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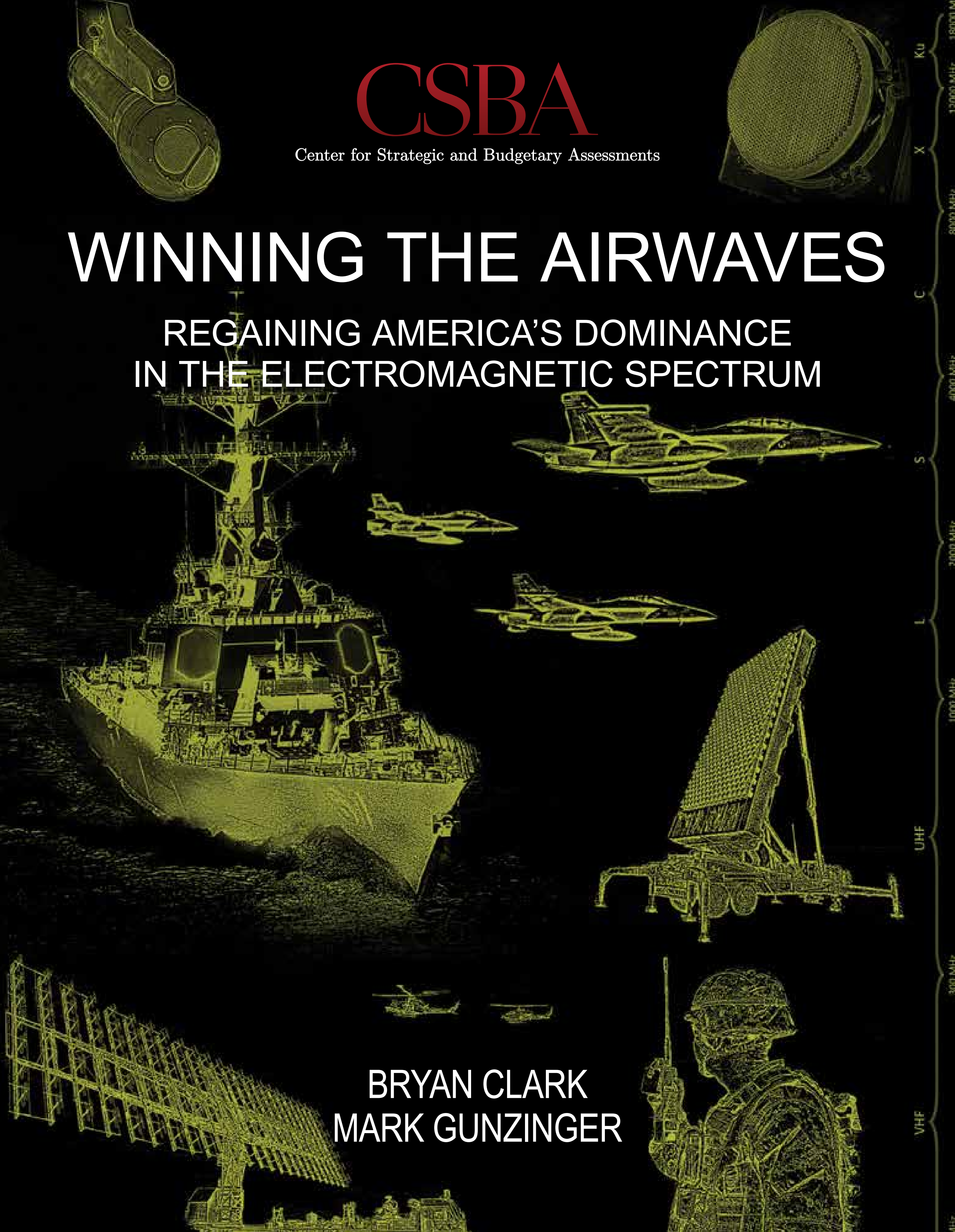
WINNING THE AIRWAVES

REGAINING AMERICA'S DOMINANCE IN THE ELECTROMAGNETIC SPECTRUM



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The Center for Strategic and Budgetary Assessments is an independent, nonpartisan policy research institute established to promote innovative thinking and debate about national security strategy and investment options. CSBA's analysis focuses on key questions related to existing and emerging threats to U.S. national security, and its goal is to enable policymakers to make informed decisions on matters of strategy, security policy, and resource allocation.

ABOUT THE AUTHORS

Bryan Clark is a Senior Fellow at the Center for Strategic and Budgetary Assessments. Prior to joining CSBA in 2013, Mr. Clark was special assistant to the Chief of Naval Operations and director of his Commander's Action Group, where he led development of Navy strategy and implemented new initiatives in electromagnetic spectrum operations, undersea warfare, expeditionary operations, and personnel and readiness management. Mr. Clark served in the Navy headquarters staff from 2004 to 2011, leading studies in the Assessment Division and participating in the 2006 and 2010 Quadrennial Defense Reviews (QDR). His areas of emphasis were modeling and simulation, strategic planning, and institutional reform and governance. Prior to retiring from the Navy in 2007, Mr. Clark was an enlisted and officer submariner, serving in afloat and ashore submarine operational and training assignments, including tours as chief engineer and operations officer at the Navy's nuclear power training unit. Mr. Clark holds an M.S. in National Security Studies from the National War College and a B.S. in Chemistry and Philosophy from the University of Idaho. He is the recipient of the Department of the Navy Superior Service Medal and the Legion of Merit.

Mark Gunzinger is a Senior Fellow at the Center for Strategic and Budgetary Assessments. Mr. Gunzinger has served as the Deputy Assistant Secretary of Defense for Forces Transformation and Resources. A retired Air Force Colonel and Command Pilot, he joined the Office of the Secretary of Defense in 2004. Mark was appointed to the Senior Executive Service and served as Principal Director of the Department's central staff for the 2005–2006 QDR. Following the QDR, he served as Director for Defense Transformation, Force Planning and Resources on the National Security Council staff. Mr. Gunzinger holds an M.S. in National Security Strategy from the National War College, a Master of Airpower Art and Science degree from the School of Advanced Air and Space Studies, a Master of Public Administration from Central Michigan University, and a B.S. in Chemistry from the United States Air Force Academy. He is the recipient of the Department of Defense Distinguished Civilian Service Medal, the Secretary of Defense Medal for Outstanding Public Service, the Defense Superior Service Medal, and the Legion of Merit Medal.

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Contents

EXECUTIVE SUMMARY i
Viewing EM Warfare as a Long-Term Competition i
Need for New Operational Concepts ii
Investing in New Technologies and Capabilities iii
Barriers to Transitioning to the Next Competitive Regime iii
Conclusion and Recommendations iv
CHAPTER 1: INTRODUCTION 1
EM Warfare Defined 2
Thinking in Terms of a Long-Term EM Warfare Competition 3
EM Warfare Challenges for U.S. Power Projection Forces 13
The Next Phase of the EM Warfare Competition 17
CHAPTER 2: POTENTIAL OPERATIONAL CONCEPTS FOR "LOW-TO-NO POWER" EM WARFARE 19
Finding Enemy Forces Using Passive or Multistatic Detection 19
Locating Enemy Forces Using Reflected Ambient Energy 21
Operating Inside Enemy A2/AD Envelopes 22
Protecting Penetrating U.S. Forces from Detection and Attack 24
A Final Word on the Need for New Operational Concepts 27
CHAPTER 3: NEW TECHNOLOGIES AND CAPABILITIES 29
Networked 29
Agile 30
Multifunctional 33
Small 35
Adaptive or Cognitive 35
CHAPTER 4: BARRIERS TO IMPLEMENTATION 39
Immature Operational Concepts and Requirements 39
A Continuing Bias Toward Research Instead of Procurement 41
Fractionated Acquisition 42
CHAPTER 5: CONCLUSION AND RECOMMENDATIONS 45

FIGURES

FIGURE 1: THE ELECTROMAGNETIC SPECTRUM 2

FIGURE 2: EM WARFARE PHASES. 4

FIGURE 3: THE DAWN OF EM WARFARE 5

FIGURE 4: THE ACTIVE NETWORKS VERSUS ACTIVE COUNTERMEASURES COMPETITION DURING WORLD WAR II 7

FIGURE 5: THE ACTIVE NETWORKS VERSUS ACTIVE COUNTERMEASURES COMPETITION DURING THE VIETNAM WAR. 8

FIGURE 6: THE ACTIVE NETWORKS VERSUS ACTIVE COUNTERMEASURES COMPETITION AT SEA 10

FIGURE 7: HAVE BLUE DEVELOPMENTAL AIRCRAFT AND THE B-2 BOMBER 12

FIGURE 8: HOME-FIELD ADVANTAGES IN EM WARFARE 14

FIGURE 9: CHINA'S SENSOR AND WEAPON NETWORK. 15

FIGURE 10: LOCATION OF U.S. SENSOR AND COMMUNICATION SYSTEMS IN THE EMS 17

FIGURE 11: CONCEPTS FOR PASSIVE AND MULTISTATIC DETECTION 20

FIGURE 12: PASSIVE RADAR OR PASSIVE COHERENT LOCATION 21

FIGURE 13: USING NETWORKED DECOYS AND LOW-POWER STAND-IN JAMMING AGAINST PASSIVE AND ACTIVE SENSORS 23

FIGURE 14: HOW DECOY AND JAMMING OPERATIONS AFFECT WHAT SENSORS SEE 23

FIGURE 15: NEW APPROACHES FOR U.S. STRIKE OPERATIONS IN CONTESTED AREAS 25

FIGURE 16: NEW APPROACHES FOR U.S. GROUND ASSAULTS IN CONTESTED AREAS 27

FIGURE 17: NETWORKING EM WARFARE. 30

FIGURE 18: SPECTRAL AGILITY 31

FIGURE 19: SPATIAL AGILITY 32

FIGURE 20: NEXT GENERATION JAMMER AND APG-81 RADAR 33

FIGURE 21: CHARACTERISTICS NEEDED IN VARIOUS EM WARFARE SYSTEMS. 34

FIGURE 22: TOWED DECOY AND MINIATURE AIR-LAUNCHED DECOY 35

FIGURE 23: ADAPTIVE EM WARFARE OPERATIONAL CYCLE. 36

FIGURE 24: DOD SPENDING ON EW RESEARCH AND DEVELOPMENT 41

FIGURE 25: DECLINING FUNDING TO PROCURE EW CAPABILITIES 42

FIGURE 26: AIR FORCE ACQUISITION ORGANIZATION 43

Executive Summary

The electromagnetic spectrum (EMS) is one of the most critical operational domains in modern warfare. Although militaries have used it for decades to communicate, navigate, and locate friendly and enemy forces, emerging technological advances promise to dramatically change their operations. In the same way that smartphones and the Internet are redefining how the world shares, shops, learns, and works, the development and fielding of advanced sensors and networking technologies will enable militaries to gain significant new advantages over competitors that fail to keep pace.

Unfortunately, "failed to keep pace" is an appropriate description of the Department of Defense's (DoD) investments in EM warfare capabilities over the last generation. In the absence of a peer rival following the end of the Cold War, DoD failed to pursue a new generation of capabilities that are needed to maintain its EMS operational superiority. This pause provided China, Russia, and other rivals with an opportunity to field systems that target vulnerabilities in sensor and communication networks the U.S. military has come to depend on. As a result, America's once significant military advantage in the EMS is eroding, and may in fact no longer exist. This does not have to remain the case. DoD now has the opportunity to develop new operational concepts and technologies that will allow it to "leap ahead" of its competitors and create enduring advantages in EM warfare.

Viewing EM Warfare as a Long-Term Competition

EM warfare can be roughly described as military communications, sensing, and electronic warfare (EW) operations that occur in the EM domain. While the term EM warfare may be new, military operations in the EMS are not. Excluding simple visual signaling, armies, navies, and air forces have used EMS capabilities for more than a century to support their operations. Communication and sensing systems such as radios and radar that operate in the radio frequency (RF) portion of the EMS have provided militaries the ability to coordinate their actions since the opening stages of World War II.

How militaries conduct EM warfare, however, has changed significantly over the last 100-plus years. This report describes these changes as a series of major phases, each of which placed a different emphasis on the use of active or passive EMS capabilities and countermeasures. Within each phase, incremental improvements to existing EMS capabilities allowed militaries to gain temporary advantages over their competitors. Advantages that are more enduring have proven to be the product of new operational concepts and capabilities that enabled militaries to transition to the next phase of the EM warfare competition before their rivals.

It is the thesis of this report that the U.S. military has an opportunity to make another such leap ahead, one that will allow it to regain and maintain an enduring advantage in the EM warfare competition. Specifically, DoD could shift toward using low-power countermeasures to defeat enemy passive and active sensors, as well as low probability of intercept/low probability of detection (LPI/LPD) sensors and communications to reduce the likelihood that its forces will be counter-detected. This report uses the term "low-to-no power" EM warfare to describe this approach. If embraced by DoD's leadership and funded by Congress, low-to-no power operational concepts and capabilities would help the U.S. military to take back the airwaves and dominate a critical domain—the electromagnetic spectrum—in which future wars may be won or lost.

Need for New Operational Concepts

Shifting into a new EM warfare competitive regime should begin with the development of new operational concepts that inform DoD's EMS capability priorities, doctrine, and tactics. The Services are already pursuing some operational concepts for low-to-no power EM warfare. The Navy, for instance, is developing tactics for E/A-18G Growler electronic attack aircraft to use passive capabilities to geo-locate threat emitters alone or in concert with other aircraft through the Navy Integrated Fire Control (NIFC) network. This report describes a set of illustrative concepts that would apply more broadly across the joint force and for a wider range of missions and scenarios in the low-to-no power EM warfare regime, including:

- Using passive or multistatic detection capabilities to find hostile forces while avoiding detection by their active and passive sensors;[1]
- Finding enemy forces by using reflected ambient electromagnetic energy that can come from enemy communications systems, emitters of opportunity such as television and radio transmitters, or even the sun;
- Taking advantage of enhanced emissions control and low-power countermeasures to avoid detection while operating inside enemy anti-access/area-denial (A2/AD) zones;

1 According to DoD, a multistatic radar is a "radar system with a transmitter and several receivers, all separated. An advantage of multistatic radar over monostatic radar [a radar with a co-located transmitter and receiver] is that even if transmitters, which might be detected by the enemy when operating, are attacked, receivers in other locations might not be noticed and might thereby escape attack." Department of Defense, *Ballistic Missile Defense Glossary* (Washington, DC: Ballistic Missile Defense Organization, June 1997), p. 189.

- Protecting U.S. forces that must operate in contested and denied areas; and
- Conducting strike operations enabled by low-to-no power EM warfare capabilities.

Investing in New Technologies and Capabilities

Executing these new operational concepts will require the U.S. military to evolve and expand its portfolio of EMS capabilities. To operate effectively in contested and denied environments, DoD should field EM warfare systems that have the following attributes:

- **Networked:** able to communicate and coordinate operations with neighboring EM warfare systems using LPI/LPD data links;
- **Agile:** able to maneuver in power, frequency, space, and time to remain undetected, target enemy networks, and avoid enemy countermeasures;
- **Multifunctional:** able to perform multiple EM warfare functions such as communications, active and passive sensing, jamming, deception, or decoying;
- **Small and affordable:** can be procured and deployed in large numbers on small unmanned vehicles and systems or large platforms to enable diverse EM warfare networks; and
- **Adaptive or Cognitive:** able to characterize the EMS, including previously unknown emitters, and respond to exploit opportunities or counter enemy EMS operations.

Some systems with these attributes are already in the U.S. military's inventory or will be fielded in the next several years. Other potential capabilities are languishing in research and development due to a lack of new, validated requirements and other barriers that inhibit their transition into DoD's acquisition system.

Barriers to Transitioning to the Next Competitive Regime

Operating concepts and capabilities similar to those suggested above would help DoD to transition to the low-to-no power phase of EM warfare. For this transition to occur, however, DoD will first need to address major conceptual, organizational, and programmatic impediments to progress that derive from the lack of an institutional vision for how U.S. forces should fight in the EMS. These barriers include:

- **Impediments to developing new operational concepts.** Technologists, operators, and policy-makers often do not communicate effectively on the potential for emerging technologies to enable new approaches to warfare. Some in DoD are beginning to develop new concepts for the next phase in the EM warfare competition. Their efforts are hindered by the U.S. military's continued emphasis on operating as it has in the past, rather than embracing new ways of operating and fighting in the EMS.

- **A continuing bias toward research instead of procurement.** The lack of new operational concepts inhibits DoD's development of formal requirements that would "pull" new EM warfare technologies into its acquisition process. Moreover, new systems that could support low-to-no power operations that are already fielded, such as active electronically scanned array (AESA) radars, are prized more for their ability to support old operational concepts rather than their potential to enable different approaches to EM warfare.

- **Fractionated acquisition.** DoD acquisition organizations are now structured to procure single-mission EMS capabilities that are upgraded or modernized versions of their predecessors, rather than pursue new, more agile and multifunction systems needed for future EM warfare.

Conclusion and Recommendations

The Department of Defense has an opportunity to establish an enduring advantage in the EMS by adopting a low-to-no power approach for conducting EM warfare. Technologies that would enable DoD to make this shift are largely mature and could be integrated on DoD's manned and unmanned platforms, expendable payloads, and ground systems. Missing are the operational concepts and formal requirements that would help transition these capabilities to U.S. warfighters, organizations to develop and acquire more versatile EM warfare systems, and sufficient resources allocated to procure them. The following initiatives could help DoD to address these shortfalls and create a network of capabilities suited for the next phase of the EM warfare competition, rather than wars of the past:

- **Create a vision for EM warfare.** The EW executive committee (EXCOMM) should oversee the development and implementation of a new vision for how future U.S. forces will operate and fight in the EMS consistent with DoD's recent EW strategy. This vision should guide the efforts of the Services and Defense Agencies to implement low-to-no power EMS warfighting approaches.

- **Develop new EM warfare operational concepts.** The Services should create operational concepts and doctrine for low-to-no power EM warfare to guide acquisition initiatives and the development of new doctrine and tactics, techniques, and procedures (TTP).

