAMP's completion, it is now funding a High-power Joint Electromagnetic Non-Kinetic Strike (HiJENKS) initiative to explore a more operationally relevant version of a CHAMP-like weapon.[67]

FIGURE 14: DEVELOPMENTAL PHASER MICROWAVE WEAPON SYSTEM

Figure courtesy of Raytheon

Like almost all future directed energy weapons, self-contained HPM defenses that create their beams using electricity from a generator or other source will have "deep magazines." Since HPM weapons will only require a very small fraction of a second to create desired effects on threats located within their beamwidths, they could be a very effective means of countering swarms of small UAVs.[68] These UAVs have become widely available over the last few years, can be very low cost, and can be used for missions ranging from surveillance to kamikaze-like attacks. One U.S. developmental HPM system called Phaser (see Figure 14) is designed to counter Group 1 (small) and Group 2 (medium) UAVs. In December 2017, a Phaser participating in an Army Maneuver and Fires Integration Experiment achieved 33 mission or catastrophic kills.[69]

Future operational HPM defenses that could simultaneously disrupt or destroy multiple UAVs within their beamwidths could also quickly move their beams to counter UAV swarms

67 James Drew, "USAF Spending Big on Technology Transition Projects," *Aerospace Daily & Defense Report*, January 25, 2018, available at http://aviationweek.com/defense/usaf-spending-big-technology-transition-projects. See also Office of Naval Research (ONR), *Naval Air Warfare and Weapons* (Arlington, VA: ONR, 2017), available at https://www.onr.navy.mil/en/Science-Technology/Departments/Code-35.

68 Alexander George, "Stopping Killer Drone Swarms Before They Kill Us," *Popular Mechanics*, July 5, 2018, available at https://www.popularmechanics.com/military/research/a21272146/swarm-killer-drone-defese/.

69 "Raytheon Downs UAVs with High-Power Microwaves and Lasers," *Microwave Journal News,* March 22, 2018, available at http://www.microwavejournal.com/articles/30014-raytheon-downs-uavs-with-high-power-microwaves-and-lasers.

attacking a base from different directions. This is another advantage over lasers, which, as aforementioned, must sequentially dwell for seconds at a time on each UAV in a swarm.[70] HPM defenses could have even greater advantages over current surface-to-air kinetic interceptors. Surface-to-air missiles may have low probability of kill values against small, highly maneuverable UAVs, and expending a kinetic interceptor against each low-cost UAV in a swarm would likely be cost-prohibitive.

China and Russia. It is important to note that America's great power competitors are developing offensive and defensive directed energy weapon systems. The Chinese leadership in particular believes directed energy weapons could be game changers in future conflicts; it has established directed energy, including high-power microwaves, as one of the nation's top five technology development areas.[71] According to published reports, Huang Wenhua, deputy director of China's Northwest Institute of Nuclear Technology, received an award for what is thought to be research on the development of an HPM weapon. The article alludes that HPM weapons can be used to degrade and damage missile data links, GPS receivers, and other guidance mechanisms.[72] Based on Wenhua's prior writings, this HPM weapon could be intended for initial employment as a ship-borne anti-missile system for the PLA Navy to defend against anti-ship cruise missiles or other cruise missiles.

Russia also has a number of active directed energy programs. In 2001, Russia disclosed it intended to produce a Ranets-E HPM weapon mounted on a ground vehicle that could counter aircraft and airborne guided weapons.[73] More recently, Russia announced its 6th generation unmanned combat drones will carry HPM-like weapons capable of frying their opponents' electronic equipment over distances of "tens of kilometers."[74] The drones are expected to be operational in the mid-2020s. Russia has also tested microwave weapons to disable UAVs and demonstrated that capability over ranges as great as 6 miles.[75]

70 Kyle Mizokami, "Watch Microwave and Laser Weapons Knock Drones Out of the Sky," *Popular Mechanics*, March 26, 2018, available at https://www.popularmechanics.com/military/research/a19599393/watch-microwave-and-laser-weapons-knock-drones-out-of-the-sky/.

71 Tate Nurkin, "China's Advanced Weapon Systems," testimony for the U.S.-China Economic and Security Review Commission, Jane's by IHS Markit, May 12, 2018.

