Air and Missile Defense: Transformations for 21st-Century Warfighting

Conrad J. Grant and Matthew Montoya

ABSTRACT

At the turn of the century, air and missile defense (AMD) warfighting challenges had become increasingly complex, requiring defensive systems to be more capable, resilient, robust, and able to fulfill multiple missions. In response to these challenges, the AMD community made significant advances in the use of multispectrum and multilayered engagement systems, as well as space systems, and cooperation with partners. The transformation of AMD capabilities during the early 21st century pushed the edges of technology integration, operational utility, and coordination of complex global systems of systems. At the forefront of these advances, the Johns Hopkins University Applied Physics Laboratory (APL) has provided game-changing thought leadership, capability innovations, and timely, pragmatic solutions. This article describes some of these transformative capabilities and is dedicated to the APL Air and Missile Defense Sector staff members who contributed to them.

THE TURN OF THE CENTURY: FOUNDATIONAL AIR AND MISSILE DEFENSE WARFIGHTING CAPABILITIES

The US Navy's air and missile defense (AMD) capabilities at the turn of the century relied on solid foundational elements, many of which derived from initial concepts developed by APL staff members and later from rigorous systems engineering performed by APL staff members. The hallmark of APL's contributions was the development of close working relationships with government and industry, enabling delivery of significant capabilities to counter the advance of air and missile threats.

These foundational warfighting capabilities became the backbone of 20th-century AMD and enabled the US Navy to counter a host of evolving threats. Capabilities included phased-array radars to handle multiaxis threats; integrated combat system decision aids to help reduce engagement timelines; complex missile systems to counter more challenging air and ballistic missiles; and integrated combat systems to coordinate the planning, detection, control, and engagement functions for synchronized fire control solutions.

During this period of foundational AMD development, APL created seminal capability concepts for the Standard Missile, Aegis, and Ship-Self Defense System (SSDS) combat systems, as well as for the SPY-1 radar system. Working as either a technical direction agent or a trusted agent for the government team, APL led the way in development of innovative algorithms; advanced radar concepts; complex multisensor solutions; open-architecture approaches; and integrated missile and combat system solutions.

During the latter part of the 20th century, APL led the way to network these individual combat and sensor systems to enhance situational awareness of the battlespace, provide multisensor and multispectral threat pictures, and form the foundation for extended engagements and fire control solutions using nonorganic sensors. Leading the innovation, demonstration, and fielding of the Cooperative Engagement Capability (CEC), APL teamed with government and industry partners to provide the warfighter with extended fire-control-quality data at longer ranges, increasing missile engagement battlespace and over-the-horizon capability. This extended engagement capability helped pave the way for 21st-century warfighting and set the stage for transformational 21st-century AMD.

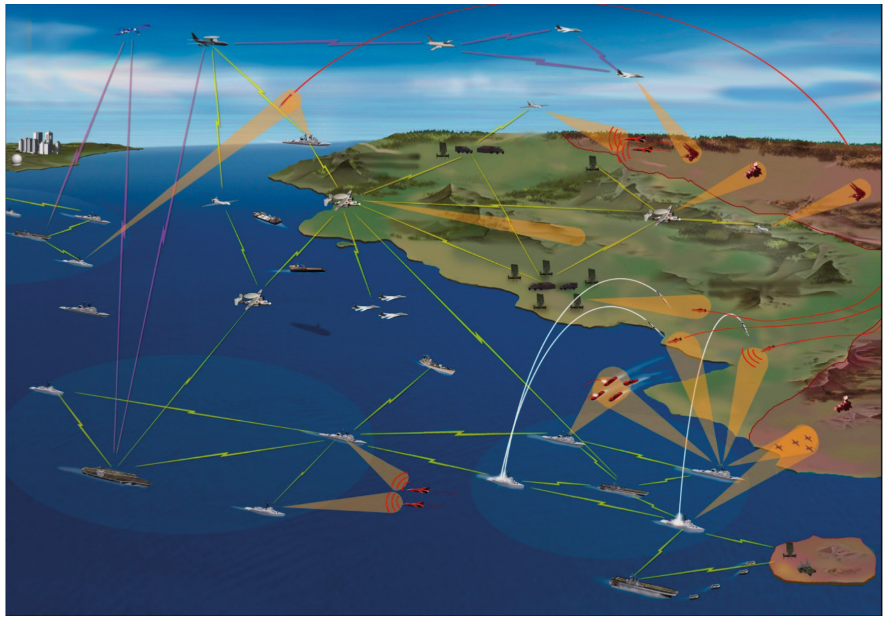

Figure 1. A scenario illustrating the complex AMD mission context. Current and emerging challenges are highlighted, including extended battlespace and multiaxis, multispectral, and multimission threats.