- **Establish requirements for new capabilities and refine DoD's acquisition process.** DoD is slow to field new EM warfare systems in large part due to the lack of formal requirements that are used to begin acquisition programs. Using new operational concepts, Services should develop capability requirements that will shift acquisition priorities toward systems that will be effective in the next phase of the EM warfare competition. To aid this process, DoD and Congress should work together to streamline DoD's requirements development process; reduce cumbersome, often time-consuming and redundant analyses for new requirements; and base more new requirements on the capabilities delivered by prototypes and demonstrations.

- **Accelerate development of new EM warfare technologies.** DoD should prioritize its research and development investments to further mature networking, agility, multi-functionality, miniaturization, and adaptability technologies needed in the next phase of EM warfare.

- **Integrate the acquisition of EM warfare systems.** The Services should greatly increase cooperation between multiple executive and management offices now responsible for developing and procuring new EM warfare systems. This would help DoD as a whole to field more agile, multifunction capabilities essential to future EM warfare operations.

- **Demonstrate new EM warfare capabilities.** The Services and Combatant Commands (COCOMs) should expand the number and scope of EM warfare experiments they undertake that feature new operational concepts and capabilities that have yet to transition into DoD's existing program of record.

Chapter 1 summarizes how American and allied military forces have gained significant advantages over their enemies in previous EM warfare competitive regimes. Follow-on chapters will assess operational concepts and capabilities needed for DoD to transition to a low-to-no power approach of operating in the EMS domain. A successful transition would give future U.S. power projection forces a significant edge over their opponents. A failure to develop new operational concepts and capabilities needed for this next phase of EM warfare, however, could result in situations where the U.S. military will be at risk of losing the battle for the airwaves.

This is the revised version of the original study published in December 2015. Among the revisions, it incorporates a new figure (Figure 9) to better explain the A2/AD concept and other revised figures, updates those measures DoD has taken since the initial writing in line with the report's recommendations, and adds detail and clarity to several concepts that have been better fleshed out within the community since the initial publishing.

CHAPTER 1

Introduction

The electromagnetic spectrum is one of the most critical operational domains in modern warfare. In the same way that smartphones and the Internet have redefined how we share, shop, learn, and work, advances in sensors and networking technologies over the last generation have fundamentally changed how the U.S. military conducts its operations. 20 years ago, American ships, aircraft, and other major weapon systems communicated with one another through voice transmissions or by sending contact reports through low-bandwidth datalinks. Today, individual military platforms can track multiple contacts across wide swaths of the EMS while continuously sharing data with distant platforms and command centers through high-bandwidth satellite communications and Internet protocol-based radio networks.

While it is fair to say that the U.S. military fields the most extensive and effective network-enabled sensing and communication capabilities in the world, its networks are increasingly fragile and vulnerable to enemy attacks. In the absence of a rival who could contest its EMS superiority over the last generation, DoD failed to invest in capabilities that are needed to maintain the effectiveness of its future operations in this critical domain. As a result, America's once significant advantage in the EMS is eroding, and may in fact no longer exist. Rivals such as China and Russia have taken advantage of DoD's investment pause to build systems that exploit America's sensor and communication vulnerabilities with the intent of taking apart U.S. military networks during a conflict. They have fielded radars that operate outside the frequency range of U.S. jammers and developed their own jammers that are capable of targeting frequencies used by U.S. sensors and radios. Moreover, China, Russia, and other adversaries have exploited their home-field advantage by deploying large, complex sensor arrays that outrange most sensors carried by U.S. power projection forces.

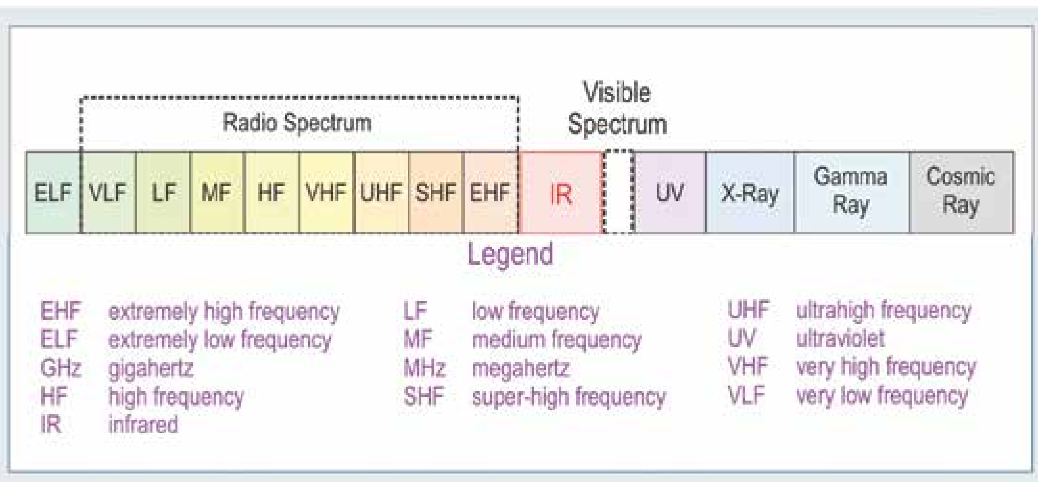
DoD could regain the upper hand over its competitors by taking measures such as fielding new active sensors that avoid areas of the electromagnetic spectrum where enemy jammers operate and modernizing electronic attack systems to target emerging threats. This incremental, short-term approach might yield temporary advantages—but only until adversaries deploy their next set of countermeasures.

A better approach would view EM warfare as a long-term competition consisting of a series of phases characterized by the predominant approaches used by military forces for sensing, communicating, and conducting EMS countermeasure operations. From this perspective, the DoD could establish a more enduring advantage by developing new operational concepts and capabilities that allow it to leap ahead into the next phase of EM warfare. Technologies needed for this leap are rapidly maturing, and new operating concepts are already beginning to emerge. If embraced by DoD and funded by Congress, the U.S. military could choose a path that would allow it to take back the airwaves and dominate a critical operational domain—the EMS domain—in which future wars may be won or lost.

EM Warfare Defined

EMS operations can be roughly broken down into communications, sensing, and electronic warfare. Most people are familiar with communication and sensing systems such as radios and radar in the RF portion of the EMS. In the future, military systems will use a wider swath of the EMS, including capabilities that use laser light, infrared (IR) and ultraviolet (UV) radiation, or emitters and detectors that radiate in the X-ray and gamma ray regions of the spectrum. Figure 1 illustrates the different bands in the electromagnetic spectrum.

FIGURE 1: THE ELECTROMAGNETIC SPECTRUM



The term electronic warfare refers to the use of electromagnetic energy and directed energy (DE) to control the EMS or to attack an enemy's capabilities. DoD divides EW operations into three major categories:[2]

2 Definitions for EW, EA, EP and ES are from The Joint Staff, *Electronic Warfare,* Joint Publication 03-13.1 (Washington, DC: DoD, February 8, 2012).

- Electronic attack (EA) involves the use of EM energy, DE, or anti-radiation weapons to attack personnel, facilities, or equipment with the intent of degrading, neutralizing, or destroying enemy combat capability and is considered a form of fires;
- Electronic protection (EP) refers to actions taken to protect personnel, facilities, and equipment from the effects of friendly, neutral, or enemy use of the EMS, as well as to naturally occurring phenomena that degrade, neutralize, or destroy friendly combat capability; and
- Electronic warfare support (ES) includes actions to search for, intercept, identify, and locate or localize sources of intentional and unintentional radiated EM energy.

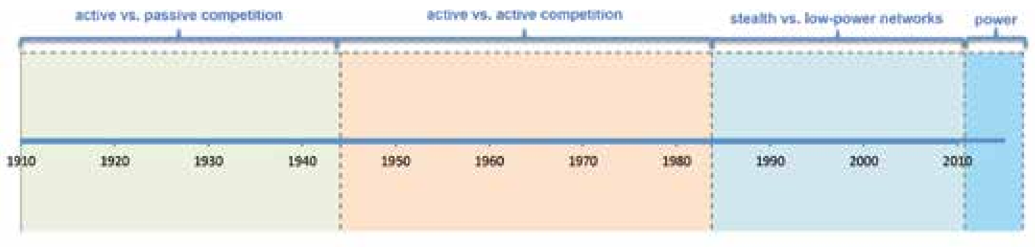
Although this taxonomy describes the various components of electronic warfare, in reality military operations in the EMS are becoming increasingly interrelated. For example, modern computer-based signal processing can enable the same RF signal or laser beam to sense targets like radar, communicate messages like a radio, and act like a jammer simultaneously or in rapid succession. The operation of one EMS system can also affect other EMS systems. For example, the use of electronic warfare systems must be coordinated with the simultaneous use of radios and radars to ensure they are not jammed, as well as with the use of passive sensors to ensure they are able to differentiate friend from foe. This is not much different from operations on the land, in the air, or at sea, where the actions of individual weapon systems affect other weapon systems operating in the same domain. Accordingly, this report will consider *all* operations conducted by the U.S. military in the EMS as elements of EM warfare, similar to how all combat operations on the ground are considered elements of land warfare and all combat aviation operations are considered part of air warfare.

Since most computer networks now have wireless components, the relatively new mission of computer network operations (or cyber operations) can also be conducted through the EMS. While this report will not consider cyber warfare as a separate mission area, it will primarily focus on how U.S. forces can best use the EMS to sustain friendly communication and sensing networks while preventing enemies from doing the same. Capabilities that enable U.S. forces to gain EMS superiority would in turn help U.S. cyber warriors to use the EMS to exploit, disrupt, or attack enemy computer networks.

Thinking in Terms of a Long-Term EM Warfare Competition

While the term EM warfare may be new, military operations in the EMS are not. Armies, navies, and air forces have used EM capabilities (excluding simple visual signaling) for more than a century to support their operations. *How* militaries have conducted EM warfare, however, has changed dramatically over the last 100-plus years. These changes can be described as a series of major phases, each of which placed a different emphasis on active or passive EM capabilities and countermeasures. The brief history that follows describes three phases in the EM warfare competition, as illustrated in Figure 2.[3]

FIGURE 2: EM WARFARE PHASES



It is important to note that while incremental improvements within a phase of EM warfare have created competitive advantages, these advantages were usually temporary in nature. More enduring advantages were the product of new operational concepts and capabilities that allowed a military to shift to the next phase of the competition before its rivals. It is the thesis of this report that the U.S. military has an opportunity to make another such shift, one that will allow it to regain and maintain a more enduring dominance in the electromagnetic spectrum.

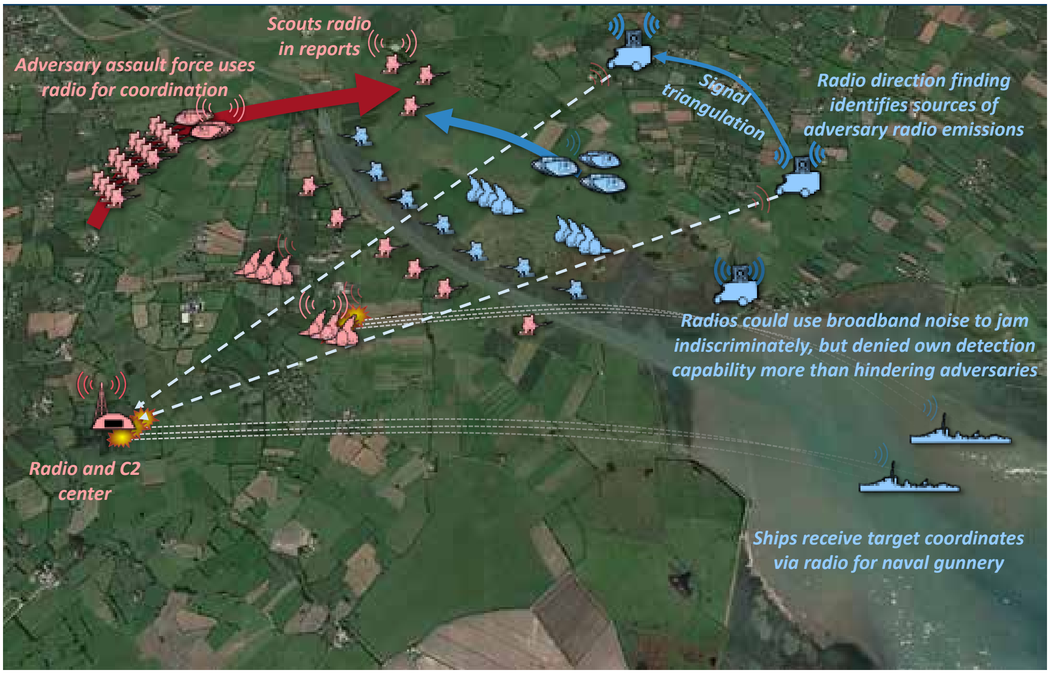
The dawn of modern EM warfare: Active networks versus passive countermeasures

The beginning of the modern-day EM warfare competition can be traced to the creation of wireless radios and their use in large-scale military operations such as World War I (WWI). This early phase of the EMS competition was exemplified by the active use of radios to coordinate troop movements and direct fires and of passive direction-finding (DF) equipment to locate or listen to enemy radio transmissions (see Figure 3).

While communications jamming emerged during this first phase of the EM warfare competition, it was not widely employed by combatants. Operators of rudimentary radios realized that keying their systems could drown out with white noise the transmissions of other radios operating at the same frequencies. This EM warfare tactic had limited operational value, since it also prevented forces doing the jamming from using the same radio frequencies to communicate. Since early radios operated in a small frequency range and were not capable of being finely tuned, it was difficult to jam one frequency and simultaneously use another frequency for friendly communications.

3 The history is drawn from John Stillion and Bryan Clark, *What it Takes to Win: Succeeding in 21st Century Battle Network Competitions* (Washington, DC: Center for Strategic and Budgetary Assessments, 2015).

FIGURE 3: THE DAWN OF EM WARFARE



Another factor that reduced the value of early jamming tactics was that it was often more valuable to *exploit* an enemy's radio communications than to disrupt them. Early DF systems enabled forces to locate enemy radios and possibly listen to their transmissions to gain intelligence. Since engagements in the WWI battlespace normally progressed at the pace of dismounted soldiers and sometimes at the speed of first-generation military trucks and tanks, this information could be used to redirect friendly forces to avoid threats or interdict opposing forces at advantageous points. If radio communications were jammed, however, relatively slow battle tempos allowed enemy maneuver forces to use alternative means of communication such as signal flags and runners or delay operations until radio communications became available.

The fielding of operational military radio detection and ranging systems, commonly known as "radars," began in the 1930s. Early radars were simply radios that bounced signals off large objects such as ships and aircraft to determine their locations. Radar antennas could be rotated to determine the approximate bearing of the ship or aircraft. Using an oscilloscope, operators would then use the time required for a radar beam to travel from its transmitter back to the radar's receiver to determine range to potential targets.

Militaries used passive DF tactics to counter nascent radars, but rarely tried to jam them. Early radars operated in the high frequency (HF) band of the electromagnetic spectrum, which required an antenna with a diameter of several meters to achieve a high effective radiated power (ERP).[4] Ships were able to carry these large radar systems, but their slow speeds made it more advantageous for opponents to determine the ship's location using DF systems and then attack it rather than to jam its radar.[5] Conversely, while shore-based radars were susceptible to jamming, this countermeasure was rarely used because shipboard and land-based jammers could easily be located by DF equipment.

The second phase of EM warfare: Active networks versus active countermeasures

The first phase of the EM warfare competition can be characterized as one of active networks and passive countermeasures where radios and radars were used to find enemies and coordinate friendly operations, and DF systems were used to locate enemy transmissions and exploit their communications. The shift to the second EM warfare phase occurred as technological advances made airborne radars and jammers practical, and the increased tempo of warfare incentivized combatants to interdict enemy transmissions as well as intercept and exploit them.

The need to improve the accuracy of air navigation helped spur the active networks versus active countermeasures competition. Before the advent of air-delivered, precision guided munitions (PGMs), the effectiveness of bombing raids depended in large part on the accuracy of aircraft navigation systems. Bomber aircraft lacked precision navigation systems during the opening stages of World War II (WWII), greatly degrading the accuracy of high-altitude bombing raids. On average, British Royal Air Force (RAF) bombers placed about 10 percent of their ordnance within 5 miles of their targets, and German bombers achieved similar results.[6] The urgent need to improve the effectiveness of bombing operations led to the use of radios and radars as aids for air navigation. During the Battle of Britain, Germany used a radio beacon system it called the "Knickebein" to guide its bombers to British aircraft factories. In 1942, the RAF fielded a "GEE" hyperbolic radio navigation system that allowed its bomber crews to use transmissions from ground stations in Britain to determine their positions inflight.[7]

The growing use of radio navigation systems helped instigate development of the first dedicated active EMS countermeasures. In 1940, the British employed fake beacons code-named

4 The radiated power of an electromagnetic system is a function of the input power from the amplifier and the gain provided to the signal by the antenna. An antenna's gain is maximized if the antenna is one-half the length of the system's radiated wavelength and decreases if the antenna is larger or smaller. An HF system has a wavelength from 10–100 meters, requiring antennas several meters across to achieve sufficient gain for a reasonable power amplifier to be used in the system.