72 Elsa Kania, "The PLA's Potential Breakthrough in High-Power Microwave Weapons," *The Diplomat*, March 11, 2017, available at https://thediplomat.com/2017/03/the-plas-potential-breakthrough-in-high-power-microwave-weapons/.

73 Carlo Kopp, "Ranets E High Power Microwave Directed Energy Weapon," *Russian/Soviet Point Defence Weapons*, Air Power Australia, updated January 2014, available at http://www.ausairpower.net/APA-Rus-PLA-PD-SAM.html#mozTocId940830.

74 Michael Peck, "Russia's Next Military Game Changer: Microwave Weapons?" *The National Interest*, July 12, 2016, available at http://nationalinterest.org/feature/russias-next-military-game-changer-microwave-weapons-16946.

75 Adam Withnall, "Russia Demonstrates First 'Microwave Gun' that Can Disable Drones and Missiles Up to Six Miles Away at Army-2015," *Independent,* June 16, 2015, available at https://www.independent.co.uk/news/world/europe/russia-demonstrates-its-first-microwave-gun-that-can-disable-drones-and-missiles-from-up-to-six-10323243.html.

FIGURE 15: RUSSIA'S RANETS-E HPM WEAPON SYSTEM

Photo courtesy of Air Power Australia, available at http://www.ausairpower.net/APA-Rus-PLA-PD-SAM.html.

Based on the maturity of HPM technologies and successful demonstrations of the U.S. CHAMP and Phaser developmental systems, it is reasonable to assume that DoD could field an operational HPM directed energy weapon within the next 5 years.[76] Future HPM capabilities could include ground-based mobile or relocatable transmitters that are able to engage multiple cruise missiles, UAVs, and other threats to U.S. bases.

Air-Launched Kinetic Interceptors

The U.S. military has long been concerned about its lack of air-launched weapons to defeat airborne threats over long ranges.[77] DoD intends to develop capabilities to defeat ballistic missiles in their boost phase, and the 2019 NDAA requires the MDA to "carry out a program to develop boost phase intercept capabilities that (A) are cost effective; (B) are air-launched, ship-based, or both; and (C) include kinetic interceptors."[78]

Ballistic missile and HGV defense. Extended-range air-launched interceptors could greatly increase the lethal radius of U.S. combat aircraft and allow them to attack some high-value airborne targets while remaining out of range of many enemy defenses. The weapons could also enable attacks against ballistic missiles in their boost phase when they have a limited

76 The CHAMP missile was a prototype for a future offensive counter-electronics weapon. Based on the CHAMP's success, DoD could develop operational HPM defensives that take advantage of known or suspected electronics vulnerabilities to defeat a range of air and missile threats. Future land-based HPM weapons could emit pulses designed to damage unshielded circuits in cruise missiles and UAVs.

77 For more on the value of using long-range, air-to-air missiles against bombers and other high value aircraft supporting an adversary's A2/AD operations, see Gunzinger and Clark, *Sustaining America's Precision Strike Advantage*; and Gunzinger and Clark, *Winning the Salvo Competition*.

78 *The John S. McCain National Defense Authorization Act for Fiscal Year 2019,* 115th Congress, 2nd Session, p. 525, available at https://www.govtrack.us/congress/bills/115/hr5515/text.

ability to maneuver and their plumes can be detected by IR sensors.[79] This would help fill a major capability gap that now exists in the U.S. military's ballistic missile defense system.

U.S. aircraft equipped with highly agile extended-range interceptors that have appropriate sensors and kinematics could also be effective against HGVs—and possibly other hypersonic weapons. Since fighters and UAVs with these weapons supporting an inner ring base defense would likely operate in areas covered by other U.S. defenses, they would not need to be stealthy. Using Avenger-ER/MQ-25-class UAVs or 4th generation F-15 fighters for this mission would help free the Air Force's stealth aircraft for other tasks.