CRITICAL CONTRIBUTIONS TO 21ST-CENTURY WARFIGHTING

Background

Warfighting approaches in the mid-20th century often focused on single-purpose/single-mission systems because enabling technologies were not mature enough to support more complex warfighting needs. Examples of these germinal warfighting capabilities include early radar systems and manually targeted and gravity guided bombs. However, the latter part of the 20th century saw the emergence of enabling technologies that provided the necessary materials, computer processing, software approaches, and systems engineering knowledge to realize more complex warfighting capabilities. These advanced warfighting technologies and capabilities are the foundation for 21st-century warfighting.

As the AMD warfighting mission becomes even more complex, with extended battlespaces and multiaxis, multispectral, and multimission threats, there is greater potential for adversaries to overwhelm our defensive systems. Therefore, warfighters and system developers must team to develop concepts and capabilities that proactively address current and emerging AMD mission challenges. Figure 1 depicts the current and emerging complex AMD mission context. Within this operational tapestry, all the previously mentioned challenges are highlighted: extended battlespace and multiaxis, multispectral, and multimission threats. Over the last

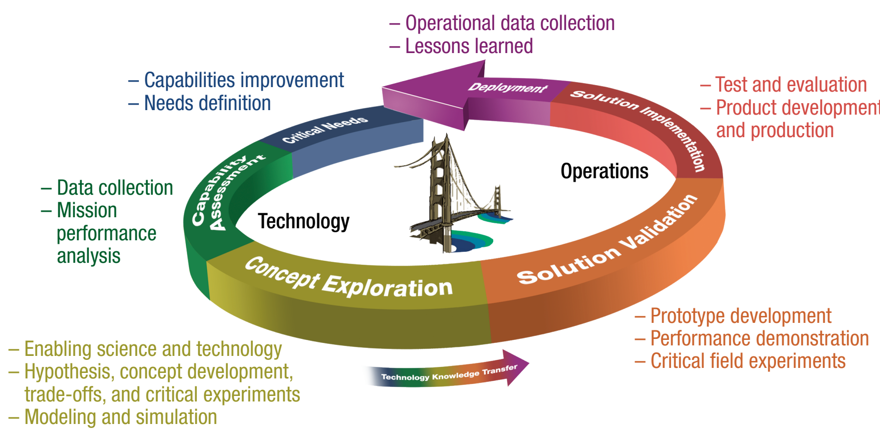

Figure 2. APL's leadership roles across the life cycle of AMD capability development. As a technical direction agent and trusted agent to the government, APL staff members collaborate with government and industry partners to develop, test, and field essential capabilities.

20 years, APL has contributed to developing new and essential capabilities by working with government sponsors and stakeholders as a technical direction agent and trusted agent (Figure 2). APL staff members collaborate with government and industry partners to develop comprehensive and extensible requirements and solutions, as well as to execute rigorous test, evaluation, and operational fielding approaches.

Aegis Weapon System

Many of the new and essential AMD capabilities that have evolved over the last 20 years are built on the foundation of the Aegis Weapon System. Near the end of the 20th century, the Aegis system largely focused on anti-air warfare (AAW) to counter threat aircraft and cruise missiles. However, with the onset of the first Gulf War in the early 1990s, defense against ballistic missile threats (Ballistic Missile Defense, or BMD) became a key driver for the next 20 years of Aegis Weapon System evolution.

As part of a team whose members spanned government, industry, and government laboratories, APL helped develop the new Aegis requirements and capabilities associated with engaging ballistic missile threats in both exo- and endo-atmospheric regions. These essential developments included the ability to counter a threat that flew much higher, farther, and faster than anything Aegis had engaged before. With APL staff members' expertise in all phases (detect, control, and engage) of the fire control loop and the various elements of the Aegis weapon system involved in each of those phases, the Lab played a central role in this development. The Aegis BMD capability was iteratively designed, built, and successfully tested in 33 of 40 test missions of increasing difficulty and complexity. This development, integration, and aggressive test activity led to a robust and versatile system design.