5 The large size of early radars and jammers made them impractical for WWI-era aircraft.

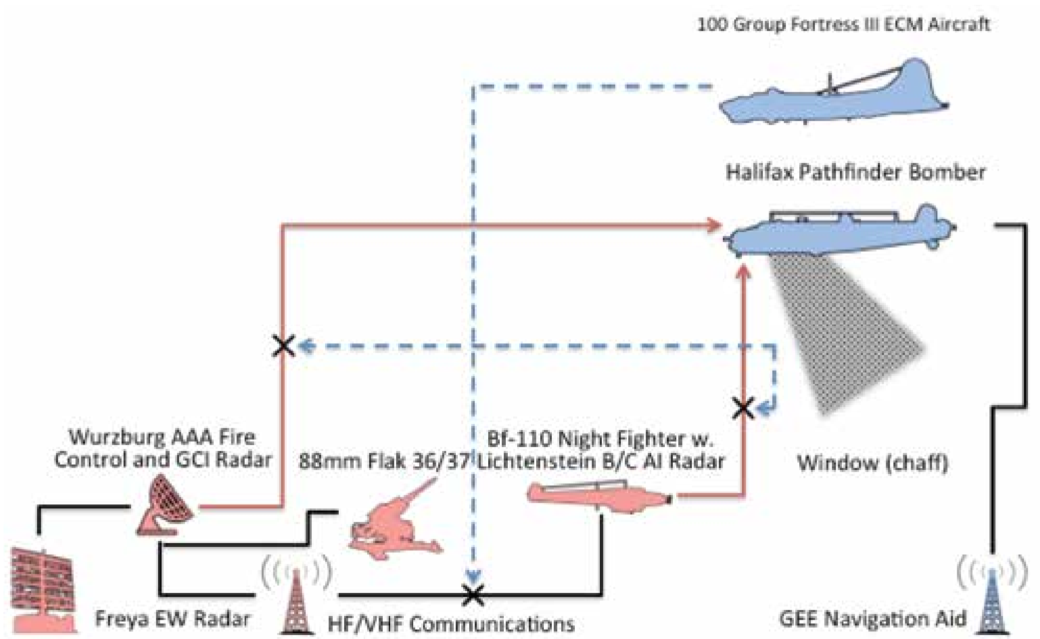
6 This result was in the "Butt Report" compiled by Frederick Lindemann and D.M. Butt in 1941. See Richard G. Davis, *Bombing the European Axis Powers: A Historical Digest of the Combined Bomber Offensive, 1939–1945* (Maxwell AFB, AL: Air University Press, 2006), pp. 29–30.

7 Knickebein used two ground-based radio beacons in Germany transmitting directional beams that intersected over the Merlin aircraft engine factory located in Darby, England. Luftwaffe bombers would use a DF system to stay between the two beams and navigate to Darby. The British GEE system used omnidirectional antennas that created hyperbolic lines of bearing. The transmitters had a master-slave arrangement in which one station would transmit and trigger transmissions from the slave station. Using the known delay between master and slave transmissions and the difference in time between receiving the transmissions, aircraft could determine their approximate location. This system is similar to the LORAN system used by the U.S. military into the late 1990s.

"Aspirin" to counter Germany's Knickebein system, while German air defenses used jammers to prevent RAF bombers from receiving GEE transmissions. Active countermeasures were also used against enemy sensor and communication networks. As shown in Figure 4, RAF bombers dispensed clouds of metallic chaff to confuse German air defense radars by creating thousands of false radar targets, and "Jostle" very high frequency (VHF) communication jammers to interfere with German ground controllers attempting to vector fighters toward targets.[8]

Another factor influencing the adoption of more radar and communications jamming during and after World War II was the increasing speed of combat. During the bombing and air defense operations described above, passive DF sensors were sometimes used to identify the location of enemy bombers or night fighters by their radar and radio transmissions. Because they were traveling at several hundred knots, however, defensive fighters would often not be able to engage the emitting aircraft before they reach their targets or evade. Ground-based air defenses of the time consisted of short-range anti-aircraft guns that would only be able to exploit DF information if the enemy aircraft overflew the defenses; even then, DF information would not be processed quickly enough to guide artillery fires.

FIGURE 4: THE ACTIVE NETWORKS VERSUS ACTIVE COUNTERMEASURES COMPETITION DURING WORLD WAR II

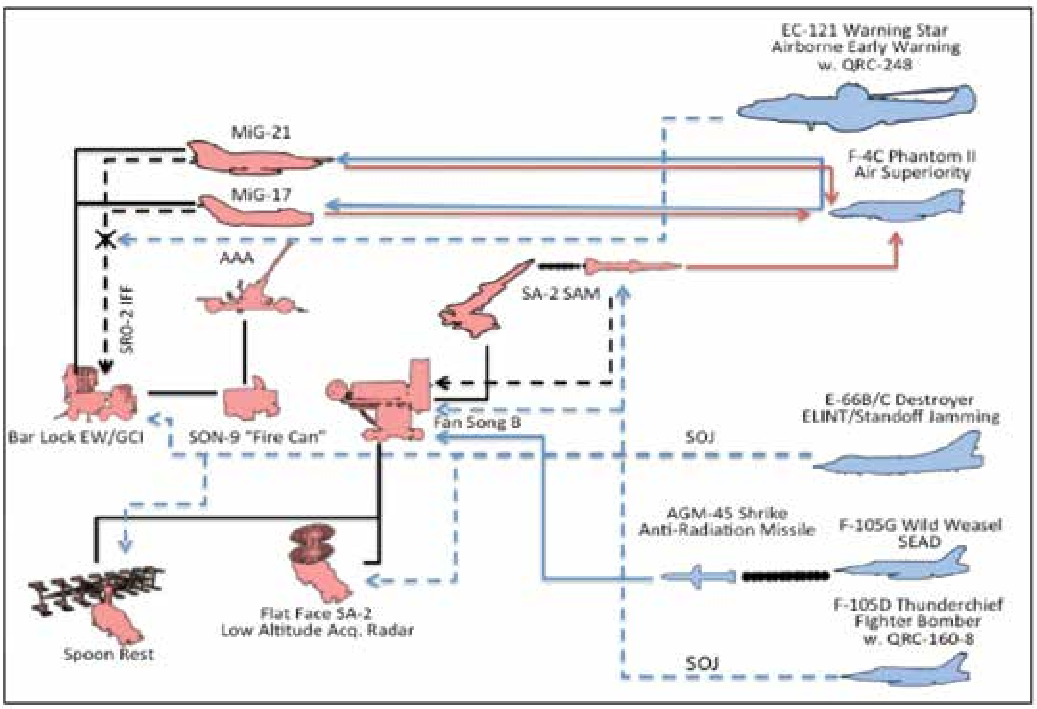


8 Chaff consisted of strips of aluminized paper that were carried in air-dropped dispensers. It was not deployed until 1943 because both sides were concerned it could be quickly replicated by their opponents. The Jostle jammer was carried by B-17s of the RAF Bomber Command's No. 100 (Bomber Support) Group. Each bomber carried two jammers that took up an entire bomb bay. Power limitations precluded smaller aircraft such as fighters to carry radar jammers during WWII.

Passive electromagnetic countermeasures were used effectively at sea during the second phase of the EM warfare competition. During the Battle of the Atlantic, German listening posts decoded Allied convoy orders and positioned U-boats to intercept shipping between the United States and Europe. Allied ships and shore-based stations exploited German radio transmissions to determine U-boat patrol areas and locate roving "wolf packs" in order to vector Allied convoys around them. This game of cat and mouse was possible because WWII-era ships and submarines traveled at 10 knots or less most of the time, which provided ample time for an opponent to intercept, decipher, and take advantage of enemy communications.

The move-countermove cycle between active networks and active countermeasures accelerated as the Soviet Union became a new threat to global peace and stability in the 1950s. The use of active countermeasures expanded as technological advances made possible the development of EM warfare systems with greater power, wider frequency ranges, and more sophisticated waveforms that were practical for aircraft as well as ships. During the Vietnam War, U.S. air forces deployed a growing array of active countermeasures to suppress and defeat increasingly complex North Vietnamese air defenses. Figure 5 illustrates EM warfare in Vietnam near the end of Operation Rolling Thunder in 1968.

FIGURE 5: THE ACTIVE NETWORKS VERSUS ACTIVE COUNTERMEASURES COMPETITION DURING THE VIETNAM WAR



U.S. forces used jammers against each element of North Vietnam's air defense network, attacking early warning and fire control radars, communication links between enemy fighters and ground controllers, and seekers on SA-2 surface-to-air missiles (SAMs). Nearly half of U.S. strike packages penetrating defended airspace could consist of aircraft carrying these countermeasures, imposing a kind of virtual attrition on U.S. forces by reducing the number of aircraft in each package able to perform strikes.[9]

The active network versus active countermeasure approach to EM warfare continued over the course of the Cold War as U.S. air forces fielded high-power sensor platforms to find targets and threats at increasing ranges. These included the E-8 Joint Surveillance Target Attack Radars System (JSTARS), E-2 and E-3 Airborne Warning and Control System (AWACS) aircraft, and the ship-based SPY-1 radar. The EF-111A Raven and EA-6B Prowler became mainstays in the U.S. military's inventory of high-power standoff jamming aircraft that countered enemy sensors.

In addition to long-range active sensors and countermeasures, the U.S. military increased its use of shorter-range, active self-protection countermeasure systems such as the QRC-160-8 jammer carried by the F-105 fighter depicted at the bottom right of Figure 5. These jammers could transmit an RF pulse to drown out enemy radar signals bouncing off friendly aircraft or emit a modulated pulse to force threat radars to break their lock on an aircraft. Self-protection jammers were later complemented with active IR countermeasure (IRCM) systems that used flares and, more recently, low-power lasers to confuse IR seekers on air-to-air and surface-to-air missiles.

The Navy also installed self-protection systems on its ships to help counter Soviet anti-ship cruise missiles (ASCMs). After the number and sophistication of the Soviet Union's ASCMs increased throughout the 1960s and 1970s, the U.S. Navy realized that kinetic ship-based anti-aircraft guns and SAMs would be unable to defeat large salvos of ASCMs. To meet this challenge, the Navy prioritized the development of non-kinetic EW systems that took advantage of the need to use external radars and/or an on-board seeker to guide ASCMs to targets.[10] The Navy pursued several EW systems that were ineffective or deemed too expensive for surface ships before settling on the SLQ-32 system in the mid-1970s.[11] As Figure 6 illustrates, an SLQ-32 can detect EMS emissions at long ranges and engage several ASCMs at once with multiple EW techniques to force missile seekers to break their lock on ships or deceive seekers as to the actual locations of ships.

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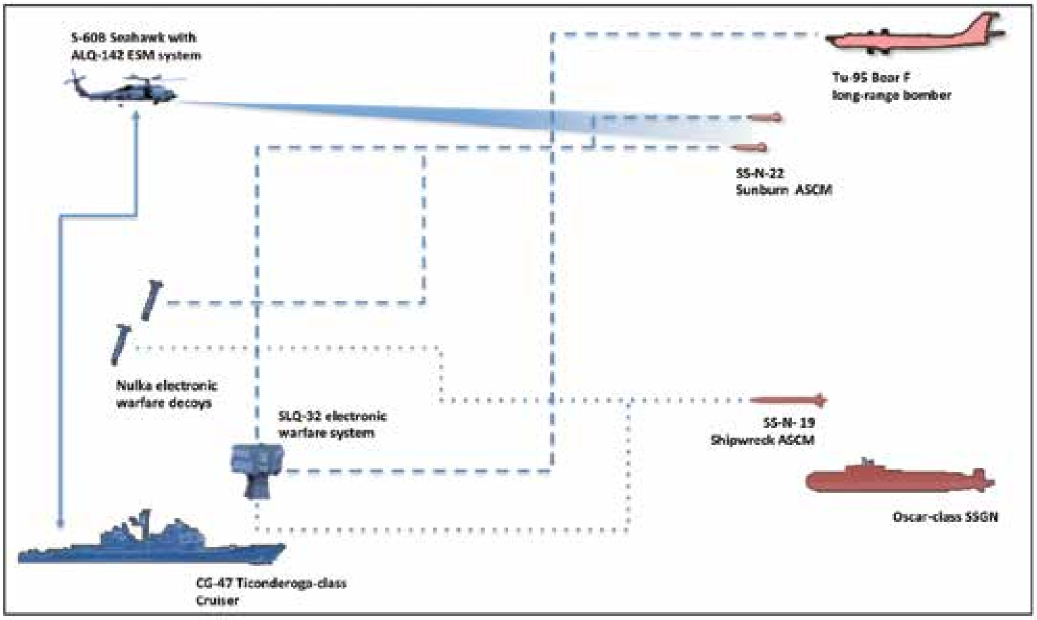
9 The concept of "virtual attrition" is explained in detail in several warfare areas in Stillion and Clark, *What it Takes to Win,* pp. 86–89.

10 Other anti-ship weapons such as artillery, torpedoes, and bombs were unguided and aimed at the target by pointing the gun, ship, or aircraft at the target. In contrast, ASCMs could guide themselves or be steered to the target. This made them vulnerable to jamming as well as able to conduct attacks from well over the horizon.

11 The SLQ-32 improved upon its predecessor, the SLQ-27, in that is was less expensive and came in three variants. The SLQ-32(V)1, which had a passive capability across one portion of the microwave frequency range and could cue chaff launchers, was designed for small auxiliary and amphibious ships. The SLQ-32(V)2, which could receive signals across the whole microwave frequency range and cue chaff, was intended for frigates and destroyers. The SLQ-32(V)3 had full frequency coverage and could both receive and jam enemy radars.

FIGURE 6: THE ACTIVE NETWORKS VERSUS ACTIVE COUNTERMEASURES COMPETITION AT SEA



To reduce the ranges at which systems like the SLQ-32 could detect incoming cruise missiles, the Soviet military developed ACSMs that could fly at very low altitudes or be launched from submarines.[12] To provide advance warning of sea-skimming ASCMs, the Navy procured the ALQ-142 airborne electronic support measure (ESM) system carried by helicopters to detect threat emissions from over the horizon. The Soviets, in turn, developed ASCMs with guidance systems capable of homing on jamming signals or defaulting to its last good line of bearing to the target if confused by jammers. This led the United States and Australia to develop the Nulka EW decoy to lure ASCMs away from target ships, complementing ship-based SLQ-32 operations.

The Navy also procured the Aegis Combat System and SPY-1 radar to improve the air and missile defenses of its surface forces. The Aegis Combat System controlled operation of the SPY-1 and the ship's Standard Missile (SM) series SAMs, and it was networked with the SLQ-32 and Nulka to coordinate kinetic and non-kinetic defenses against incoming ASCMs and to better take advantage of the SLQ-32's passive sensing. As time wore on, however, the growing number of Soviet ASCMs and missile launch platforms made it clear that kinetic and non-kinetic defensive systems would not be sufficient—the Navy would have to attack Soviet ships and aircraft before they could launch their missiles. In the late 1970s, the Navy developed its "Outer Air Battle" concept that emphasized using long-range F-14 Tomcat fighters with

12 Radar and other EMS systems that operate above the HF range emit and detect emissions in a straight line. Therefore, they can only detect objects if they are above the horizon. The distance to the horizon is a function of the system's height of eye per the equation where HOE is the system's height in feet above the earth's surface.

long-range AIM-54 Phoenix air-to-air missiles to engage Soviet bombers before they could launch their ASCMs at U.S. aircraft carriers.[13]

The use of active networks and active countermeasures that characterized phase two of the EM warfare competition became increasingly unsustainable during the Cold War. In air defense operations attacking "archers" before they launch their "arrows," as in Outer Air Battle, became more difficult as ASCM ranges increased in the late Cold War. Moreover, air defense radars and active countermeasures created an increasing risk for U.S. forces of being counter-detected and targeted by passive EM sensors.

In strike operations, the increasing range and lethality of air defense interceptors like the SA-2 and its successors required the U.S. military to dedicate a growing portion of its offensive forces to counter the whole enemy air defense network of sensors (including weapons seekers) and communications. During operations toward the end of the Vietnam War, one half to three quarters of U.S. aircraft in strike packages were allocated toward suppressing air defense threats, reducing the number of strike weapons they could deliver to targets. At the same time, a "salvo competition" began in which defenders hardened and dispersed potential targets to increase the number of weapons U.S. forces needed to deliver.[14]

Even with the increasing number and capability of aircraft devoted to suppressing air defenses, losses during Operation Rolling Thunder II in 1972 and the 1972–1973 Arab-Israeli War reached 2 percent per strike package, corresponding to the loss of about 25 percent of strike aircraft after 15 missions.[15] Acknowledging that this cycle of moves and countermoves was becoming unsustainable, the U.S. military began to explore a different approach to conducting EM warfare.

Phase three of the EM warfare competition: Stealth versus low-power networks

As Soviet military sensors, SAMs, and ASCMs grew in their sophistication and numbers, DoD sought to leverage emerging stealth technologies as a means to break out of the active sensor and countermeasure competition. The U.S. defense community has explored ways to reduce the radio frequency, infrared, acoustic, and visual signatures of its ships and aircraft since the 1950s. Since radars were the most capable contemporary systems for detecting aircraft and ships at long ranges, DoD initially emphasized stealth techniques and technologies to reduce the radar cross section of platforms, as well as the use of passive sensors and sensors with waveforms and adjustable power levels to reduce the EM emissions of stealth platforms that could be detected by an enemy's passive sensors.

13 James Winnefeld, "Winning the Outer Air Battle," *U.S. Naval Institute Proceedings,* August 1989, pp. 37–44, available at http://www.usni.org/magazines/proceedings/1989-08/winning-outer-air-battle; and Joseph Metcalf, "Surface Warfare and Surface Warriors," *U.S. Naval Institute Proceedings,* October 1985, pp. 68–80.

14 The salvo competition between precision defensive weapons and precision strike weapons is described in detail in 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).

15 Stillion and Clark, *What it Takes to Win,* pp. 86–87.

The Defense Advanced Research Projects Agency (DARPA) developed the first acknowledged U.S. aircraft to use stealth technology, the Have Blue demonstrator, in the 1970s (see Figure 7). Have Blue was designed to exploit the fact that an aircraft's radar signature depends more on its overall shape and the number and configuration of edges on its surface that could reflect RF energy than on its overall size.[16] The demonstrator was part of a system-of-systems concept called Assault Breaker that proposed using stealthy aircraft equipped with less-detectable radars (known as Pave Mover) and surface-launched, long-range guided weapons to attack enemy ground forces.[17]

Although Assault Breaker was never fully completed, the U.S. Air Force used Have Blue as a jumping off point to develop a new stealth attack aircraft, the F-117 Nighthawk. Despite the F-117's successful use during Operation Desert Storm, its design was limited. For example, it was optimized to diminish RF returns from its nose and tail at frequencies used by contemporary fire control radars. The F-117's radar signature was much greater from its side aspect and in other frequency ranges, including frequencies used by long-range early warning systems.[18] A major insight from F-117 operations, however, was that aircraft with stealth radar signatures could use jammers that emit at lower power levels and employ other countermeasures that reduce their risk of detection compared to non-stealth aircraft.