Near-term potential to field an extend-range, air-launched missile interceptor. Technology is sufficiently mature to field air-launched interceptors with extended ranges that are effective against ballistic missiles, HGVs, and other airborne threats. In the near-term, DoD could take advantage of off-the-shelf seekers, guidance systems, data links, rocket motors, and other major components to quickly develop and field these weapons. This is similar to what the Navy is doing to improve the performance of its ship-launched SM-6s.[80] Taking advantage of non-developmental components could significantly reduce their unit costs. Moreover, major modifications to their prospective launch platforms may not be needed. F-35As would likely be able to carry dual-stage interceptors in their internal weapon bays and have a Distributed Aperture System (DAS) and electro-optical targeting systems (EOTS) that could track ballistic missile threats.

Unmanned Aerial Vehicles

Similar to its earliest military fixed-wing aircraft, the U.S. military has used its 1st generation of operational UAVs and remotely piloted vehicles mostly for ISR and light attack missions.[81] More advanced UAVs, such as the aircraft that competed for the Navy's MQ-25 unmanned refueling aircraft program and initial designs for a U.S. stealth unmanned combat air vehicle (UCAV), will soon be capable of performing a much wider range of missions with significant endurance and persistent advantages. UAVs that have the potential to find, fix, target, track, engage, and attack salvo threats could dramatically change the U.S. military's integrated air and missile defense operations. The MDA, which is funding the development of "high-flying

79 Vincent Alcazar, "The Overdue Case for Better Defending America & Its Allies: Aerial Boost Phase Missile Defense…Using US Air Dominance to Thwart Ballistic Missile Aggresion [sic]," *Medium*, June 16, 2018, available at https://medium.com/@vincent.alcazar/the-overdue-case-for-better-defending-america-its-allies-aerial-boost-phase-missile-e6895b31d00d.

80 Jason Sherman, "Navy Looking to Increase Range, Speed of SM-6 with Larger Rocket Motor," *Inside Defense*, July 18, 2018, available at https://insidedefense.com/inside-pentagon/navy-looking-increase-range-speed-sm-6-larger-rocket-motor.

81 Chloe Thompson, "The Advent of the UAV Era," *Defense Dossier*, American Foreign Policy Council, issue 20, November 2017, pp. 23–24.

UAVs armed with advanced sensors and laser weapons could hold the key to defeating [missiles],"[82] is already on the path to making this vision a reality.

Near-term potential for integrating lasers on UAVs. Considering advances in unmanned systems technologies, some UAVs in development or flying today would have the attributes needed to support the base defense concept proposed by this report. UAVs with 150 kW-class lasers flying inner ring defense CAPs would not need to be stealthy, since they should be operating under the cover of other base defense assets. HEL UAVs will also need approximately 3,000 lbs of internal payload capacity to carry the laser, its beam director, and the laser cooling system. HEL UAVs must be capable of generating sufficient electric power to replenish their laser's batteries while in flight and disposing the waste heat generated by a laser's operation, which could damage other aircraft systems. There are likely several state-of-the-art UAVs that have these capabilities, including the Avenger ER, which was designed to carry a 150 kW-class laser. It may be possible to upgrade other existing UAVs or modify designs for UAVs in development to perform base defense missions.

The potential may also exist to realize savings by using UAVs instead of manned aircraft for long-duration base defense CAPs. Operational cost per flying hour (OCPFH) is a significant consideration for sustaining CAPs over long periods of time, especially for CAP aircraft that require air refueling. The MQ-9 Reaper UAV had an OCPFH in FY 2017 of less than $5,000. Although only a small number of Predator C-class Avenger UAVs have been produced to date, their OCPFH is likely multiple times less than the OCPFH of the Air Force's manned fighter aircraft. In addition, a 2015 study estimated that replacing F-18E/F fighters with MQ-25 UAVs to refuel carrier airwing aircraft could eventually save the Navy billions in life-cycle costs.[83]