The versatility and effectiveness of the Aegis BMD capability was demonstrated during Burnt Frost (Figure 3) in February 2008. For this important mission, the government, industry, and laboratory team was called on to make rapid changes (in less than 6 weeks) to the weapon system so that it could be used to destroy the errant NROL-21 satellite before it could threaten population centers with a full tank of frozen hydrazine. The initial concept was based on a paper APL staff members had authored. APL engineers did the predictive performance analysis used to verify the capability for the National Security Council and ultimately the president of the United States. APL worked alongside Lockheed Martin and Raytheon to propose and implement the changes to Aegis and Standard Missile. APL tested the final seeker and guidance code for the Standard Missile-3 (SM-3) in its Guidance Systems Evaluation Laboratory (GSEL) before the mission and uncovered

Figure 3. Aegis/SM-3 launch during the Burnt Frost event. This critical operation required the APL, government, and industry team to make rapid modifications to the Aegis BMD System so that it could successfully intercept an errant intelligence satellite and rupture its fuel tank before the satellite reentered Earth's atmosphere.

an error that would have resulted in mission failure had it not been found and fixed.

These new and essential AAW and BMD capabilities were tremendous breakthroughs; however, the need to merge AAW and BMD capabilities into a more robust integrated air and missile defense (IAMD) approach was evident. IAMD is both operationally and programmatically necessary because it provides the ability for a single integrated combat system to flexibly perform multimission operations, giving each ship greater flexibility and utility. IAMD was introduced into Aegis ships through Baseline 9 and will be incorporated in the majority of the Aegis ships in the coming decades.

Another innovation APL contributed was the ability to deploy the Aegis BMD capability in an "ashore" configuration to support the defense of inland assets. This capability is called Aegis Ashore (Figure 4). APL proposed the original concept for Aegis Ashore in a Missile Defense Agency study, helped drive the systems engineering with rigorous requirements analysis, and proceeded in its technical direction agent role through system development,

Figure 4. Aegis Ashore. This configuration supports the defense of inland assets.

integration and test, and fielding of the system. The Aegis Ashore system conducted its first flight test intercept against a live target at the Pacific Missile Range Facility in December 2015. Progressing from concept exploration through fielding of the first capability in Romania in just over 6 years, Aegis Ashore was developed on a very compressed timeline, a noteworthy accomplishment that is a testament to the whole team, including APL.

Standard Missile

Another cornerstone of new and essential US Navy AMD capabilities that has evolved along with the Aegis Weapon System is the family of Standard Missiles (Figure 5). Working closely with the Aegis team, the Standard Missile team develops companion interceptors to work in concert with the evolving Aegis Weapon System. The Standard Missile family currently includes SM-2, SM-6, and SM-3. APL serves as the technical direction agent for the all-up-round (AUR) for all variants of Standard Missile. As the technical direction agent, APL is a community thought leader for the overall strategy, development, and fielding of Standard Missile systems.

SM-2 is the primary defense for Aegis AAW capability as well as for several international combat systems. The SM-2 missile system has evolved during the 21st century to handle more complex and challenging targets and environmental conditions with more stressful endgame requirements, and to include capabilities to communicate with other combat systems and in alternative operating modes. As the 21st century continues, SM-2 will continue to add capabilities that will make it even more flexible to support the increasingly complex and challenging threat environment.