Radar signature reduction was also a priority for a new strategic bomber intended to replace the Air Force's venerable and increasingly vulnerable B-52. Applying lessons from the F-117, designers of the Advanced Technology Bomber (ATB), later known as the B-2 Spirit, chose a tailless design and used advanced technologies to reduce its RF signature from all aspects.[19]

FIGURE 7: HAVE BLUE DEVELOPMENTAL AIRCRAFT AND THE B-2 BOMBER

16 Alfred Price, *The History of Electronic Warfare,* Volume III, *Rolling Thunder Through Allied Force,* 1964 to 2000 (Alexandria, VA: Association of Old Crows, 2000), p. 98.

17 Richard H. Van Atta et al., *Transition and Transformation: DARPA's Role in Fostering an Emerging Revolution in Military Affairs,* Vol. 2, *Detailed Assessments* (Alexandria, VA: Institute for Defense Analyses, November 2003), p. VI-30.

18 These characteristics made it possible for the F-117 to be tracked from the side or with early warning radars. This is believed to be how an F-117 was shot down over Kosovo in 1994. See Price, *The History of Electronic Warfare.*

19 Ibid.

The F-117 and Advanced Technology Bomber programs represented a new approach to countering active sensor and communication networks. This approach relied on using stealth, passive sensors, and low-power communications and countermeasures instead of developing ever-more powerful jammers and decoys to counter enemy sensors. By the 1980s, DoD recognized that it should take this approach for other new platform designs. The Navy's DD(X) destroyer program and the Air Force's Advanced Tactical Fighter (ATF) both incorporated signature reduction features and systems to sense and communicate passively or at low radiated power levels. The DDG-1000 that came from the DD(X) program was intended to include the SLQ-32 and radar that would be more accurate and less detectable than the SPY-1 on other surface combatants.[20] The F-22, which won the ATF competition, was equipped with new passive electro-optical (EO) and IR sensors, and it incorporated the ALR-94 integrated electronic warfare system that could detect threats passively and manage aircraft communications to reduce their probability of detection.

DoD's shift toward stealth and low-power EMS capabilities was abruptly curtailed after the end of the Cold War. In the absence of significant EM warfare competitors, DoD decided to sustain and improve its active networks based on the SPY-1 radar, E-3 AWACS, and E-8 JSTARS and active countermeasures such as the EF-111, EA-6B, and SLQ-32. DoD halted B-2 production at 21 aircraft, and the Air Force was directed to procure only 187 operational F-22 aircraft. Similarly, DoD capped DDG-1000 procurement at three ships and replaced its radar with a less capable one.[21]

Unfortunately, the shift to the third phase of EM warfare did not end just because DoD decided to truncate its procurement of new low-to-no power EMS capabilities. Adversaries such as China and a resurgent Russia have pursued their own low-observable platforms, advanced sensor and communication networks, and countermeasures designed to defeat America's Cold War-era EM warfare systems. The next section summarizes some of the challenges these capabilities now present to the U.S. military.

EM Warfare Challenges for U.S. Power Projection Forces

America has the luxury of being surrounded by oceans that separate it from distant theaters of conflict. The downside of this situation is that the U.S. military must be organized, trained, and equipped to project power over long distances to defend our nation's allies and interests. This geostrategic reality disadvantages U.S. EM warfare operations in the following ways.

Adversaries can exploit their home-field advantage

Adversaries in distant theaters are able to use the strategic depth of their home territory to build communication and sensor networks that are difficult for U.S. expeditionary forces to

20 Ronald O'Rourke, *Navy DDG-51 and DDG-1000 Destroyer Programs: Background and Issues for Congress* (Washington, DC: Congressional Research Service, June 25, 2014), p. 29.

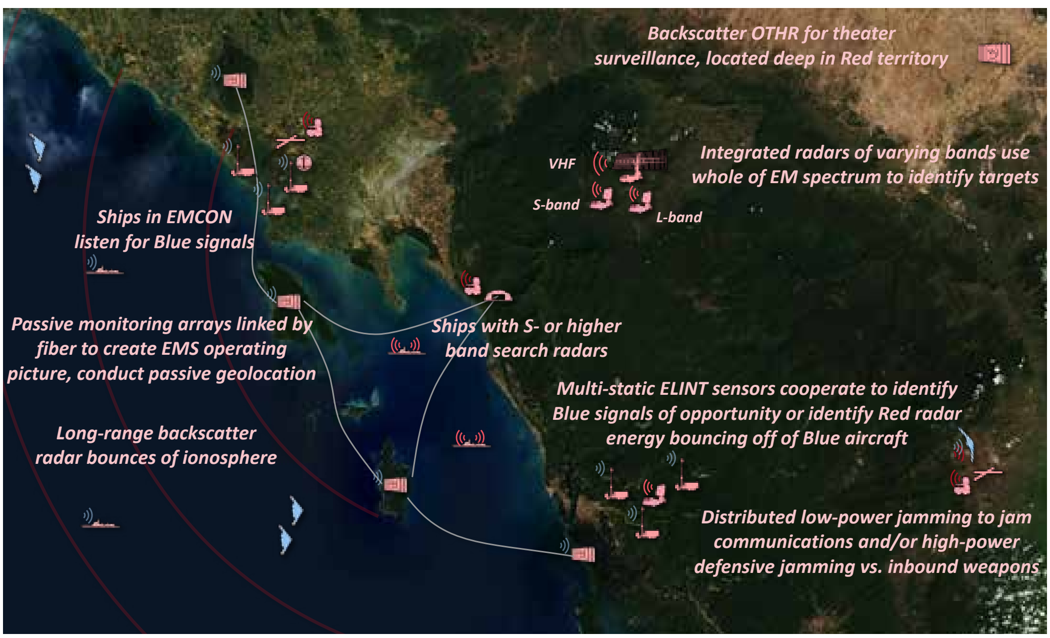
21 O'Rourke, *Navy DDG-51 and DDG-1000 Destroyer Programs,* p. 18.

match. As illustrated in Figure 8, defenders can use larger, lower frequency (such as HF or VHF) sensors that operate at long ranges and use large, powerful computer processors to improve the precision of their returns. They can also geographically disperse sensor arrays to enable multistatic radar operations in which one array transmits and other arrays receive reflected radar energy. And because these dispersed arrays are ashore, they can be connected using landline communications that are highly resistant to jamming.

Defenders can also leverage their knowledge of the local environment to exploit passive detection techniques made possible by advances in large-scale computer processing. These techniques can triangulate the location of emitters using multiple passive ESM arrays or geolocate U.S. emitters by analyzing the Doppler shift in their emissions.[22] They can also emplace arrays of passive EM receivers to detect ambient EM energy reflected off incoming ships and aircraft. These passive techniques require sophisticated modeling of the local EMS and meteorological environments that can be difficult for expeditionary forces to replicate.

The combination of long-range active and passive EMS sensors with robust, jam-resistant communications give adversaries an advantage against U.S. expeditionary forces that operate smaller and lower-power active sensors and countermeasures, lack hard-wired communications, and are less able to exploit multiple array sensing techniques. As shown by the red areas in Figure 8 that represent the range of seekers, this could result in situations where expeditionary U.S. forces could be detected, tracked, and engaged before they could do the same to enemy forces.

FIGURE 8: HOME-FIELD ADVANTAGES IN EM WARFARE

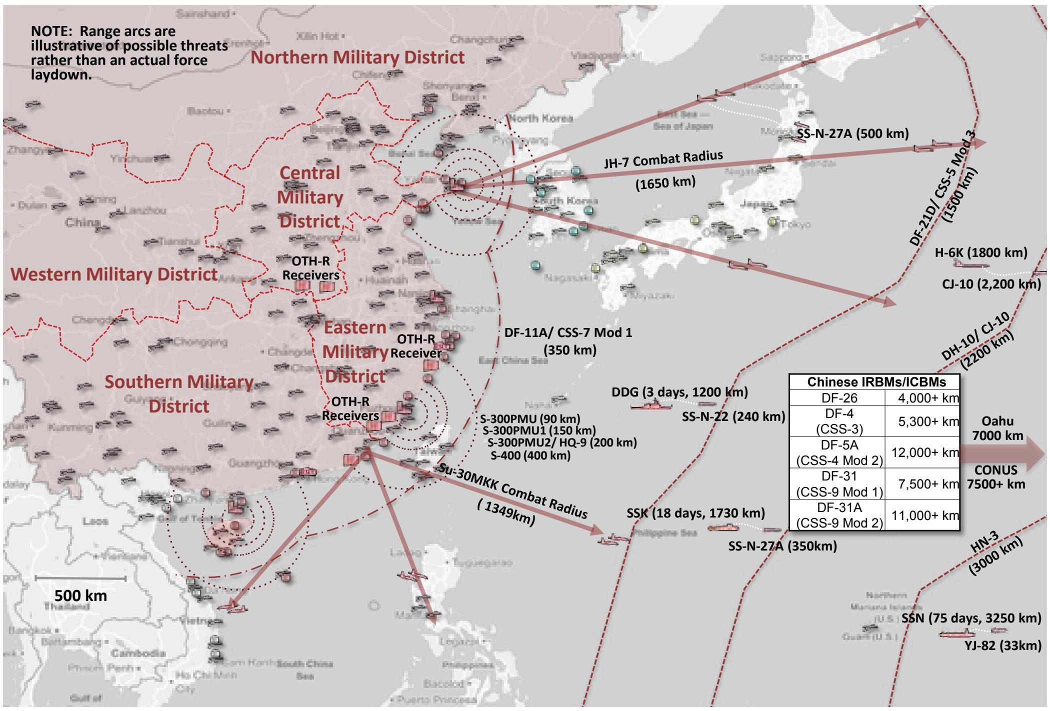


22 Hanna Witzgall, John Covington, and Austin Pierce, "Single Aircraft Passive Doppler Location of Radios," *Aerospace Conference, 2015 Institute of Electrical and Electronics Engineers,* March 7, 2015.

Improving anti-access/area-denial threats

Potential adversaries such as China, Iran, and Russia can use shore-based sensor and communication networks, SAMs, cruise missiles, and ballistic missiles to attack U.S. ships, aircraft, and other power projection forces at long ranges. Called A2/AD threats by DoD, these capabilities and are increasing in their accuracy, reach, and numbers. For example, Russia's S-400 SAMs, which it recently sold China, have a range of about 200 nm.[23] China and Iran both maintain large inventories of ballistic missiles, some with ranges that exceed 1,000 nautical miles that can attack targets located across their respective regions.[24] A notional laydown of China's sensor and network is shown in Figure 9.

FIGURE 9: CHINA'S SENSOR AND WEAPON NETWORK[25]



23 George C. Marshall and Claremont Institutes, "Sophisticated Russian S-400 missiles for Iran under new military pact, S-300s for Egypt, Syria, Hizballah," *Missile Threat Watch,* January 21, 2015, available at http://missilethreat.com/sophisticated-russian-s-400-missiles-iran-new-military-pact-s-300s-egypt-syria-hizballah/; and Wendell Minnick, "S-400 Strengthens China's Hand in the Skies," *Defense News,* April 18, 2015, available at http://www.defensenews.com/story/defense/air-space/strike/2015/04/18/china-taiwan-russia-s400-air-defense-adiz-east-china-sea-yellow-sea/25810495/.

24 U.S. Institute of Peace, "Iran's Ballistic Missile Program," *U.S.I.P. The Iran Primer,* August 2015, available at http://iranprimer.usip.org/resource/irans-ballistic-missile-program.

25 Office of Naval Intelligence (ONI), The PLA Navy: New Capabilities and Missions for the 21st Century (Washington, DC: ONI, April 9, 2015), pp. 13–25, available at http://www.oni.navy.mil/Portals/12/Intel%20agencies/China_Media/2015_PLA_NAVY_PUB_Print.pdf?ver=2015-12-02-081247-687; and Office of the Secretary of Defense (OSD), Military and Security Developments Involving the People's Republic of China 2016, Annual Report to Congress (Washington, DC: DoD, 2016), pp. 22–29, available at http://www.defense.gov/Portals/1/Documents/pubs/2016%20China%20Military%20Power%20Report.pdf.

The increasing range of A2/AD networks will compel many U.S. forces to operate further from an enemy and require them to use higher-power active sensors and countermeasures. An even higher-power, longer-range approach to EM warfare would further increase the detectability of U.S. forces and may not be achievable given the power limitations of combat aircraft and ships. To make matters worse, DoD lacks sufficient stealth platforms and LPI/LPD or passive sensors and communication systems for large-scale operations in highly contested A2/AD environments.[26]

U.S. EMS capabilities lack agility

Theoretically, DoD could reduce the vulnerability of its forces in the near-term by making greater use of parts of the electromagnetic spectrum where many enemy EMS capabilities do not operate. In reality, this would be a significant challenge, since DoD's current EMS capabilities lack the ability to maneuver in the EMS. In large part, sensors and communication systems now used by U.S. forces have been in service for decades, and despite upgrades they still operate in frequency bands and have other characteristics similar to their Cold War predecessors (see Figure 10). Since they are largely hard-wired with these characteristics, modifying them to use new frequency bands or waveforms would be very expensive.

DoD's EM warfare systems are also constrained by regulatory restrictions. The Federal Communications Commission apportions military use of the EMS to certain frequency ranges and desires to transfer more of these frequencies to commercial applications.[27] DoD's current EM warfare systems lack the agility to share the frequencies they use with commercial systems; although efforts are underway to develop new spectrum sharing technologies.[28]

Adversaries have exploited the static nature of the U.S. military's EM warfare capabilities. Today, Russia, China, Iran, and others have fielded countermeasures such as jammers and decoys that target the characteristics of U.S. systems. They have also been afforded sufficient time to develop their own active sensor and communication systems that are less susceptible to current U.S. countermeasures.

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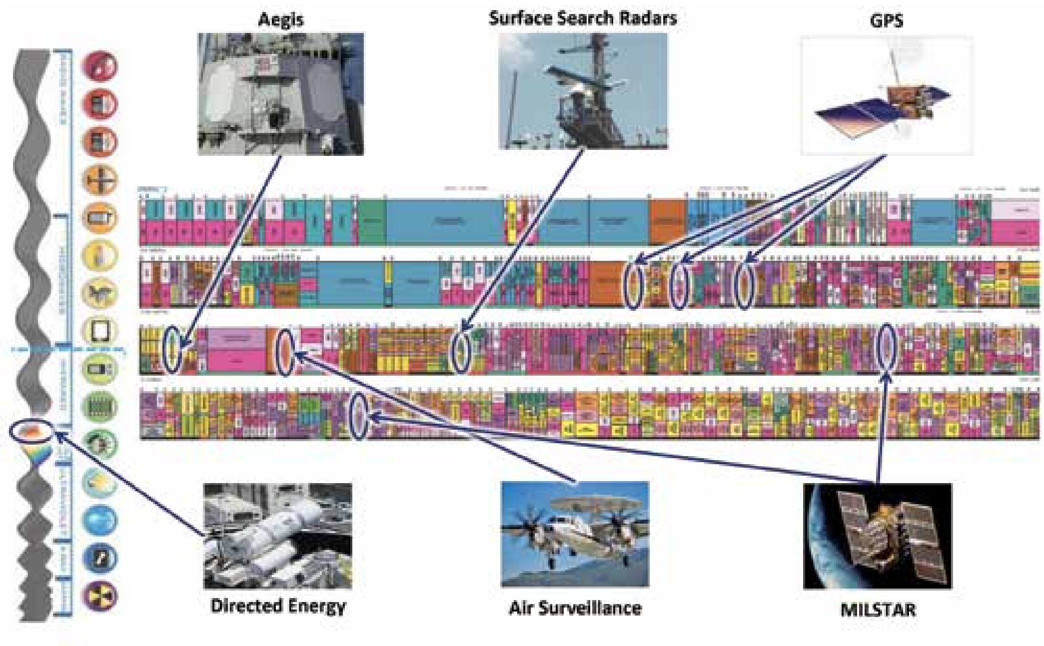
26 Gunzinger and Clark, *Sustaining America's Precision Strike Advantage*, p. 14–16.

27 Ed Wyatt, "Bidding in Government Auction of Airwaves Reaches $34 Billion," *New York Times,* November 22, 2014, p. B1, available at http://www.nytimes.com/2014/11/23/business/media/bidding-in-government-auction-of-airwaves-reaches-34-billion.html?_r=0.

28 "Spectrum Access Research and Development Program Builds $500M Investment Portfolio," Defense Information Services Agency, April 14, 2016, available at http://www.disa.mil/newsandevents/2016/Spectrum-Program.

FIGURE 10: LOCATION OF U.S. SENSOR AND COMMUNICATION SYSTEMS IN THE EMS



The Next Phase of the EM Warfare Competition

In light of these challenges, it is time for the U.S. military to more fully embrace changes that would give it significant operational advantages in the EMS. Specifically, the U.S. military should complete the shift it began in the late Cold War and prioritize the fielding of low-to-no power networks and countermeasures that operate passively or in ways that reduce the probability that enemies will discriminate their emissions from ambient background noise in the EM environment. Technologies in development today will support this shift.

