The microwave moment

Transforming technological advances into mission advantage

A GWT INTELLIGENCE WHITE PAPER

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Proximity, pace and complexity

The emerging 'speed of light' battlefield

"The ways in which war is waged will change as new technologies, applications, and doctrines emerge and as additional actors gain access to these capabilities. The combination of improved sensors, automation, and artificial intelligence (AI) with hypersonics and other advanced technologies will produce more accurate, better connected, faster, longer range, and more destructive weapons."

"THE FUTURE OF THE BATTLEFIELD", U.S. NATIONAL INTELLIGENCE COUNCIL, MARCH 2021[1]

Key points

- New military technologies and capabilities – autonomous, artificial-intelligence (AI)-enabled uncrewed swarms, hypersonic missiles, and cyber and electromagnetic (EM) spectrum threats – are accelerating operational challenges and stressing conventional defensive systems.
- It is no longer sustainable to rely solely (or primarily) on exquisite and expensive kinetic capabilities ill-suited to simultaneously and affordably tackling numerous urgent threats in the physical and digital worlds.
- The United States (U.S.) must pursue new approaches to layered defense, prioritizing innovative technologies that can provide the military with a competitive advantage in a more compressed and complex warfighting environment.
- Directed energy (DE) capabilities are credible options to enable this transition, owing to their speed of light target engagement, deep magazines, low logistical requirements, favorable cost profiles, precision wide-area strike, and scalable military effects.
- Radio Frequency (RF), laser- and microwave-based DE solutions have all demonstrated high technological maturity and mission readiness, with high power microwaves (HPM) in particular emerging as a compelling option for a broad range of military (and commercial) applications.
- Vacuum-tube HPM solutions offer high power capacities, but their large and heavy footprints, long start-up times, single frequency limitations and required human stand-off distances, due to Gamma and X-ray emissions, have limited their use to ground- or ship-based systems. However, breakthroughs in energy efficient and robust advanced materials have enabled the development and successful fielding of semiconductor-based HPMs with far more favorable size, weight, and power (SWAP) characteristics for deployment on more agile, mobile, and airborne platforms.
- Rapid delivery of proven HPM and other DE solutions to warfighters requires considerable structural and cultural adjustments to legacy defense requirements, acquisition and budgeting procedures, which inadequately support the development, testing and adoption of technological innovations, making it difficult for non-traditional suppliers to support the DoD mission.

Technology is transforming the modern battlefield. Nation states, seeking to solidify their competitive edge over adversaries and position for military advantage in future conflicts, are investing in the development of several advanced offensive and defensive capabilities, each with the capacity to accelerate the pace and complexity of warfare.[2]

Such technological advancements are often examined in terms of their disruptive potential on future rather than current defense and security environments, but developments in three critical capability domains point to a more urgent threat dynamic requiring more immediate response solutions. (1) autonomous systems; (2) hypersonic weapons; and (3) cyberspace / electromagnetic (EM) spectrum.

Autonomous systems

Autonomous systems, uncrewed vehicles in particular, are not new, having been pervasive features of multiple conflict environments during the past 15 years, including in Afghanistan, Iraq, Libya, and Syria.[3]

However, air-, ground-, and sea-launched uncrewed technologies have proliferated extensively in recent years, with advancements in artificial intelligence (AI), robotics and miniaturization enabling the deployment of low-cost and expendable systems capable of a broad range of mission functions.[4] As the U.S. Department of Defense (DoD) notes, "around the world, competitors are rapidly adopting [small unmanned aerial systems] sUAS into their military, civil, and commercial inventories. Both state and non-state actors are increasingly employing purpose-built military and consumer-grade sUAS to attack a range of targets including leadership, military facilities and forces, and critical infrastructure."[5]

Numerous incidents demonstrate the extent of the UAS threat, ranging from drone flights into restricted airspace around sporting venues[6], to relatively unsophisticated (yet disruptive and in some cases deadly) drone attacks on airports in Saudi Arabia[7] and the United Kingdom (UK)[8], to more comprehensive drone campaigns targeting Iraqi and coalition forces conducted by insurgents in Iraq[9], to state backed UAS employment in Ukraine and Nagorno-Karabakh[10].