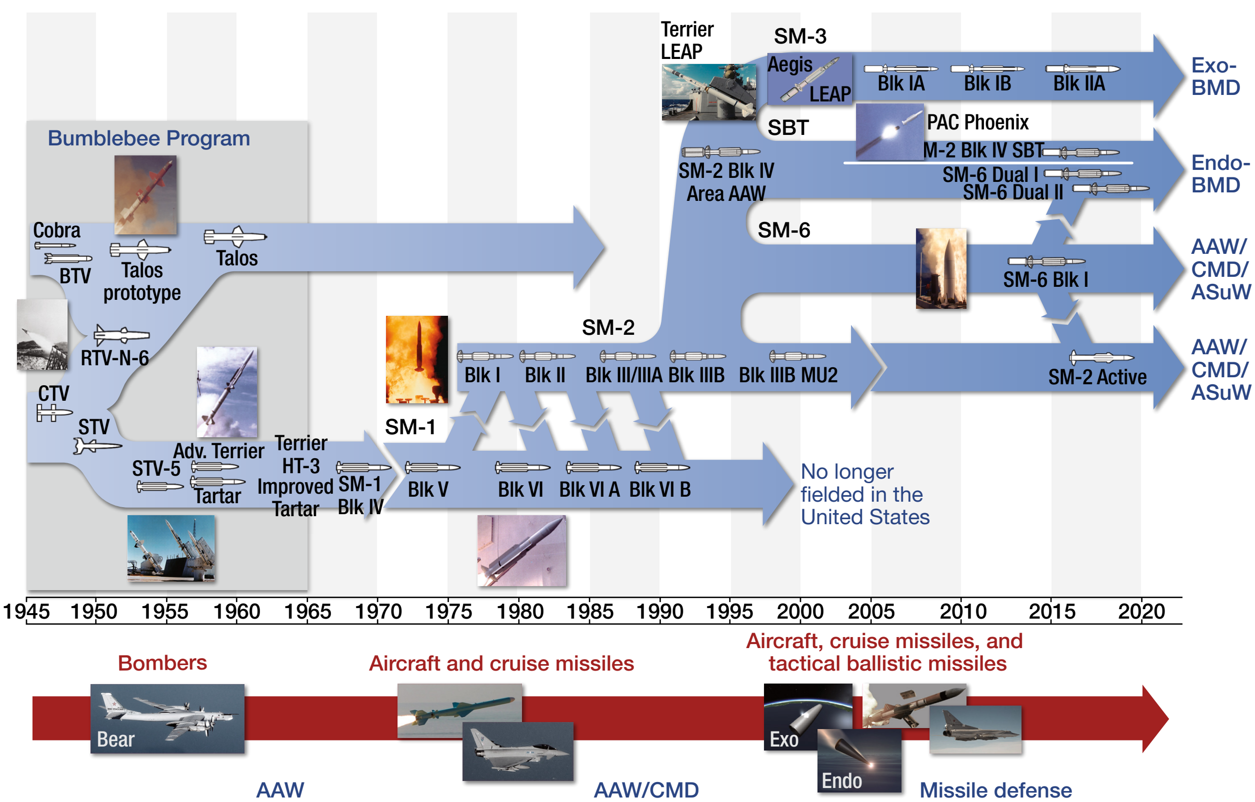

Figure 5. History of the Standard Missile family. The family currently includes SM-2, SM-6, and SM-3. APL is the technical direction agent for the all-up-round (AUR) for all SM variants. Blk, Block; BTV, burner test vehicle; CMD, cruise missile defense; CTV, control test vehicle; ENDO, endo-atmospheric; EXO, exo-atmospheric; LEAP, Lightweight Exo-Atmospheric Projectile; MU2, Maneuverability Upgrade 2; PAC, Pacific; RTV, ramjet test vehicle; SBT, Sea-Based Terminal; STV, supersonic test vehicle; TBM, tactical ballistic missile.