Passive sensors and their implications

Advances in computing technology over the last 25 years have enabled the development of passive sensors that are far more capable than their predecessors. In particular, large-scale computer processing (or "big data") and improved models of the EMS environment contributed to the development of passive and low-power RF sensors with longer range and greatly improved precision.[29] Passive IR sensors, long relegated to night vision goggles and other short-range applications, are also more effective at long ranges due to the improved acuity and

29 Richard Fisher, "Beijing Tech Show Highlights Advances in Chinese Sensors," *HIS Jane's 360,* July 19, 2015, available at http://www.janes.com/article/53064/beijing-tech-show-highlights-advances-in-chinese-fighter-sensors; and Sanghoon Nam, "Search and Tracking System Architecture Using 1-D Scanning Sensors," *Proceedings of SPIE,* May 3, 2010.

lower frequencies possible with big data. Today, militaries are increasingly turning to passive IR search and track (IRST) sensors as alternatives or adjuncts to long-range RF sensors.[30]

To address these challenges, U.S. forces will need to reduce their signatures across the EMS. DoD has worked hard to reduce the RF signatures of its platforms by using emissions control (EMCON) measures and stealth technologies. Similar efforts are required now to reduce the EO and IR signatures of platforms that will be required to penetrate contested and denied areas. Signature reduction should be complemented with passive or low-power active countermeasures that further mask a platform's signature or create more attractive false targets are also needed. Some of these countermeasures exist today, including the passive AN/SLQ-49 "rubber duck" decoy, AAQ-24(V) IRCM, and AN/ALQ-165 RF self-protection jammer, but they will need to incorporate new technologies to remain effective as described in Chapter 3.

Countering enemy countermeasures

Improved computer processing also led to the development of radar countermeasures that are more agile and resistant to counter-countermeasures (CCM). Digital RF Memory (DRFM) jamming, which digitally records an incoming signal, alters it, and then sends false returns to the enemy sensor, is one such example.[31] Technology will soon progress to the point where countermeasures will be able to characterize previously unknown sensors, adapt to them, create effects that confuse or deceive rather than just overwhelm them, and even predict the sensor's reaction.[32]

To reduce their chance of being counter-detected or defeated by enemy jammers and decoys, U.S. sensor and communication networks will need to operate passively or use LPI/LPD technologies.[33] These include capabilities to control beam width and direction, radiated power, and signal frequency as well as new technologies such as lasers and light-emitting diodes. Light-based sensors and communications would have significantly lower probabilities of being detected by enemy sensors due to the fact that they are line-of-sight capabilities with narrow beams and lack the "side lobes" that are inherent in RF signals.

In summary, the use of low-to-no power sensors, communications, and countermeasures will be dominant in the current third phase of the EM warfare competition. The U.S. military could establish an enduring advantage in this competitive regime by developing new operational concepts and capabilities similar to those described in the next two chapters.

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30 In general, an EM signal will suffer more attenuation as it increases in frequency because it will transfer more energy to the air in the form of heat. Therefore, sensor designers try to build systems capable of sensing accurately and precisely at lower frequencies.

31 Dave Majumdar, "Pentagon Worries that Russia Can Now Outshoot U.S. Stealth Jets," *Daily Beast,* December 12, 2014, available at http://www.thedailybeast.com/articles/2014/12/04/pentagon-worries-that-russia-can-now-outshoot-u-s-stealth-jets.html.

32 Defense Science Board, *21st Century Operations in a Complex Electromagnetic Environment* (Washington, DC: DoD, July 2015), p. 6.

33 An LPD transmission adjusts its power, direction, or beam width so it is only received by an intended target. While an LPI signal may be received by enemy systems, it uses signal designs that cannot be recognized or analyzed by receiving system processors.

CHAPTER 2

Potential Operational Concepts for "Low-to-No Power" EM warfare

To establish an advantageous position in the third phase of the EM warfare competition, DoD will need new operational concepts that are based on using low-power countermeasures against enemy active and passive sensors and LPI/LPD sensors and communications to reduce the probability that U.S. forces will be counter-detected. These concepts should take advantage of the fact that all platforms, vehicles, and even payloads that emit and/or receive could have a positive or negative impact on the outcome of future EM warfare engagements.

The Services are already pursuing some low-to-no power capabilities. The Navy is developing tactics for its E/A-18G Growler aircraft (the successor to the E/A-6B Prowler) to use passive ESM systems to geo-locate threat emitters alone or in concert with other aircraft through the Navy Integrated Fire Control network. Using NIFC, passive targeting information can be passed from an E/A-18G via a Link-16 secure tactical data link to an E-2D AWACS aircraft and then to surface combatants via the Cooperative Engagement Capability (CEC) datalink to enable them to attack targets with long-range cruise missiles.

While these nascent tactics are useful steps toward preparing for low-to-no power EMS operating environments, similar concepts will need to be applied more broadly across the joint force and for a wide range of missions and scenarios. The following sections describe several potential operational concepts.

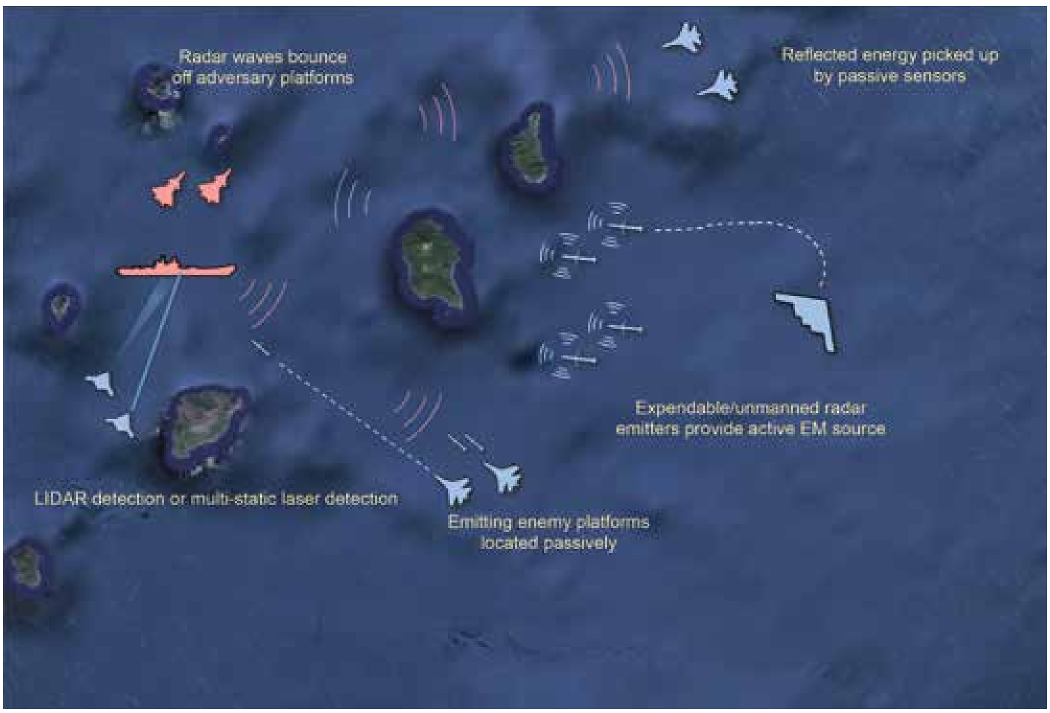
Finding Enemy Forces Using Passive or Multistatic Detection

Future sensing and communication networks will need to use operational concepts that reduce the counter-detection risk to U.S. forces. Figure 11 illustrates three approaches to do this.

The first approach would use passive sensors to detect enemy RF and IR emissions. Locations of enemy emitters can be determined by triangulating emissions received by multiple, dispersed manned or unmanned platforms or by analyzing the Doppler shift of EM emissions received by passive sensors. It is likely that some targets, such as fire control radars, will only emit after receiving a cue from a sensor. Figure 11 illustrates how the U.S. military could use emitting decoys to cause fire control radars to activate, allowing passive sensors to then geo-locate them.

U.S. forces could use a second approach that employs multistatic techniques to locate enemy platforms and systems that do not emit detectable EM energy. In this case, one emitting platform could bounce RF or IR energy off a suspected target, which is then received by other friendly passive sensors. Networking would ensure friendly receivers know the position of emitters and characteristics of their illuminating pulses. Because they are likely to be counter-detected, the emitters could be expendable payloads.

FIGURE 11: CONCEPTS FOR PASSIVE AND MULTISTATIC DETECTION



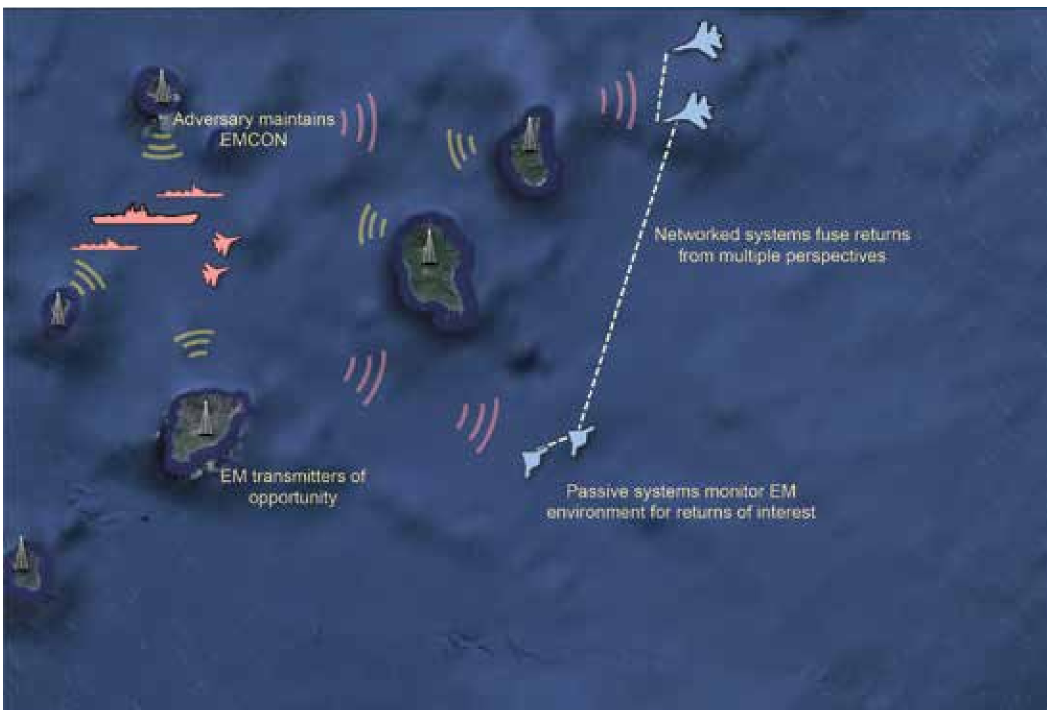
A third approach would use LPI/LPD lasers to conduct multistatic or single platform detection operations. Similar to radar, lasers scanned across targets generate a reflected "return" that can be received by sensors. Returns from Light Detection and Ranging (LIDAR) systems can be used to locate, image, and classify targets with greater fidelity than radar. LIDAR can be used mono-statically, with a laser and receiver on the same platform, or multistatically, where a laser on one platform illuminates a target for detection by separate passive electro-optical receivers. Lasers can be less detectable than RF signals because they can be focused more tightly than RF beams, lack side lobes that are a feature of RF antennas, and can be precisely adjusted to use only the minimum laser energy necessary to detect targets.

Similar to the U.S. military, potential adversaries will likely reduce the vulnerability of their platforms to detection by reducing IR emissions and modulating the power of their active sensors. As a result, U.S. passive sensors may need to get very close to enemy platforms in order to detect them. Achieving this proximity at acceptable risk may require penetrating unmanned vehicles or expendable payloads such as missiles to carry passive sensors.

Locating Enemy Forces Using Reflected Ambient Energy

Figure 12 illustrates how U.S. forces could use reflected ambient EM energy to detect potential targets. This approach, called passive radar or passive coherent location, can use ambient energy that comes from enemy communications systems, emitters of opportunity such as television and radio transmitters, or even from the sun. If there is a known predominant emitter in the area, a single receiving system could detect the target similar to a multistatic system. In the absence of a predominant emitter, U.S. forces could use multiple networked receivers to evaluate returns from different aspects of a potential target.

FIGURE 12: PASSIVE RADAR OR PASSIVE COHERENT LOCATION



Passive radars require systems that understand the characteristics of the ambient RF environment and its predominant EM sources. In order for this technique to provide accurate position information, pre-conflict intelligence preparation of the RF environment and high-fidelity models will be needed, as well as real time assessment of the meteorological and EMS environment from platform-mounted or expendable sensors.

Operating Inside Enemy A2/AD Envelopes

Long-range SAMs, cruise missiles, and ballistic missiles could compel U.S. power projection forces to operate farther from an enemy. This would require U.S. power projection forces to use active sensors and countermeasures with longer ranges that operate at much higher power levels, an approach that may prove unsustainable given the ever-increasing range of A2/AD threats and the size and power limitations of expeditionary forces. An alternative is to develop new capabilities that enable U.S. forces to operate inside A2/AD envelopes while avoiding detection. While DoD is pursuing some new tactics along these lines, it is hindered by legacy technologies resident in today's force. In particular, DoD's EA systems are predominantly oriented toward conducting either high-power standoff EA from outside the range of threat weapons, or using lower-power, very short-range self-protection EA systems on individual platforms to counter homing weapons.

In the emerging low-to-no power phase of EM warfare, A2/AD networks will increasingly rely on passive sensors. DoD should anticipate that these systems will use passive RF sensing (electronic intelligence, or ELINT) systems that have a very wide field of view to find and identify potential targets. Since passive, long-range sensors provide less precise target information, enemies would also need to use EO/IR sensors or narrowly focused radar beams to establish accurate targeting information for attacks.

Figure 13 illustrates approaches U.S. forces operating inside adversary A2/AD envelopes could take to defeat this combination of enemy active and passive sensors. To reduce the acuity of enemy passive sensors, the U.S. military could shift toward using unmanned vehicles or expendable payloads that emit low-power jamming noise in the RF spectrum (possibly using DRFM technology) or dazzling EO/IR sensors using low-power lasers. Networked with LPI/LPD communications links, EM warfare systems on these unmanned vehicles could cover a wide and diverse geographic and EMS region, as well as autonomously adapt to the behavior of an adversary's sensors. Other vehicles and payloads could carry decoy systems that simulate the EMS signature of U.S. weapon systems to attract enemy sensors to an area away from the actual U.S. force.

The objective of this "decoy and deception" operational approach is to create a false picture of the battlespace for enemy forces. As illustrated in Figure 14, jamming obscures the actual location of U.S. forces in a higher noise area to the east. To the south, the enemy detects decoys with similar EM signatures it would expect from U.S. forces.

FIGURE 13: USING NETWORKED DECOYS AND LOW-POWER STAND-IN JAMMING AGAINST PASSIVE AND ACTIVE SENSORS

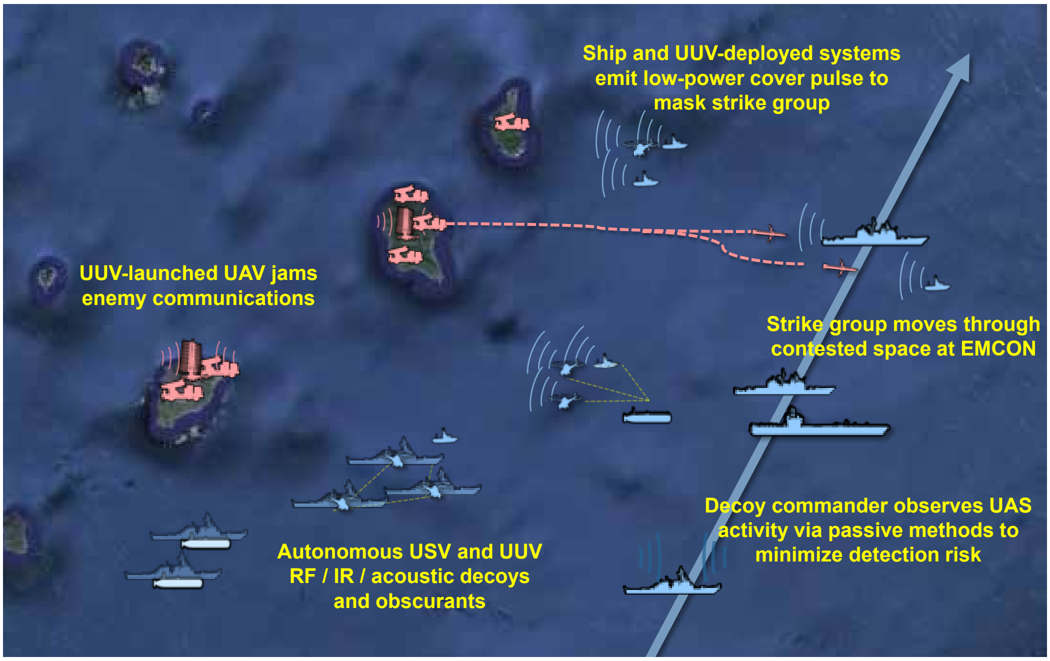
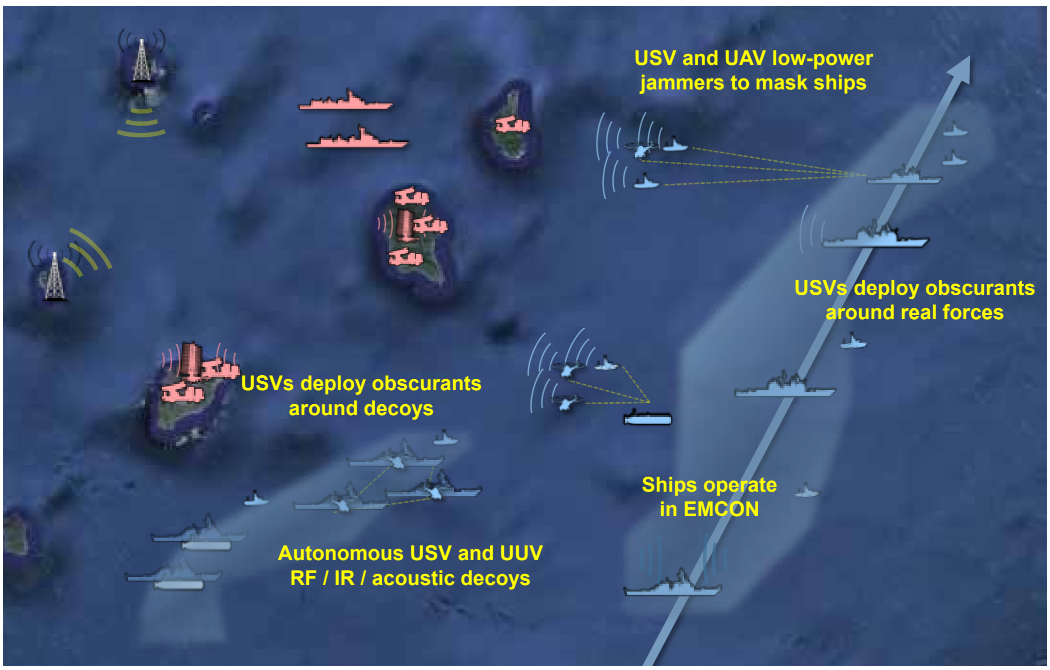


FIGURE 14: HOW DECOY AND JAMMING OPERATIONS AFFECT WHAT SENSORS SEE



Interdicting communications between enemy sensors, launchers, and weapons may be the most challenging aspect of degrading adversary networks inside A2/AD envelopes. If U.S. decoy and jamming operations are not well coordinated across geographic areas, enemy forces could determine the locations of U.S. forces by comparing in real-time information provided by multiple sensors. Communications links between many terrestrial sensors could be hard-wired landlines or fiber optic cables that are far less vulnerable to jamming and deception. In this case, U.S. forces would have to counter individual threat sensors. And although wireless communication links between mobile enemy platforms, relocatable sensors and weapons, and command centers may be vulnerable, attacking them will require U.S. low-power EM warfare systems to first position themselves in close proximity to their targets. In this case, it would make sense to use unmanned systems, particularly unmanned undersea systems, for communication interdiction operations in contested areas.