Comparing Notional Base Defense Alternatives

Salvo Engagement Potential and Cost

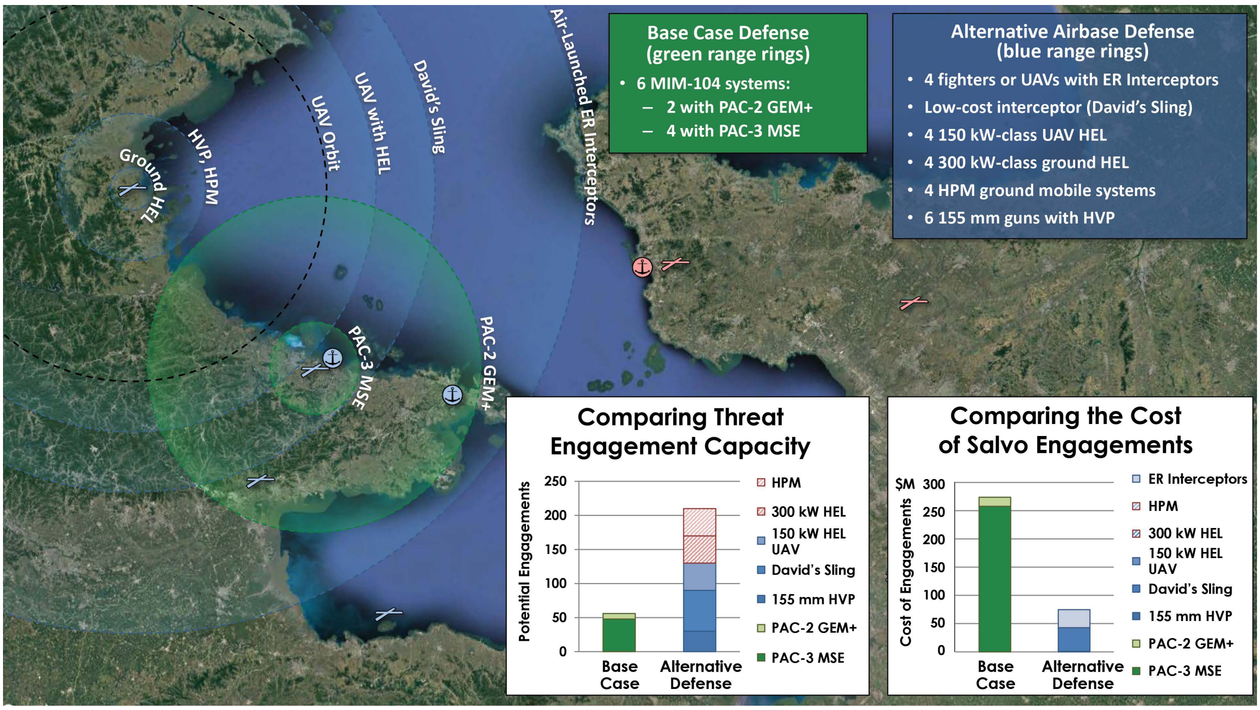
Developing and procuring new weapon systems for base defense will not be without cost. Doing so, however, could reduce the probability that U.S. bases will be subject to major salvo attacks that may be catastrophic. Moreover, new capabilities and concepts assessed in this report could greatly increase the threat engagement potential of a base defense and do so at less cost than a defense consisting of current-generation surface-to-air interceptors only.

82 James Drew, "MDA Advances Missile-Hunting UAV Programs," *Aviation Week & Space Technology,* February 16, 2018, available at http://aviationweek.com/defense/mda-advances-missile-hunting-uav-programs. Also see Lieutenant General Samuel Greaves, statement before Senate Appropriations Committee Subcommittee on Defense, April 17, 2018, p. 36, available at https://www.appropriations.senate.gov/imo/media/doc/041118%20-%20FY19%20MDA%20Greaves%20Testimony1.pdf. Greaves testified that MQ-9s are already paving the way toward helping the MDA to "understand how boost-phase intercept tracking and how an airborne layer could augment our existing sensor network."

83 Daniel Burg and Paul Scharre, *The $100 Billion Question: The Cost Case for Naval Uninhabited Combat Aircraft* (Washington, DC: Center for a New American Security, April 2015), available at https://www.cnas.org/publications/reports/the-100-billion-question.

The following example compares a notional U.S. military installation located in Europe that is defended by PAC-2 and PAC-3 missiles against salvos of ballistic and non-ballistic weapons launched by Russia. This "base case" is compared with an alternative defense that includes low-cost interceptors, HPMs, SSLs, gun-launched HVPs, and CAPs of aircraft carrying multi-stage, long-range interceptors. The green rings in Figure 16 represent the range of Patriot missiles in the base case, and the blue rings illustrate the notional coverage of the alternative defense. THAADs are not included in this example since it is assumed they would be a part of both defenses.