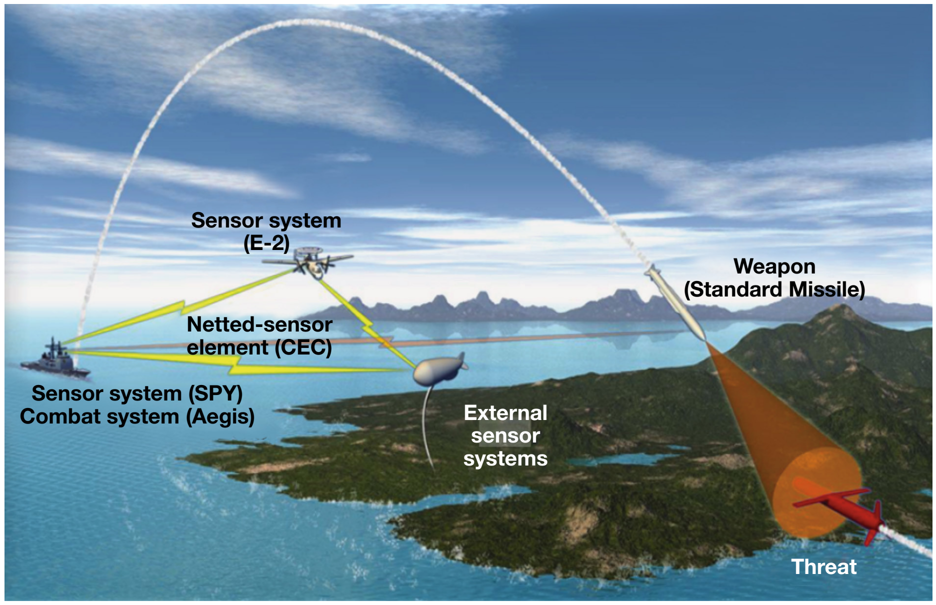

Figure 6. NIFC-CA concept and system elements. This capability extends the engagement battlespace using an elevated sensor system for over-the-horizon situational awareness and fire control engagement capabilities.

The SM-6 missile system was originally conceived to perform AAW missions at extended and over-the-horizon ranges using an active seeker that requires no remote terminal illumination of the target. The extended-range capability increases the Aegis Weapon System's battlespace to counter adversaries before they become an imminent threat to friendly forces. Fortuitously, as the capabilities of the SM-6 weapon began to be fully realized, the concept of using this missile system in multiple missions emerged. For example, the use of SM-6 for BMD missions was demonstrated as part of the Sea-Based Terminal (SBT) program to counter ballistic missile threats in endo-atmospheric regions. More recently, Aegis and SM-6 demonstrated an extended-range surface-to-surface mode for anti-ship missions, and SM-6 is being considered for a number of other uses as well.

The SM-3 evolved over the last two decades to counter threat ballistic missiles in exo-atmospheric regions. The SM-3 missile system tightly coordinates with the Aegis BMD Weapon System to provide robust hit-to-kill capability. Over the last 20 years, the SM-3 missile system has evolved to handle more complex target scenes and more challenging end-game requirements, and to better integrate with the global Ballistic Missile Defense System (BMDS). Most recently, Aegis BMD successfully conducted its first live intercept test of the SM-3 Block IIA missile. The SM-3 Block IIA is a 21-inch-diameter AUR with significant upgrades in the range and complexity of threats that can be engaged. The SM-3 Block IIA is developed cooperatively by the United States and Japan to defeat medium- and intermediate-range ballistic missiles. Moving forward, the US Navy and MDA will continue to rely on SM-3 to provide reliable and highly effective BMD.

Naval Integrated Fire Control

To generate the best possible track picture among a diverse set of operational sensors, extend the blue-force battlespace, and support engagements based on data from remote sensors, APL conceived of and helped develop CEC during the 1980s and 1990s. CEC became operational at the turn of the 21st century and is currently one of the pillars enabling future flexible warfighting paradigms. Because of its inherent capabilities to network fire-control-quality data among force participants, CEC provides the foundation for net-centric and kill-web concepts recently articulated by Navy leadership. APL provided the thought leadership and vision to conceive, develop, integrate, and field this foundational capability that enables the larger Navy approach of Naval Integrated Fire Control – Counter Air (NIFC-CA).

NIFC-CA (Figure 6) capability extends the engagement battlespace using an elevated sensor system for over-the-horizon situational awareness and fire control engagement capabilities. This extended battlespace allows blue forces to intercept incoming threats at greater ranges, adding a significant defense-in-depth layer for emerging warfighter needs. APL was one of the original authors and thought leaders of the NIFC-CA concept, supporting requirements development, early prototyping, element-level testing and demonstrations, and integrated demonstrations of the system of systems. Early evolutions of the NIFC-CA capability have been successfully demonstrated, and APL is currently working with sponsors to evolve and expand on this new and essential capability for use with other platforms and missions.

Ballistic Missile Defense

Beyond the evolution of the Aegis, Standard Missile, and CEC capabilities, APL has been an AMD community driver, thought leader, and capability provider for a number of other sponsors and stakeholders. One