Swarming tactics, involving the use of multiple UAS, create distinct operational challenges given their ability to overcome traditional defensive capabilities. AI-enabled intelligent swarm attacks are especially problematic, whereby multiple UAS can interact with each other and adjust their tactics and targets as theater circumstances evolve.[11]

The 14 September 2019 Iranian-backed attack on Saudi Arabian oil production facilities in Abqaiq was a pivotal indicator of the swarm threat. The attack, involving eighteen drones and seven cruise missiles, demonstrated an inventive blend of various technologies and tactics. More critically, it exposed fundamental weaknesses in conventional air

> **"Swarming tactics, involving the use of multiple UAS, create distinct operational challenges given their ability to overcome traditional defensive capabilities"**

defense capabilities (specifically surface-to-air missiles) which proved ineffective against the UAS swarm, highlighting the pressing need for the integration of more appropriate counter-UAS (c-UAS) solutions into a layered defense architecture.[12]

Meanwhile, the U.S., China and others continue to advance their respective UAS swarm capabilities. The US military launched 103 miniature swarming drones from fighter jets during a test in California in October 2016[13], and in early 2017 China launched a swarm of 119 fixed-wing UAVs. The UK[14] and India[15] both held tests of autonomous swarms in January 2021, and Israel become the first country to actually deploy an intelligent drone swarm during combat with Hamas in May 2021.[16]

Multiple countries (including the U.S., China, Russia, UK, Australia, and India) are also pursuing so-called 'loyal wingman' programs – involving smart teaming of uncrewed, autonomous systems with existing crewed aircraft to extend the range and lethality of airborne missions in contested environments.[17] These programs involve the use of three or more uncrewed aircraft flying ahead of crewed aircraft and/or the use of drones carrying and launching swarms of smaller UAS.

Each of these developments led U.S. Secretary of Defense Lloyd Austin to conclude in November 2021 that the employment of mass and swarming tactics "are likely to feature prominently in the conflicts of the future, and they already threaten civilian aircraft. And that's why [DoD] has made it a priority to address the drone threat."[18]

Going forward, as airpower continues to evolve, less emphasis will be placed on exquisite and expensive systems, with more focus instead placed on expendable force multipliers and teaming of crewed and uncrewed systems, rendering existing air and missile defense systems vulnerable to being overwhelmed by the combination of speed and mass.

Smart teaming

Several countries are exploring teaming of uncrewed, autonomous systems with existing crewed aircraft to extend the range and lethality of airborne missions in contested environments. For instance, the Gremlin program, operated by the U.S. Defense Advanced Research Projects Agency (DARPA), is designed to launch groups of UAS from existing large aircraft such as bombers or transport aircraft, as well as from fighters and other small, fixed-wing platforms, while those aircraft are out of range of adversary defenses.

CREDIT: DARPA

Hypersonic weapons

Technological advances are also enabling the development and testing of hypersonic missiles – high-precision, long-range systems capable of travelling at more than five times the speed of sound (at least 3,800 miles per hour) and reaching most targets globally within minutes.

Given these operating speeds, hypersonic capabilities have the potential to push the pace of warfare and compress the timeline decisionmakers have to understand, decide, and act against offensive threats.[19] As a result, these capabilities have emerged as critical national defense priorities that will require focused investments in advanced defensive capabilities to outpace the evolving threat.[20]

Unlike conventional ballistic missiles – which operate at comparatively lower subsonic and supersonic speeds and have predictable flight trajectories – hypersonic missiles have the ability to adjust their trajectories and maneuver in flight, flying at either lower altitudes enabling them to evade early-warning radar detection, or at higher altitudes beyond the reach of traditional cruise or ballistic missile defenses.