Protecting Penetrating U.S. Forces from Detection and Attack

U.S. forces that penetrate A2/AD areas will still need to avoid detection by enemy short-range sensors and weapon seekers.[34] Even if the operational concepts described above are effective against A2/AD sensors, adversaries could deploy ships and aircraft with short-range passive ES, radar, or IR sensors to search for U.S. forces. They could also launch guided weapons at every possible target to gain information through weapon telemetry. In this case, self-protection capabilities with the following characteristics could increase the survivability of U.S. platforms:

- To counter enemy long-range passive and short-range active sensors, self-protection systems will need to detect threats and generate effects over a wide frequency range and against RF antennas, IR focal plane arrays, and laser seekers. They should also have LPI/LPD features such as the ability to direct their beams precisely at threat sensors, operate only as long as necessary, and be able to quickly reduce their emissions to the minimum power level needed.

- Penetrating forces will need to increase their use of deployable decoys that are capable of coordinating their emissions with other EM warfare capabilities. Current U.S. decoys such as the Miniature Air-launched Decoy (MALD), aircraft-towed ALE-50, and rocket-propelled Mk-53 Nulka ship-launched countermeasure do not yet have the needed level of EMS agility and connectivity to create a convincing and persistent deception against emerging passive sensors.

- Countermeasure control systems will need the ability to compensate for intelligent adversary sensors and seekers that change frequencies, waveforms, and between passive and active modes to avoid U.S. countermeasures. This will require a greater degree of adaptability than in today's self-protection jammers.

34 Improving air and missile defenses will drive attackers to use more weapons to overwhelm the adversary's defensive capacity. This dynamic, also known as a "salvo competition," is described in detail in Mark Gunzinger and Bryan Clark, *Sustaining America's Precision Strike Advantage* (Washington, DC: Center for Strategic and Budgetary Assessments, 2015).

The following example illustrates how a combination of low-observable manned and unmanned platforms, expendable jammers, and decoys could increase the survivability of penetrating strike forces in the emerging low-to-no power phase of EM warfare.

Illustration: Strike operations in the low-to-no power EM warfare regime

Four clusters of air defenses and associated active and passive sensors shown in Figure 15 (in red) are postured to counter a U.S. strike force. To defeat enemy sensors and gain access to the contested area U.S. forces could use jammers and decoys launched from the strike aircraft, or more effectively, deploy them from other platforms. For example, Figure 15 illustrates how submarines and unmanned underwater vehicles (UUVs) could take advantage of their ability to close in on target areas to launch large numbers of small, short-range decoys and jammers that disrupt enemy air defenses. Further, this use of UUVs would not necessarily require the degree of human-in-the-loop command and control needed for weapon launches and would be a good application of their payload capacity.

After penetrating contested areas, U.S. surveillance and strike systems could use decoys and low-power stand-in jammers on unmanned vehicles or expendable payloads to obscure their true locations and create false targets for enemy air defense systems. Expendable payloads could stimulate inactive enemy SAM systems, causing their fire control radars to activate and providing an opportunity for U.S. anti-radiation homing weapons to attack them.

FIGURE 15: NEW APPROACHES FOR U.S. STRIKE OPERATIONS IN CONTESTED AREAS

High-power electromagnetic energy weapons launched by standoff and penetrating platforms could also help defeat enemy air defenses. Technologies are sufficiently mature to develop expendable weapons that use high power microwave (HPM) energy to disrupt or damage specific components in sensor and communication systems.[35] Within the next five years, DoD could field cruise missiles with HPM warheads that could be launched from standoff distances to attack electronics-based A2/AD systems.[36]

Once strikes begin, it is likely that enemies will attempt to intercept incoming PGMs. The following concepts could increase the probability that these PGMs will arrive at their designated targets:[37]

- **Collaborative weapons operations.** U.S. strike forces could use networked PGMs that are capable of autonomously coordinating their attacks on a set of targets. These weapons could have the ability to pass target information and adaptively retarget while inflight to compensate for intercepted weapons.
- **Weapons with improved survivability.** Signature reduction features such as edge designs and affordable radar absorbing coatings can improve the survivability of individual PGMs, including relatively inexpensive weapons such as Small Diameter Bombs (SDBs) and Joint Standoff Weapons (JSOWs). Further, PGMs could be equipped with small RF and IR jammers that confuse SAM seekers or increase the general EMS noise around a PGM salvo, improving its survivability.
- **Tunneling operations.** Enemy short-range point defenses such as rapid-fire guns and short-range missiles that are co-located with a target are difficult for attackers to circumvent. PGM survivability against these threats could be improved if strike salvos include small, expendable decoys that emit EM energy to simulate a larger strike weapon. These decoys would attract defensive attacks, helping to create a temporary "tunnel" of less-defended airspace close to targets.

Figure 16 illustrates similar concepts that could improve the survivability of surface-to-surface strikes. In this example, the objective is to conduct an assault with Special Operations Forces (SOF) on an enemy headquarters located to the northeast, preceded by a surface-to-surface missile attack. A U.S. battalion located to the south launches decoys that simulate aircraft to draw the attention of enemy air and missile defenses, keeping them engaged by U.S. decoys and jammers for the duration of the attack. To the north, unmanned aerial vehicles (UAVs)

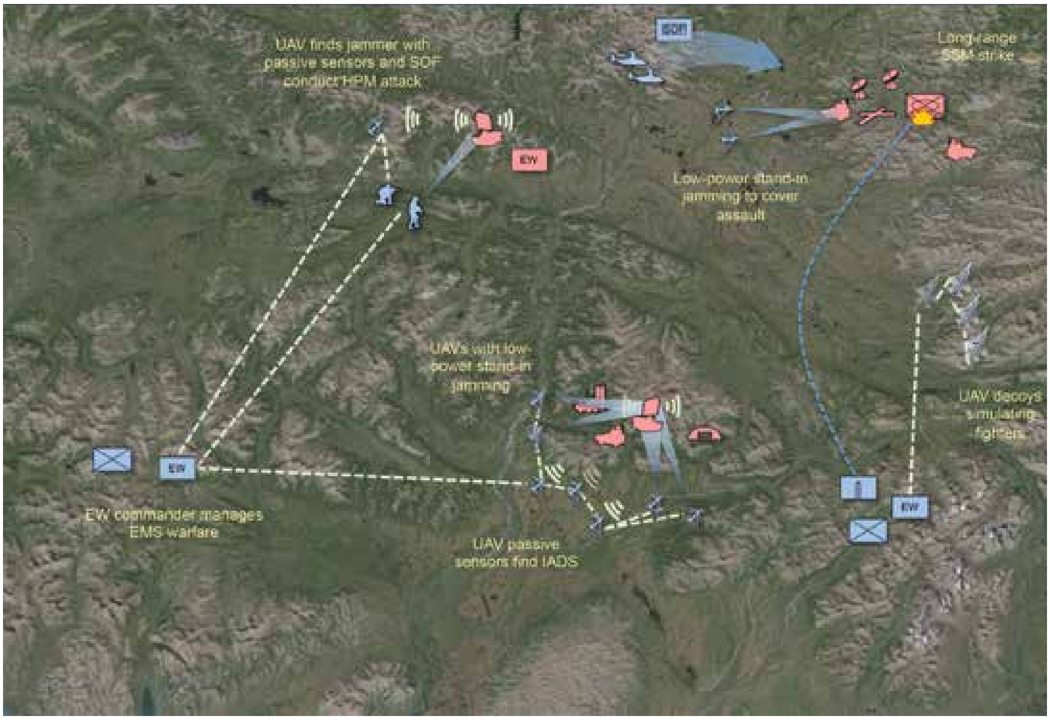
35 HPM weapons will have a greater effect if details are known about the design and vulnerabilities of enemy networks. See U.S. Air Force, "Fact Sheet: High Power Microwave Weapons," available at http://www.de.afrl.af.mil/pa/factsheets.

36 "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.

37 For additional information on these concepts, see Gunzinger and Clark, *Sustaining America's Precision Strike Advantage,* pp. 43–55.

with low-power jammers deployed by the SOF unit help mask insertion of its assault team, and a crew-launched UAV with an HPM weapon finds and attacks enemy jammers.

FIGURE 16: NEW APPROACHES FOR U.S. GROUND ASSAULTS IN CONTESTED AREAS



A Final Word on the Need for New Operational Concepts

DoD uses operational concepts as starting points to assess its future capability requirements.[38] Previous U.S. military leap ahead initiatives for EM warfare began with the development of new operating concepts that helped it to create advantages that have, at least in the case of stealth, lasted for more than 25 years. DoD now has an opportunity to repeat this process by creating a new generation of operational concepts and funding the technologies and capabilities needed to execute them. As will be discussed in the next chapter, requisite technologies to transition to the next phase of EM warfare are mature or rapidly maturing.

38 Operating concepts can also be used to describe to warfighters, policymakers, and technologists how a particular set of systems or capabilities will be used to accomplish specific military objectives.

CHAPTER 3

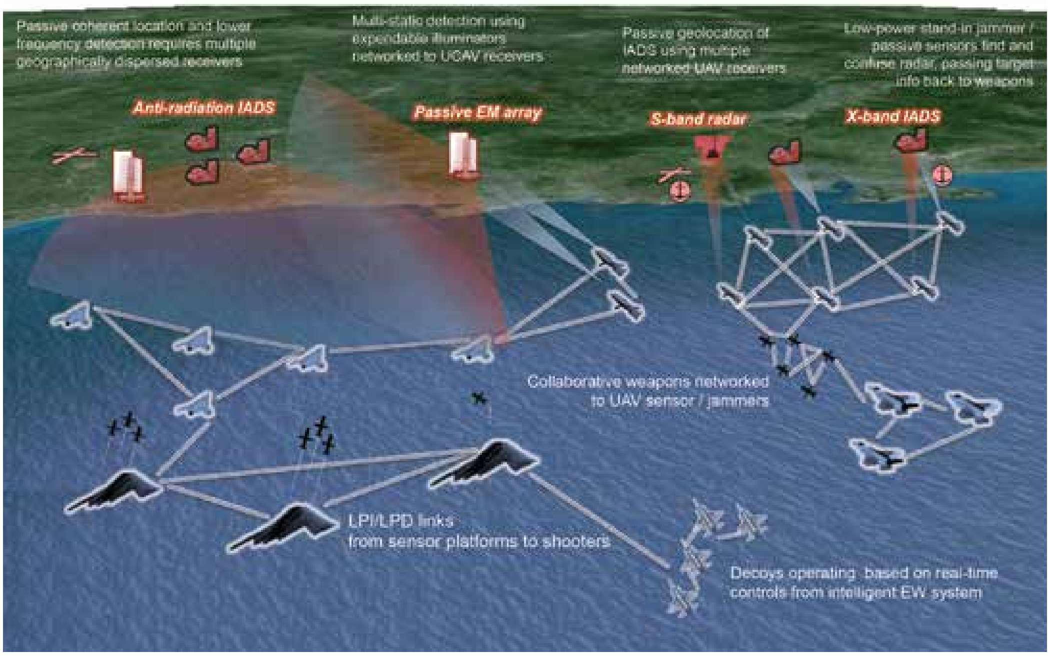
New Technologies and Capabilities

A shift to the third phase of EM warfare would require the U.S. military to expand and evolve its portfolio of EMS capabilities. In particular, a new generation of EM warfare systems that are networked, agile, small, multifunctional, and adaptive will be needed. This chapter assesses these capability attributes and describes how they could help future U.S. power projection forces to operate effectively in the low-to-no power EM warfare regime.

Networked

Operational concepts summarized in Chapter 2 require sensors and countermeasures to effectively network with each other and with geographically dispersed shooters as well as command and control centers. Networking platforms and sensors with decoys and jammers would help create a shared understanding of the threat and allow them to coordinate their movements and emissions to improve the survivability of penetrating platforms. As shown in Figure 17, techniques such as using multistatic radars, passive geolocation, and passive coherent detection all rely on inputs from multiple sensors.

FIGURE 17: NETWORKING EM WARFARE

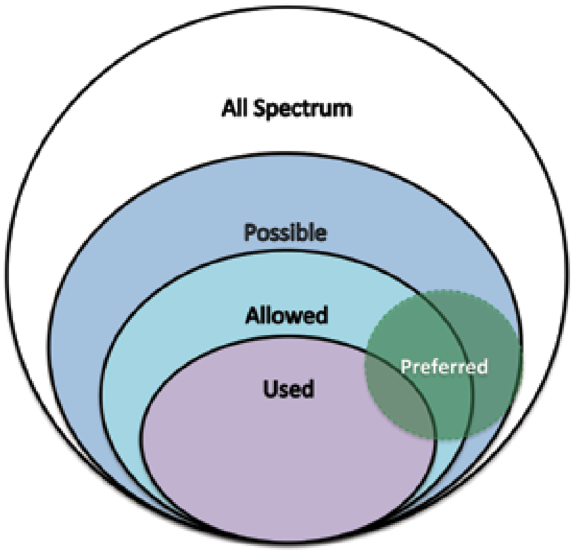


Networked EM warfare operations depend on two key technical elements: control systems that manage and coordinate the operations of distributed participants and secure LPI/LPD datalinks that connect friendly forces and capabilities operating in contested areas. DoD and industry are pursuing several programs to command and control distributed EM warfare systems, including the Office of Naval Research's NEMESIS and Future Joint Counter-Radio Controlled Improvised Explosive Device Electronic Warfare (JCREW) programs, which could be incorporated into the joint force. DoD also has several high-bandwidth LPI/LPD communication links in development or recently fielded, such as the F-35's Multifunction Advanced Data Link (MADL), the F-22's Intra-flight Data Link (IFDL), and the E-2D's Tactical Targeting Network Technology (TTNT). The problem with incorporating LPI/LPD communication links into a broader spectrum of DoD's forces is not as much a lack of technology as it is a lack of joint standards. DoD will need to provide system developers consistent specifications for datalinks that will enable new operating concepts for EM warfare and avoid the development of new secure datalinks which could further complicate the U.S. military's communications interoperability challenges.

Agile

Future U.S. EM warfare systems should be able to change their frequencies, beam direction, pattern, power level, and timing in order to operate effectively and counter enemy EMS operations. Spectral or frequency agility could give U.S. sensors and communication systems the ability to maneuver around enemy passive detection systems by operating in areas of the EMS that are not monitored by enemies or are more effective for current environmental conditions. As Figure 18 illustrates, only a small part of the entire frequency spectrum is technically and legally available for U.S. forces to use in peacetime. Limiting U.S. sensors and communications to these parts of the spectrum can give an edge to enemy EMS forces searching for them. Future U.S. systems that can maneuver across a larger part of the EMS would increase the time needed for enemies to find, jam, decoy, or otherwise counter them.

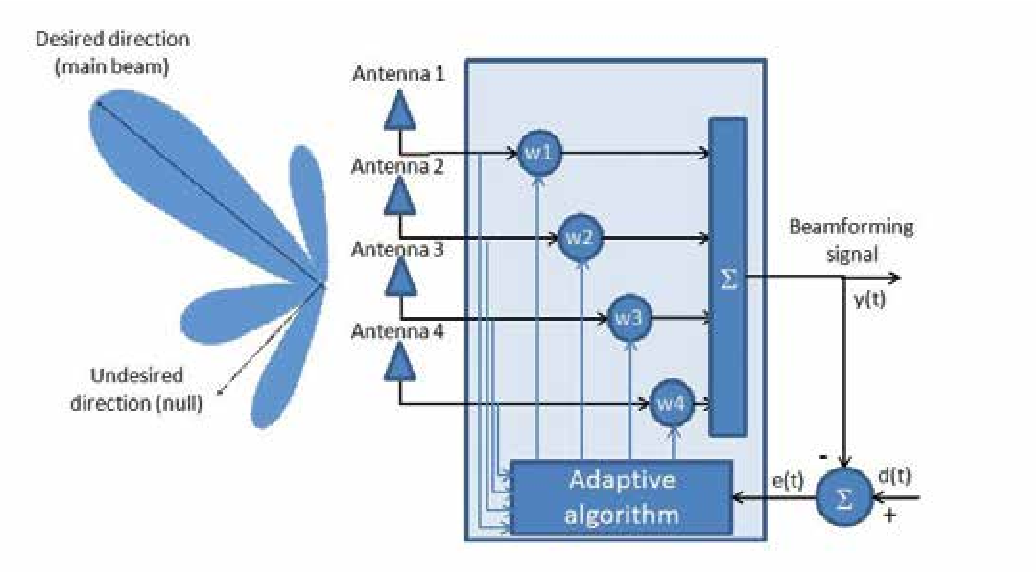
FIGURE 18: SPECTRAL AGILITY



Spectral agility is similarly important for U.S. countermeasure capabilities that must chase increasingly agile enemy sensor or communication systems. The need for increased agility in the IR region of the EMS is of particular concern. Most contemporary IR countermeasures are focused on countering short-range seekers on IR-based missiles. Future IR countermeasure systems will need to be effective against long-range sensors in the lower frequencies of the IR spectrum, especially as new focal plane sensor technologies and greater computer processing power improve the precision and detection range of passive IR sensors.