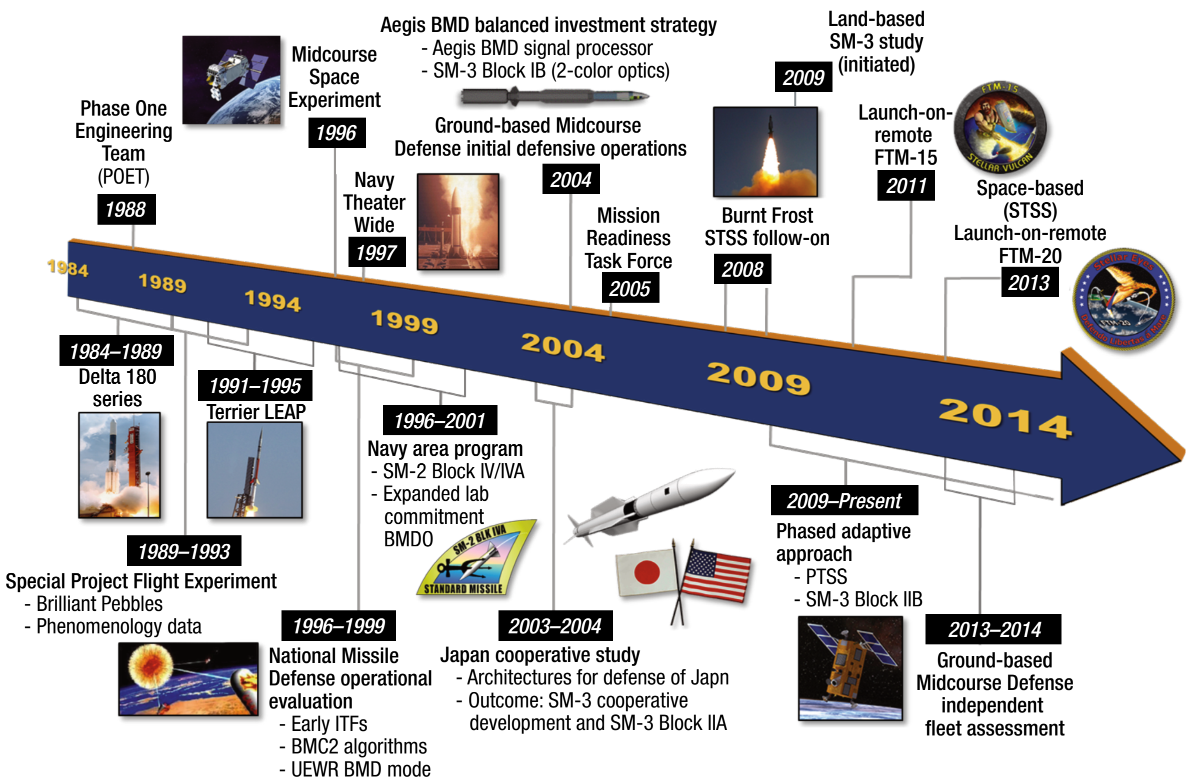

Figure 7. APL's history in BMD. BMC2, battle management command and control; FTM, flight test mission; ITF, interoperability task force; PTSS, Precision Tracking Space System; STSS, Space Tracking Surveillance System; UEWR, Upgraded Early Warning Radar.

of those primary stakeholders is the Missile Defense Agency (MDA). MDA was established in 2002 with the primary mission of architecting, developing, testing, and fielding BMD systems in close coordination with the services (Air Force, Army, and Navy). APL joined as an early technical leader with MDA (and predecessor organizations the Strategic Defense Initiative Office, or SDIO, and the Ballistic Missile Defense Organization, or BMDO) by generating early ballistic missile adversary frameworks along with approaches to counter these adversaries through integrated capability concepts that coordinate BMDS assets. Figure 7 shows APL's history in BMD.

Over the last 20 years, APL has made critical contributions to concept development, requirements development, system engineering, and fielding of the BMDS radar, the TPY-2. The TPY-2 is currently deployed in coordination with several coalition partners. Developing the TPY-2 system allowed MDA to begin realizing its vision for an agile, relocatable, and extensible set of capabilities that could be deployed around the world. In addition, APL has led the way on the use of space systems and associated command and control capabilities for the BMDS and has worked closely with the Ground-based Midcourse Defense (GMD) program to enable a more robust BMD capability for MDA and associated stakeholders.

LOOKING AHEAD: FURTHER TRANSFORMATION OF 21ST-CENTURY AMD CAPABILITIES

The capabilities APL spearheaded during the first part of the new millennium have contributed significantly to achieving needed 21st-century warfighting capabilities. However, as the threat becomes more challenging, there is a need to further advance the state of AMD.