FIGURE 16: COMPARING THREAT ENGAGEMENT CAPACITY AND COST PER SALVO



The comparison in Figure 16 assumes the attacker has timed its weapons to arrive at their aimpoints over a one-minute period in order to saturate U.S. defenses. Table 3 lists other assumptions for this comparison.

TABLE 3: COMPARING COSTS AND POTENTIAL THREATS ENGAGED IN A ONE-MINUTE SALVO

Patriot Missile Only Airbase Defense (Base Case)				
Patriot System		Total Potential Threat Engagements	Estimated Cost per Engagement	Total Cost of Engagements
2 PAC-2 GEM+ launchers		8	$2 million	$16 million
4 PAC-3 MSE launchers		48	$5.38 million	$258 million
	Grand Totals	**56 engagements**	**$4.9 million**	**$274 million**
Alternative Future Airbase Defense				
Defensive System	**Rate of Fire per Minute**	**Total Potential Threat Engagements**	**Estimated Cost per Engagement**	**Total Cost of Engagements**
6 155-mm HVP launchers	5 HVPs per launcher	30	$25 thousand	$750 thousand
4 David's Sling-like launchers	16 interceptors per launcher	64	$700 thousand	$44.8 million
4 ground-based 300 kW-class lasers	10 shots per laser (assume 6 sec/threat engaged)	40	$100	$4 thousand
4 ground-based mobile HPM weapons	10 shots per system (assume 6 sec/threat engaged)	40	$100	$4 thousand
4 UAVs w/150 kW-class lasers	10 per laser (assume 6 sec/threat engaged)	40	$500	$20 thousand
4 fighters w/multi-stage extended-range interceptors	4 interceptors per fighter or UAV	16	$2 million	$32 million
	Grand Totals	**214 engagements**	**$363 thousand**	**$77.6 million**

Although Table 3 assumes a David's Sling interceptor costs approximately $700,000, its cost in the future could be much lower. Table 3 also assumes the unit cost of a future air-launched, multi-stage interceptor missile will be approximately $2 million. This estimate is notional and for the purposes of this comparison only. Although the 16 ER interceptors in this table could be used to engage individual weapons launched at a U.S. base, they could also be used to intercept bombers and other enemy strike aircraft before they launch their weapons payloads. As a result, the total number of threat engagements in this example could range from 214 to 230 total threats, depending on how the ER interceptors are utilized.

As shown by Table 3 and the bar charts in Figure 16, the number of potential threats engaged over a one-minute period by the alternative defense is almost four times greater than the threats engaged by the Patriot-only defense in the base case. For the base case, the cost of weapons expended for 56 threat engagements is $274 million. This is significantly larger than the $77.6 million expended for 214 engagements by the alternative defense.[84]

These totals count the unit costs of weapons expended only, not the cost to develop and acquire new weapon systems. Although these acquisition programs would not be cheap, it is important to remember that the base case expended a quarter of a billion dollars to defend against a single one-minute weapons salvo. The cumulative cost savings of using the alternative defense against subsequent salvos could quickly offset its procurement cost. Furthermore, the alternative defense includes directed energy weapons with nearly self-replenishing virtual

84 Notional costs in Figure 16 and Table 3 exclude the cost of developing and procuring new weapon systems. The bar charts in Figure 16 indicate potential threats engaged by the two defenses, not actual intercepts.

magazines as well as guided projectile launchers with smaller and easier to store kinetic munitions, both of which could greatly reduce logistics strains for a force engaged in a high-intensity conflict.

This comparison supports the larger point that DoD has the opportunity to acquire systems in the near to medium term that could greatly increase capacity of its base defenses and, at the same time, reduce the cost to defend against recurring salvos. In addition, adversaries will likely use kinetic and non-kinetic munitions to degrade and eliminate sensors. Therefore, having multiple shots in a layered configuration with multiple sensors could defeat an adversary's salvos at a reduced cost, effectively inverting the offense/defense imbalance in favor of U.S. forces. It also provides multiple ways to defend a base that can largely be conducted by the Air Force. These defenses could be forward deployed with a very small footprint and moved quickly between airbases, making these capabilities synergistic with the Air Force's Adaptive Basing concept.