Agility can also reduce the probability that enemy passive sensors will detect U.S. active sensors, communications, and countermeasures. DoD is beginning to incorporate features that enable EM warfare systems to change the size, shape, and direction of their beams as shown in Figure 19. U.S. sensor and communication systems should also have the ability to change their operating patterns to deny opponents opportunities to intercept, classify, and exploit a predictable series of signals. Sensors or communication systems that are able to adjust their power to the minimum needed for an operation can reduce their risk of being exploited by the enemy.

FIGURE 19: SPATIAL AGILITY



DoD is fielding several systems that use AESA technology to increase their RF agility. AESA systems consist of scalable arrays of hundreds to thousands of small transmit/receive modules that are electronically controlled by a computer processor. This enables an AESA system to scan areas without using a rotating antenna, create multiple beams of variable size and power, and operate across a wider range of frequencies than older systems whose physical construction constrains their spectral, temporal, or spatial agility.

AESA systems are used in the F-22 APG-77 radar and F-35 APG-81 radar, and they will be part of new systems such as the AN/SPY-6 Air and Missile Defense Radar (AMDR), the Next Generation Jammer for the E/A-18G Growler, and the Surface EW Improvement Program (SEWIP) upgrade of the SLQ-32 shipboard EW system (see Figure 20). AESA systems can be small and inexpensive enough to be payloads on expendable missiles and small UAVs, and they can be placed in numerous locations on larger manned or unmanned platforms. With gallium nitride (GaN) amplifier technology, AESA arrays can generate high gains for active and passive systems which enable greater power agility and improve their passive sensitivity. If networked, these distributed arrays as a whole could transmit and receive in multiple directions and across a wide band of frequencies while simultaneously coordinating their operations to respond to enemy transmissions.

FIGURE 20: NEXT GENERATION JAMMER AND APG-81 RADAR

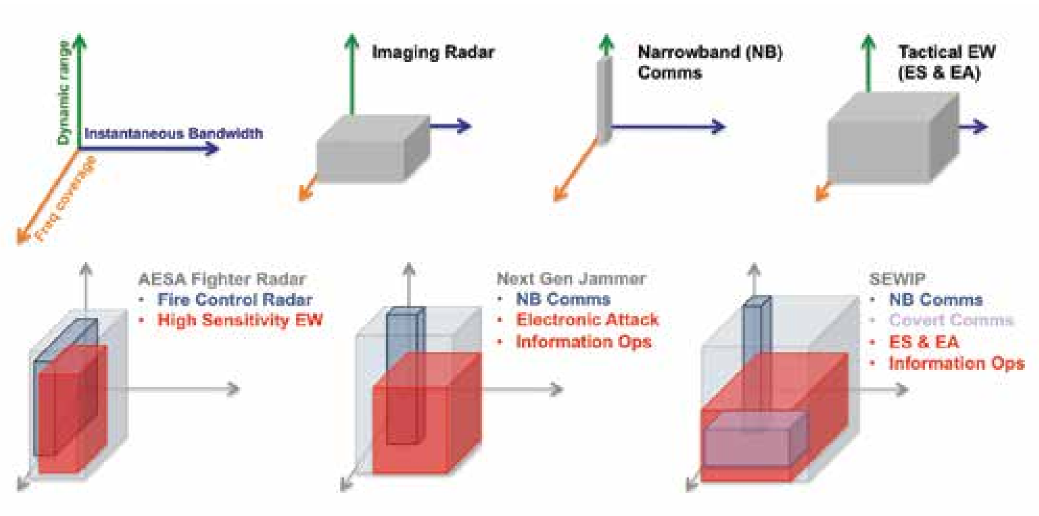
Finally, EMS capabilities that can maneuver in space, frequency, and time would improve the U.S. military's ability to share the spectrum with civilian users. The EMS is becoming increasingly congested as new mobile communication and sensing technologies become commercially available. The growing need for commercial bandwidth is encroaching on areas of the EMS used by the military. EMS agility would help commercial and military users to develop procedures and automated controls that deconflict their emissions in time and space.

Multifunctional

The operational concepts illustrated in Chapter 2 would require almost every U.S. platform, payload, and vehicle in the future battlespace to be part of a network for EM warfare. Achieving the needed amount of flexibility and geographic and spectral coverage would be a challenging task for DoD's current single-mission radios, radars, and jammers. Equipped with single-mission capabilities, a platform would need three or more separate systems to communicate, conduct passive sensing, and conduct noise jamming operations. A second approach would be to operate separate platforms for each function. Magnified across the force, either approach would be complex, costly, and probably unsustainable.

A third approach would be to develop individual EM warfare systems that are each able to communicate, sense, jam, decoy, or illuminate targets. This would provide capabilities needed by the future force at much less cost. This requires new technology because different EM warfare functions require different combinations of frequency, dynamic or power range, and bandwidth. As shown in Figure 21, a radio requires high bandwidth but not necessarily broad frequency coverage, while a radar requires wide frequency coverage but not necessarily large dynamic range. Because they are wideband transmitters and receivers, modern AESA systems, for example, can perform multiple functions in the RF spectrum—in most cases simultaneously.[39] To be both a radio and a radar, an AESA-equipped weapon system would need a balance of these characteristics.

FIGURE 21: CHARACTERISTICS NEEDED IN VARIOUS EM WARFARE SYSTEMS



It is also possible to use multifunction focal plane arrays that operate in the IR, visual, or UV regions of the EMS. New semiconductor technologies are enabling development of systems with focal plane arrays that can detect signals across wider frequency ranges, allowing them to perform as passive sensors *and* communications receivers. Combined with low-power lasers or light-emitting diodes (LEDs), these systems could also provide LPI/LPD communications and act as multistatic IR/UV sensors.[40]

In addition to expanding the operating characteristics of EM warfare systems, DoD will need to develop and field common multifunction controllers. Today's processors and signal generators were often designed to control a specific single mission system even though the system's array would support different EM warfare missions. The lack of multifunction controllers is a major reason explaining why current EM systems are not multifunctional. These controllers are now emerging from industry research and from government efforts such as the DARPA ReACT program.

39 Lisha Zhang, Zhaojun Liu, Wenpo Ma, Shaofan Tang, and Bin Hu, "An Infrared Remote Sensor with High Integration and Multi-Spectral Bands," *Proceedings of SPIE,* November 18, 2014; and Liwen Sang, Meiyong Liao, and Masatomo Sumiya, "A Comprehensive Review of Semiconductor Ultraviolet Photodetectors: From Thin Film to One-Dimensional Nanostructures," *Sensors,* August 2013, pp. 10482–10518.

40 A. Dubok, A. Al-Rawi, M.H.A.J. Herben, and A. B. Smolders, "Fundamental Challenges for Wideband Antenna Elements in Focal-Plane Arrays," Antennas and Propagation (EuCAP), 9th European Conference, Conference Paper, April 13, 2015; and S. Cote, "Naval Multi-Function Radar," *Aerospace and Electronic Systems Magazine,* IEEE, 26, No.9, September 1, 2011, pp. 34–40.

Small

Operating concepts in Chapter 2 suggest using small, expendable unmanned aircraft and powered payloads for multistatic and passive sensing; low-power, stand-in jamming; and decoy operations in contested areas. Smaller EM arrays could also allow larger manned and unmanned platforms to have more EMS apertures, increasing their transmission and reception coverage. Given distributed arrays, a single UAV could launch a missile that illuminates a target with an IR laser, passively receive the reflected IR energy using one array, and simultaneously use a directional RF datalink from another array to communicate with manned platforms prepared to strike the illuminated target.

Small EM arrays are now carried by towed decoys, MALDs, F-22s, F-35s, and self-protection jammers. These systems are still relatively expensive, and they and their controllers are not “commoditized” to be produced in the quantities needed for a large EM warfare network. To take full advantage of the opportunities possible with agile, networked, multifunction capabilities, future EM warfare capabilities should be much smaller and less expensive than today’s systems.

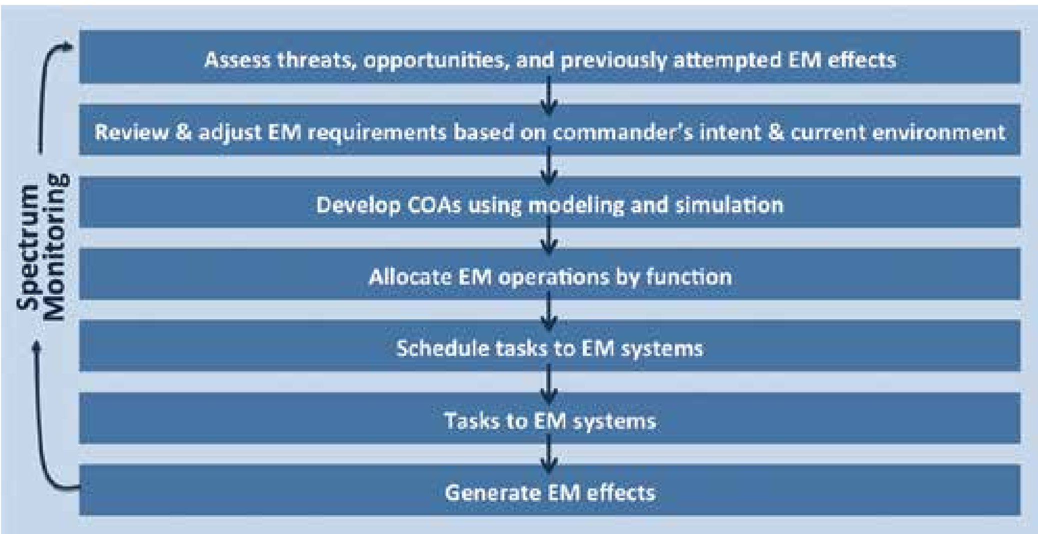
FIGURE 22: TOWED DECOY AND MINIATURE AIR-LAUNCHED DECOY

Adaptive or Cognitive

Agile, multifunction, and networked EM warfare capabilities should be more adaptive if they are to reach their full potential. Adaptive or cognitive systems are different than the automatic functionalities that are now common in radios, jammers, radars, or decoys. For instance, automated systems have the ability to shift their frequencies across a narrow range to find a clear part of the spectrum (for a radio) or to find a threat sensor (for a decoy). They can also respond to threats with pre-planned countermeasures such as jamming or shaping their signals to counter a recognized enemy radar or jammer. DRFM jamming is a recent example of automation. Today’s automated EM warfare systems are not, however, truly adaptable. They generally cannot recognize or create effects against new threats not already in their threat library or rapidly shift from managing one function to another. They also lack the ability to assess the EMS across a wide frequency range to detect threats and determine opportunities such as open areas of the EMS or enemy communication vulnerabilities.

Technologies for adaptive EM warfare systems in development for more than a decade are now reaching a level of maturity that would allow their integration into new EM warfare systems.[41] Sometimes called "intelligent" or "cognitive" EW programs, adaptive algorithms and hardware are being demonstrated in the Navy's EW Battle Management (EWBM) and DARPA's BLADE programs, as well as in several internal industry-funded projects. Figure 23 describes basic steps these systems take to control adaptive EM warfare operations. They begin by developing an awareness of the EMS environment, which includes measuring the strength and frequency of signals in the EM environment; determining their locations; characterizing them as friendly, threat, or unknown (even if they don't have any recognizable features); and assessing their operating pattern.[42]

FIGURE 23: ADAPTIVE EM WARFARE OPERATIONAL CYCLE



An adaptive EM warfare control system would use its spectrum awareness to determine what actions it should take based on the "commander's intent" provided to it in the form of a list of prioritized tasks. Unlike automated systems, adaptive EM warfare systems will go well beyond generating jamming signals against recognized threat radars or shifting their radio frequencies

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

42 Enabling this analysis requires an understanding of the local meteorological environment and modeling and simulation of how it is likely to affect EMS operations.

to uncontested portions of the spectrum. Adaptive systems will identify threats based on their characteristics, location, and behavior (since many threat systems will not use their normal parameters in wartime) and determine which to address based on their likelihood of detecting or countering friendly forces in the current, local EMS environment. Adaptive systems will then evaluate opportunities for sensing and communication afforded by the enemy's EMS operations and, using modeling and simulation, assess a variety of courses of action (COAs) that both accomplish the most important tasks to counter the enemy's use of the EMS while facilitating those of friendly forces. Adaptive EM warfare controllers will direct tasks to agile and multifunction EM systems participating in its network and then use its spectrum awareness to evaluate the extent of the effects they create on the EM environment and the enemy's EMS behavior.

In summary, while the technologies needed to achieve the shift toward the third phase of the EM warfare competition are mature or rapidly maturing, their fielding has been tentative at best. This is due in large part to a lack of urgency on the part of DoD, its failure to create new operational concepts, define formal requirements, and request funding for agile, networked, and multifunction EMS systems. The fourth chapter of this report expands on these and other barriers that inhibit DoD's progress toward creating a more capable EM warfare force, as well as how it could overcome these barriers. Bottom line, resolving these impediments to progress will require DoD to first recognize that future U.S. power projection forces cannot continue to use high-power, non-LPI/LPD active sensors and countermeasures against capable enemies without accepting undue risk of counterattacks.

CHAPTER 4

Barriers to Implementation

This chapter expands on the major conceptual, organizational, and programmatic barriers that have impeded DoD's progress toward creating the operational concepts and capabilities needed to succeed in the next phase of EM warfare.

Immature Operational Concepts and Requirements

New or updated requirements for EM warfare systems depend on new operational concepts and doctrine that describe how the future force will operate, the capabilities needed to do so, and gaps in the ability of current systems to support the new operational concepts. Over the last year, the Services and Joint Commands have published new concepts that describe principles and organization for operations in the EMS, such as the Army's concept for Cyber Electromagnetic Activities (CEMA), the Navy's concept for Electromagnetic Maneuver Warfare (EMW), the Marine Corps Marine Air Ground Task Force (MAGTF) Information Warfare Group, and the Joint Concept for EMS operations (JEMSO).[43] These concepts reflect a low-to-no power approach to EM warfare. They are, however, very general and do not provide the detail needed to establish requirements for new or adapted EM warfare systems. Without requirements, program managers will not be able to start a new acquisition program or modify an existing one.

The process of developing concepts, translating them into requirements, and developing acquisition programs is guided by three major communities in DoD. Each of these

43 U.S. Army, *Cyber Electromagnetic Activities,* FM 3-38 (Washington, DC: DoD, February 2014), available at http://armypubs.army.mil/doctrine/DR_pubs/dr_a/pdf/fm3_38.pdf; Ted Branch, "Electromagnetic Spectrum Maneuver Warfare," *Navy Live Blog,* October 30, 2013; Joshua Stewart, "Electronic Warfare a Growing Part of Aviation Training," *Marine Corps Times,* April 5, 2015, available at http://www.marinecorpstimes.com/story/military/tech/2015/04/05/electronic-warfare-aviation-training-marine-corps/70829414; and U.S. Joint Staff, *Joint Electromagnetic Spectrum Operations*, Joint Doctrine Note 3-18 (Washington, DC: DoD, 2016), available at https://fas.org/irp/doddir/dod/jdn3_16.pdf.

communities has a role in impeding progress today, but they could contribute to improved fielding of new EM systems in the future:[44]

- **DoD's operational community.** Warfighters in operational units or staffs determine how the force will fight and guide the establishment of new requirements. Operators at training and doctrine development organizations such as the Navy Warfare Development Command and Army Training and Doctrine Command are responsible for developing new operational concepts. In the past, their efforts were often not fully informed of emerging technologies that could significantly change how the joint force operates in the future. Today, these organizations are aware of EM technology developments and closely tied to government research organizations and laboratories, which informed the new concepts described above. The onus now falls to operators on DoD's joint and Service staffs to translate these concepts into new capability requirements by analyzing the gaps in the ability of the current force to execute new concepts against potential adversaries. COCOM staffs could accelerate this process by creating Joint Urgent Operational Needs (JUON) statements that establish critical, near-term requirements for new capabilities.