It is clear that the primary challenges posed by air and missile threats will continue to become more difficult to counter. Large coordinated threat raids, sophisticated multimode seekers, precision guidance systems, highly maneuverable airframes, low signatures, and complex countermeasures and decoys are but a few areas of rapid threat evolution. Less traditional air threat capabilities are also emerging, including those associated with small- and medium-size controlled or autonomous air vehicles operated singly or in coordinated swarms. These threats, when combined with more sophisticated electronic warfare and cyber warfare, will create a very complex environment for AMD systems. Finally, the introduction of hypersonics has created a new threat challenge-regime for air defense systems.

Along with these challenges, advances in threat technology offer an opportunity. The potential adversary's use of multiaxis and multispectral systems to stress current AMD capabilities has brought to light the need to develop more robust defenses that work in different spectrums and modes to avoid single-point failures. The use of robust electronic warfare systems, coordinated across ships and aircraft in the force at subwavelength timing, can create effective countermeasures to even the most sophisticated threat seekers when combined with coordinated decoys.

The addition of lasers on some of those ships and aircraft provides countermeasures for multimode seekers and electro-optic/infrared sensors. Increasing the power on those lasers, along with the employment of pulsed energy weapons (such as high-power microwave), could create effective and efficient weapons to counter small, unattended air vehicles and, in the future, perhaps even the more hardened air and missile threats.

These new capabilities, coupled with traditional hard-kill systems with improvements of their own, will help lead the way for future integrated AMD systems. Multipurpose systems must be the norm in the future to address the stressing adversary environment, dynamic operating needs, and ever-present fiscal realities.

The use of autonomous surface, air, and subsurface vehicles, in numbers, will also be necessary to achieve asymmetric AMD advantages. These autonomous vehicles will carry sensor and weapon payloads to the locations where they are most effective, while reducing their vulnerability through dispersal around the force being protected. As our forces of the future become more agile and dispersed to counter a more robust and dispersed threat environment, the means by which we provide AMD must follow suit.

Accounting for our dependence on sensors and assured communications, and considering the adversary's electronic warfare and cyber warfare capabilities, future AMD systems will require robust electronic protection, information assurance measures, and proactive cyber defenses to survive even the early stages of warfare. Incorporating communications that are not based on radio frequency, like free-space optics, will provide high-bandwidth data transfers, while being virtually undetectable and immune to jamming.

Finally, the continued evolution of synchronized comprehensive layered defense concepts and system-of-systems approaches will be necessary to integrate and orchestrate these new and essential capabilities into a unified 21st-century AMD warfighting model.

We recognize the APL Air and Missile Defense Sector staff members for their innovation and systems engineering discipline that helped create the essential 21st-century AMD transformations discussed in this article. It is clear from the capabilities delivered in just the last 20 years that this organization is poised to carry on the legacy of its 75+-year heritage when countering future air and missile threats.

Conrad J. Grant, Chief Engineer, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Conrad J. Grant, APL's chief engineer, earned a BS in physics from the University of Maryland, College Park, and an MS in applied physics and an MS in computer science from Johns Hopkins University. He served for over a decade as the head of the APL Air and Missile Defense Sector, where he led 1100 staff members developing advanced air and missile defense systems for the US Navy and the Missile Defense Agency. He has extensive experience in the application of systems engineering to the design, development, test and evaluation, and fielding of complex systems involving multisensor integration, command and control, human–machine interfaces, and guidance and control systems. His engineering leadership in APL prototype systems for the Navy is now evidenced by capabilities on board over 100 cruisers, destroyers, and aircraft carriers of the US Navy and its allies. His email address is conrad.grant@jhuapl.edu.

Matthew Montoya, Asymmetric Operations Sector, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Matthew Montoya is a chief engineer in APL's Asymmetric Operations Sector. He earned a BS in physics from Colorado State University, MS degrees in mathematics/applied math and systems engineering from Johns Hopkins University, an MBA from Loyola College Maryland (now Loyola University Maryland), and a DEng in systems engineering from George Washington University. He has worked across several APL mission areas and sectors where he has been responsible for systems engineering, technical direction, systems integration, and performance assessments. During his nearly 20 years in the Air and Missile Defense Sector, he was a project, program, and program area manager and mission area chief engineer. In his current role as chief engineer in the Asymmetric Operations Sector, Dr. Montoya has led technical efforts for several engineering studies and assessments to help guide and impact programmatic and operational decisions. Additionally, he has been a key thought leader in incubating and implementing APL strategic plans and initiatives. His email address is matthew.montoya@jhuapl.edu.