Recommendations and Conclusion

Developing cost-effective, high-capacity defenses to protect America's forward bases against guided weapon salvos will be vital to deterring great power aggression and other threats to the security and stability of the Indo-Pacific region, Europe, and the Middle East. Without these defenses, the U.S. military may not have the ability to counter other A2/AD threats quickly and project offensive power in future operations.

The concepts and capabilities assessed in the report constitute one possible path toward developing a layered, distributed defense with novel non-kinetic and kinetic systems to defeat salvo attacks. The combination of UAVs with sensors, directed energy weapons, lower-cost kinetic weapons, and extended-range air-to-air missiles could greatly increase the level of effort an adversary would need to commit to in order to attack U.S. bases successfully. This level of effort could cause an adversary to conclude that the cost of attacking defended bases would be prohibitive.

Recommendations for Future Base Salvo Defenses

DoD and Congress should support the development of operating concepts and a new generation of cost-effective defenses that could harden the U.S. military's forward bases against salvos attacks. The first step toward achieving this objective is to frame the challenge as a salvo competition between adversaries that each have mature capabilities to attack with hundreds and possibly thousands of guided weapons instead of a small number of ballistic missiles.[85] Investing in non-kinetic and kinetic systems effective against the growing threat of cruise missile and UAV attacks would create more robust defenses for the theater bases that DoD continues to rely on for its operations.

In summary, this report makes the following recommendations:

<u>Develop and field UAVs with sensors to detect and provide early warning of salvo attacks</u>. Sensors (active electronically scanned arrays, infrared, and others) could be integrated on current-generation and future UAVs to help detect and provide early warning of missile salvos. Integrated with other space, ground, and sea-based sensors, CAPs of long endurance ISR UAVs could help fill DoD's existing gap in capabilities to detect salvos of land-attack cruise missiles, armed UAVs, and other threats.

<u>Acquire UAVs with HELs</u>. DoD should assess the feasibility of quickly integrating 150 kW-class lasers in current-generation UAVs. Unmanned systems such as the Avenger ER

85 See Gunzinger and Clark, *Winning the Salvo Competition*.

and possibly variants of the MQ-4C Triton could have sufficient payload, power generation capacity, and other performance characteristics needed to support the integration of HELs.

Acquire ground-based mobile or fixed-site HELs. DoD should develop, test, and field solid-state 300 kW-class lasers that could be vehicle mounted and emplaced at fixed sites around the perimeter of its theater bases. Combining two or more SSL modules to create 300 kW-class lasers is feasible in the near term.

Acquire several types of HPM defenses. DoD should take advantage of nascent HPM technologies demonstrated by the Phaser counter-UAV system to develop and procure higher-power and longer-range systems that are capable against cruise missiles and other airborne threats. HPM systems promise to be true salvo defense weapons since they will quickly degrade or defeat multiple weapons per salvo. This would provide a significant advantage in salvo competitions with adversaries that remain dependent on using one or more expensive interceptors against individual air and missile threats.

Field lower-cost short-to-medium-range kinetic defenses. DoD should continue to request funding to develop, test, and, if feasible, procure HVPs launched by Paladins and other artillery that would provide a high-capacity defense against multiple classes of air and missile threats. Other affordable medium-range defenses that should be a high priority for investment include lower-cost interceptors such as NASAMS, David's Sling, and Skyhunter. More affordable kinetic interceptors would reduce the overall cost of defending against salvos and help shift the cost imposition burden toward attackers.

Develop and procure multi-stage extended-range air-launched interceptors. The Air Force should support the rapid development and fielding of extended-range air-to-air missiles capable of countering ballistic missiles in their boost and terminal stages of flight, high-value aircraft such as enemy bombers, and possibly HGVs. Taking advantage of existing sensors, rocket motors, and components from mature air-to-air capabilities could reduce the cost and time needed to acquire these weapons.