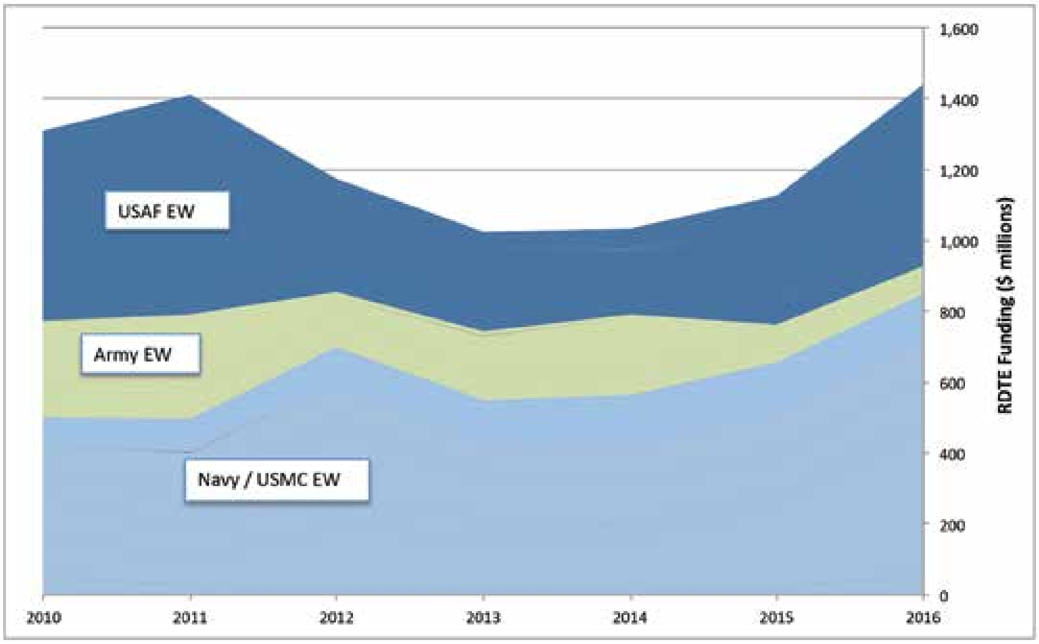
- **Technologists.** Experts dedicated to developing new defense technologies are often excluded from DoD's development of new requirements due to concerns about releasing proprietary information or giving a company or government lab an undue advantage over potential competitors. This sometimes results in requirements that do not incorporate a realistic assessment of the performance new technologies could deliver within a program's anticipated cost and schedule constraints. This can make a program more likely to have trouble transitioning into acquisition or to fail during the development and acquisition process. To accelerate its shift to the third phase of EM warfare, DoD should more fully engage technological experts in requirements development and empower them to work with operators and policymakers to bring new concepts and needed capabilities to fruition.

- **Policymakers.** Civilian officials in DoD, the Executive Office of the President, and members of the House and Senate are responsible for allocating funding for military programs. New operational concepts and requirements would help inform these stakeholders why DoD needs new EM warfare capabilities and how they will be used in the future. The lack of procurement funding for new EM warfare systems indicates remaining disconnect between the DoD's new EM warfare operational concepts and the decision makers who rely on warfighter requirements to allocate resources.

44 These three groups and their role in the technology transition process are described in Richard H. Van Atta et al., *Transformation and Transition: DARPA's Role in Fostering an Emerging Revolution in Military Affairs,* Vol. 1, *Overall Assessment* (Alexandria, VA: Institute for Defense Analyses, 2003), pp. 5–13.

A Continuing Bias Toward Research Instead of Procurement

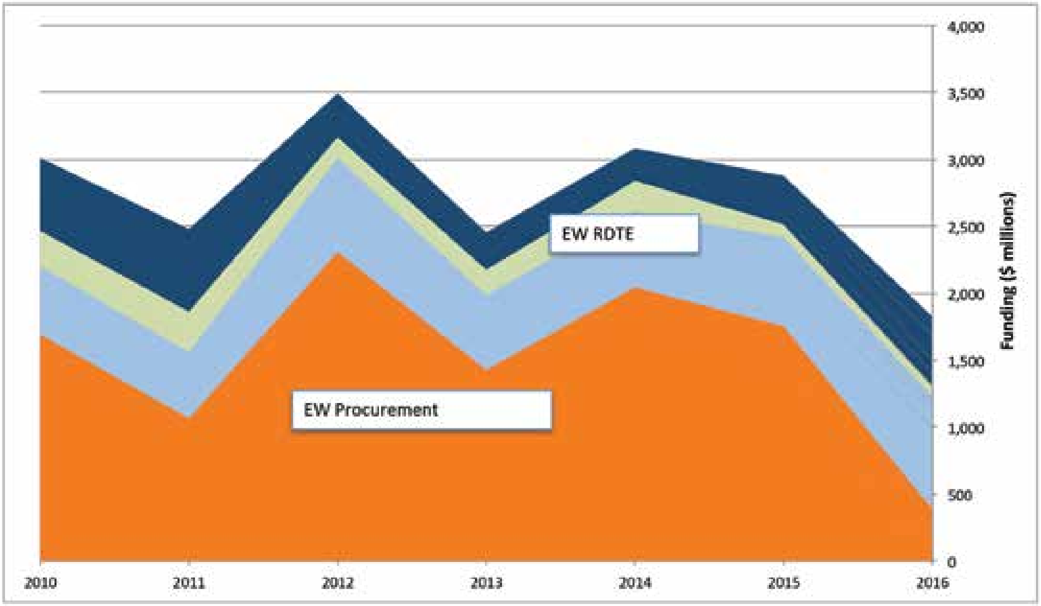
FIGURE 24: DOD SPENDING ON EW RESEARCH AND DEVELOPMENT



The technology community in and outside of the U.S. government has continued to pursue the capabilities needed for the emerging generation of EM warfare operational concepts. As illustrated in Figure 24, research and development funding for EW systems has been robust and will likely increase. The maturity of technologies described in Chapter 3 is in large part the result of these investments. Unfortunately, new EW-related technologies are slow to transition into actual acquisition programs (see Figure 25). In large part, this is due to DoD's failure to translate new EM warfare concepts into requirements. This effort could be aided if DoD were to establish a common vision for EM warfare and a champion to further its implementation. Without a vision, policymakers in the Services and joint staffs do not have the sense of urgency needed to shift funding toward needed EMS capabilities, military operators are not creating operational concepts and requirements that pull new capabilities though DoD's acquisition system, and technologists do not have the support they need to push the products of their research.

Another reason for the bias toward research is risk aversion in the acquisition community, which, as described below, is not organized to exploit new multifunction EM warfare capabilities and is not incentivized to increase the cost and schedule risk of a program to incorporate new EM technologies. In the absence of new requirements, program managers are likely to simply recapitalize their existing programs with new systems that operate in largely the same manner and offer modest improvements over their predecessors.

FIGURE 25: DECLINING FUNDING TO PROCURE EW CAPABILITIES



This situation is improving. Acting on the recommendation of the Defense Science Board (DSB), DoD established an EW Executive Committee in 2015 that is charged with focusing on "EW strategy, acquisition, operational support, and security."[45] The EW EXCOMM published a new EW strategy in January 2017 that directs actions to improve DoD's ability to control and operate in the EMS. The EW strategy is largely focused on EW concepts and capabilities rather than EM warfare more broadly.[46] With the new strategy as a starting point, however, the EW EXCOMM has an opportunity to establish a DoD-wide EM warfare vision and drive the development of operational concepts and requirements that could help U.S. forces to gain enduring advantages in the EMS.

Fractionated Acquisition

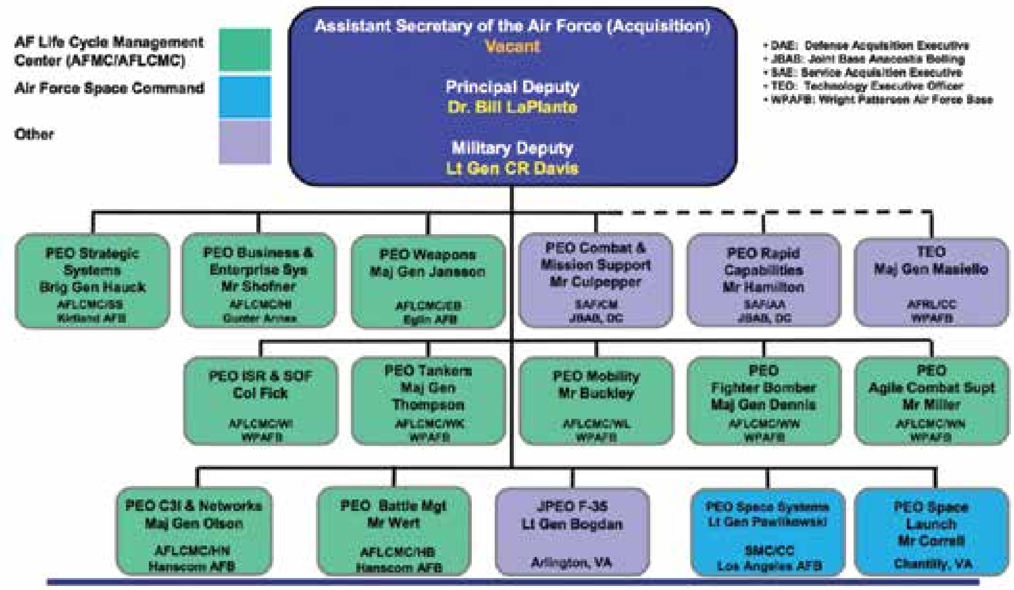
DoD develops and procures most of its new capabilities using a process that relies on program acquisition executives who are organized by types of equipment, rather than by capability areas. For example, there are separate program executive officers (PEO) in each military service for weapons, communication networks, and sensors. In turn, under each PEO there are

45 Megan Eckstein, "Executive Committee to Focus on Strategy, Acquisition," *USNI News,* March 18, 2015, available at http://news.usni.org/2015/03/18/electronic-warfare-executive-committee-to-focus-on-strategy-acquisition.

46 Sean Carberry, "DOD Releases Electronic Warfare Strategy to Stakeholders," *FCW,* June 22, 2017, available at https://fcw.com/articles/2017/06/22/ew-strategy-pentagon-carberry.aspx.

separate program managers for individual systems. Figure 26 illustrates the PEO organization in the U.S. Air Force.[47]

FIGURE 26: AIR FORCE ACQUISITION ORGANIZATION[48]



While this structure promotes learning and continuity between successive programs for similar systems, it does not facilitate the development and acquisition of multifunction systems that can replace several single-mission programs or new capabilities that employ dramatically different operational concepts than their predecessors. The Navy's new SLQ-32 SEWIP EM warfare system is a case in point. SEWIP will be able to use its AESA array as a radio, radar, and passive ES sensor in addition to performing its primary function as a jammer. To fully exploit SEWIP's potential, it should be used for some or even all of these functions. If not, the Navy could procure duplicative systems, making its future ships more complex and more expensive than necessary. Further, if these duplicative EM warfare capabilities are not fully integrated, they could conflict and degrade Navy operations in the EMS.

To achieve this integration, PEOs and program managers overseeing EW systems, radios, radars, and passive sensors will need to coordinate the requirements and schedules for their

47 For more details on the Navy's PEO IWS and PEO C4I organizations, see
http://www.secnav.navy.mil/rda/Pages/ASNRDAOrgChart.aspx;
http://www.secnav.navy.mil/rda/Pages/PEO_IWS.aspx;
http://www.public.navy.mil/spawar/PEOC4I/ProductsServices/Pages/default.aspx;
and Jerry Burroughs, "PEO C4I and PEO Space Overview," AFCEA West Conference, January 29, 2013, available at
http://www.afcea.org/events/west/13/documents/RDML_Burroughs_AFCEAWestPEOC4IKickOffR2_000.pdf.

48 U.S. Air Force, "USAF SAF/AQ overview," available at http://ww3.safaq.hq.af.mil/factsheets/index.asp.

different programs. This, however, would increase risk for each of the participating programs. Another approach would be to organize program managers by capability areas instead of specific functionalities. Instead of having separate PEOs for networks, radars and jammers, and weapons, the Air Force could have PEOs for capability areas such as "tactical aircraft EM warfare systems." Although new seams may develop between capability areas, this approach could increase the commonality and interoperability of EMS systems across major platforms.

CHAPTER 5

Conclusion and Recommendations

The U.S. military has an opportunity to establish an enduring advantage in the EMS by widely implementing new operational concepts and fielding capabilities for low-to-no power EM warfare. The following initiatives could accelerate America's transition to the next EM warfare competitive regime.

- **Establish a vision for EM warfare.** The new DoD EW strategy directs action and identifies important capabilities for EW and, to a lesser degree, EM warfare. The strategy should be expanded to describe how U.S. forces will operate and fight in the EMS. Specifically, a vision for EM warfare could direct and prioritize Service and agency efforts to implement low-to-no power EM warfare concepts and capabilities.

- **Mature and implement new operational concepts for EM warfare.** DoD has made good progress toward identifying new low-to-no power approaches to EM warfare through new Service and Joint concepts. These concepts need to be matured and implemented through development of more detailed tactics, techniques, and procedures (TTP) that could be used to guide the development of requirements.

- **Establish requirements for low-to-no power capabilities.** Using recently-developed operational concepts and emerging TTPs, the Services should develop or revise formal requirements to shift DoD acquisition toward capabilities that will be effective in the next phase of the EM warfare competition.

- **Prioritize research and development funding for future EM warfare technologies.** DoD should prioritize its research and development investments to mature technologies that will improve the networking, agility, multifunctionality, miniaturization, and adaptability of its EM warfare systems. The new EW strategy highlighted these technology areas, and DoD needs to create the conditions for them to transition into acquisition programs.

- **Integrate DoD's acquisition of EM warfare systems.** The Services should promote cooperation between and eventually merge multiple executive and management offices that develop and procure new EM warfare systems. This would help advance the fielding of more agile, multifunction capabilities that will be essential to future EM warfare. The upcoming restructuring of the DoD acquisition organization provides an opportunity to support these changes as it separates R&D offices from those focused on acquisition and sustainment.[49]

- **Refine DoD's acquisition process for EM warfare systems.** DoD is slow to field new EM warfare systems in large part due to the lack of formal requirements that are used to begin acquisition programs. Using new operational concepts, Services should develop capability requirements that will shift DoD's acquisition priorities toward systems that will be effective in the next phase of the EM warfare competition. To aid this process, DoD should take advantage of new authorities provided by Congress to streamline DoD's requirements development process; reduce cumbersome, often time-consuming and redundant analyses for new requirements; and increasingly base EM warfare requirements on the capabilities demonstrated by new prototype systems.[50] For example, the analysis required to establish specifications for new payloads such as weapons, sensors, and communication systems that will be replaced or upgraded in several years could be much less extensive than that required for a new manned platform that will remain largely the same for decades.

- **Demonstrate the potential of new EM warfare capabilities.** The Services and Combatant Commands should expand the number and scope of experiments in new EM warfare concepts, particularly concepts featuring new capabilities that have not yet transitioned to acquisition programs. The results of these experiments could be directly used to establish requirements for new programs, rather than simply being the starting point for a new series is time-consuming and expensive analysis. The Services have begun adding more EM warfare events to exercises, as evidenced most recently in Exercise Northern Edge, a predominantly Air Force and Navy exercise testing new air concepts and TTPs in Alaska.[51]

In conclusion, the U.S. military gained significant advantages over its enemies in two previous shifts in the EMS competition: with radar and active countermeasures during World War II

49 Aaron Mehta, "This is the Pentagon's New Acquisition Structure," *Defense News*, August 2, 2017, available at https://www.defensenews.com/breaking-news/2017/08/02/this-is-the-pentagons-new-acquisition-structure/.

50 Otto Kreisher, "HASC Chair Thornberry Introduces Latest Defense Acquisition Reform Plan," *USNI News,* May 18, 2017, available at https://news.usni.org/2017/05/18/thornberry-introduces-defense-acquisition-reform-plan.

51 Laura Gauna, "Electronic Warfare in Northern Edge 2017," *Defense Video Imagery Distribution System (DVIDS)*, May 8, 2017, available at https://www.dvidshub.net/video/524176/electronic-warfare-northern-edge-17.

and with stealth technologies in the final years of the Cold War. Our Nation's warfighters have another such opportunity today. By adopting a new approach to EM warfare and developing low-to-no power operational concepts and capabilities, the U.S. military could once again gain a significant edge over its future opponents. A failure to do so, however, could put America at risk of losing the battle for the airwaves.

LIST OF ACRONYMS

A2/AD	anti-access/area denial
AESA	active electronically scanned array
AMDR	Air and Missile Defense Radar
ASCM	anti-ship cruise missile
ATB	Advanced Technology Bomber
ATF	Advanced Tactical Fighter
AWACS	Airborne Warning and Control System
CCM	counter-countermeasures
CEC	Cooperative Engagement Capability
COA	courses of action
COCOM	Combatant Commands
CSBA	Center for Strategic and Budgetary Assessments
DARPA	Defense Advanced Research Projects Agency
DE	directed energy
DF	direction-finding
DoD	Department of Defense
DRFM	Digital Radio Frequency Memory
DSB	Defense Science Board
EA	electronic attack
ELINT	electronic intelligence
EM	electromagnetic
EMCON	emissions control
EMS	electromagnetic spectrum
EO	electro-optical
EO/IR	electro-optical/infrared
EP	electronic protection
ERP	effective radiated power
ES	electronic warfare support
ESM	electronic support measure
EW	electronic warfare
EWBM	Electronic Warfare Battle Management
EXCOM	executive committee
HF	high frequency
IFDL	Intra-flight Data Link

LIST OF ACRONYMS

IR	infrared
IRCM	infrared countermeasure
IRST	infrared search and track
JCREW	Joint Counter-Radio Controlled Improvised Explosive Device Electronic Warfare
JSOW	Joint Standoff Weapon
JSTARS	Joint Surveillance Target Attack Radars System
JUON	Joint Urgent Operational Needs
LED	light-emitting diode
LIDAR	Light Detection and Ranging
LPD	low probability of detection
LPI	low probability of intercept
MADL	Multifunction Advanced Data Link
MALD	Miniature Air-launched Decoy
NIFC	Naval Integrated Fire Control
PEO	program executive officer
PGM	precision guided munitions
QDR	Quadrennial Defense Review
RAF	Royal Air Force
RF	radio frequency
SAM	surface-to-air missile
SDB	Small Diameter Bomb
SEWIP	Surface Electronic Warfare Improvement Program
SM	Standard Missile
SOF	Special Operations Forces
TTNT	Tactical Targeting Network Technology
TTP	tactics, techniques, and procedures
UAV	unmanned aerial vehicle
UUV	unmanned underwater vehicle
UV	ultraviolet
VHF	very high frequency
WWI	World War I
WWII	World War II

CSBA
Center for Strategic and Budgetary Assessments

1667 K Street, NW, Suite 900
Washington, DC 20006
Tel. 202-331-7990 • Fax 202-331-8019
www.csbaonline.org