Adapt NIFC-CA to support base defense battle management and C2. Although the MDA has a ballistic missile defense BMC2 architecture, there is no air and missile defense BMC2 system for DoD's theater bases. The Naval Integrated Fire Control Counter Air system-of-systems integrates Navy counter-air platforms and a variety of sensor networks. Tying into already established sensor networks could greatly increase the effectiveness of base air and missile defenses. Developing a new BMC2 architecture for base defenses from scratch would require years of costly and possibly wasteful development.

Clarify Service responsibilities for base defense within DoD. Clarifying roles and responsibilities for base defense could help reduce the time and cost needed to develop new operating concepts and capabilities to counter enemy salvos.[86] Although this issue is beyond the scope of

86 Gunzinger and Clark, *Winning the Salvo Competition.*

this report, determining the right division of responsibilities between the MDA, the Army, and the Air Force for base defense is a critical and necessary step toward addressing, rather than simply acknowledging, the growing threat to America's theater bases.

Conclusion

It is important to reemphasize that all of the technologies and developmental capabilities assessed in this report should be sufficiently mature to support their transition to acquisition programs within the next 5 years. This timeline assumes, of course, that the DoD and Congress are willing to support the development of new approaches and capabilities for base defense. Failing to do so will increase the risk that bases located in regions critical to the security of the United States, its allies, and its partners will remain nearly undefended against salvo attacks.

LIST OF ACRONYMS

A2/AD	anti-access/area-denial
ABL	Airborne Laser
BMC3	battle management, command, control, and communications
C3ISR	Command, Control, Communications, Intelligence, Surveillance, and Reconnaissance
CAP	combat air patrols
CHAMP	Counter-electronics High-powered Microwave Advanced Missile Project
CSBA	Center for Strategic and Budgetary Assessments
DARPA	Defense Advanced Research Projects Agency
DAS	Distributed Aperture System
DoD	Department of Defense
EOTS	electro-optical targeting system
ER	extended range
FY	fiscal year
GBAD	Ground-Based Air Defense
GEM	Guidance Enhanced Missile
GEM-T	Guidance Enhanced Missile TBM
GLCM	Ground-Launched Cruise Missile
GMD	Ground-based Midcourse Defense
GPS	Global Positioning System
G-RAMM	guided-rockets, artillery, missiles, and mortars
HALE	high-altitude long endurance
HEL	high energy laser
HELIOS	High Energy Laser and Integrated Optical-dazzler with Surveillance
HELLADS	High Energy Liquid Laser Area Defense System
HGV	hypersonic glide vehicle
HiJENKS	High-power Joint Electromagnetic Non-Kinetic Strike
HPM	High-power microwave
HVP	hyper-velocity projectile
IADS	integrated air defense systems
IBCS	Integrated Air and Missile Defense Battle Command System
ICBM	Intercontinental Ballistic Missile
IFPC	Indirect Fire Protection Capability Increment
INF Treaty	Intermediate-Range Nuclear Forces Treaty
IR	infrared
IRBM	intermediate-range ballistic missiles

JHPSSL	Joint High-Power Solid-State Laser
LACM	land-attack cruise missiles
LPWS	Land-based Phalanx Weapons Systems
MDA	Missile Defense Agency
MML	Multi-Mission Launcher
MRBM	medium-range ballistic missiles
MSE	Missile Segment Enhancement
NASAMS	National Advanced Surface-to-Air Missile System
NATO	North Atlantic Treaty Organization
NDAA	National Defense Authorization Act
NDS	National Defense Strategy
NIFC-CA	Naval Integrated Fire Control-Counter Air
nm	nautical mile
O&S	operations and support
OCPFH	operational cost per flying hour
PAC	Patriot Advance Capability
Pk	probability of kill
PLA	People's Liberation Army
PLARF	People's Liberation Army Rocket Forces
RELI	Robust Electric Laser Initiative
RHEL	Ruggedized High Energy Laser
SAM	surface-to-air missile
SHiELD	Self-Protect High Energy Laser Demonstrator
SHORAD	short-range air defenses
SRBM	short-range ballistic missiles
SSL	solid-state lasers
SSL-TM	Solid-State Laser Technology Maturation
TBM	tactical ballistic missile
THAAD	Terminal High Altitude Air Defense
UAV	unmanned aerial vehicle
UCAV	unmanned combat air vehicles

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