Three types of hypersonic capabilities are in development (to various degrees) in the U.S., China, Russia, UK, Japan, and elsewhere[21]: (1) Hypersonic Glide Vehicles (HGV), which are launched on rockets into space, released at high altitudes, and then glide at speed to their targets; (2) Hypersonic Cruise Missiles (HCM), which are faster versions of traditional cruise missiles and experience powered flight throughout their trajectory;[22] and (3) Maneuvering Re-Entry Vehicles (MaRV), a type of ballistic missile equipped with a warhead capable of maneuvering prior to its descent onto a target.[23]

The U.S. DoD is conducting research, development, test, and evaluation (RDT&E) of hypersonic weapons via several Navy, Air Force, Army, and Defense Advanced Research Projects Agency (DARPA) prototype programs,[24] each designed to enable long-range precision strike with conventional warheads. Significant developments in 2021 include: a successful live fire hypersonic strike system test conducted by Lockheed Martin and Northrop Grumman in May in support of the U.S. Navy's Conventional Prompt Strike (CPS) and U.S. Army's Long Range Hypersonic Weapon (LRHW) programs[25]; and the successful test flight in September of the Raytheon- and Northrop Grumman-built scramjet-powered Hypersonic Air-Breathing Weapon Concept (HAWC).[26] Both tests constitute significant steps toward the provision of game-changing hypersonic capabilities to the warfighter.

China, meanwhile, is developing and testing nuclear-capable intercontinental-range hypersonic capabilities designed to destroy adversarial platforms and systems. According to the U.S. DoD, the People's Liberation Army Rocket Force (PLARF) began to field its first operational hypersonic weapons system, the DF-17 hypersonic glide vehicle (HGV)-capable medium-range ballistic missile (MRBM) during 2020.[27] Media reports also suggest that China tested a nuclear-capable HGV, launched by a Long March rocket, in August 2021 (reports rejected by Chinese officials) – a development described by U.S. defense officials as "very

Hypersonic capabilities have the potential to push the pace of warfare and compress the timeline decisionmakers have to understand, decide, and act against offensive threats. In support of current U.S. efforts to develop and field these capabilities, Raytheon Technologies and Northrop Grumman successfully completed the first flight test of a scramjet-powered Hypersonic Air-breathing Weapon Concept (HAWC), for the Defense Advanced Research Projects Agency and the U.S. Air Force in September 2021.

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concerning and close to a "Sputnik moment" regarding China's military modernization.[28]

Cyber and electromagnetic spectrum capabilities

Cyberspace (including computer networks, the internet, telecommunications networks, information technology infrastructure, data, and processors and controllers) and the electromagnetic spectrum (EM) have emerged as distinct battlefield domains as nations seek to target vulnerabilities associated with pervasive connectivity and the need for cross-domain communication and position, navigation, and timing (PNT) capabilities. Highly connected and information-dependent systems have become key features of modern military command and control architectures, which in turn have become targets of intense cyber and electronic warfare operations (involving the disruption, exploitation and/or disablement of these systems).[29]

Cyber and electronic attacks targeting global navigation satellite systems (GNSS) that provide PNT services to military (and civilian) users – such as the U.S.-operated Global Positioning System (GPS), the Chinese-operated BeiDou Navigation Satellite System (BDS), and the Russian-operated GLONASS (Globalnaya Navigazionnaya Sputnikovaya Sistema) – are especially concerning. These systems are used extensively to enable militaries to develop timely and comprehensive awareness of the battlespace, to make informed decisions about response options, and to execute and control a determined course of action.

As a result, electronic interference of this infrastructure (for instance, via GNSS spoofing, which involves a simulated signal designed to misdirect a platform or cause a weapons system to strike an unintended target)[30] can severely degrade command, control, communications, computers, intelligence, surveillance and reconnaissance (C4ISR) capabilities, cause more significant power projection disruptions, or create the potential for tactical and strategic response escalation and miscalculation.[31]

Combined, the emergence and expanding use of these advanced technologies creates a compressed and more complex warfighting landscape, placing real stress on conventional defensive countermeasures. To compete in this dynamic environment, the DoD acknowledges that it must explore innovative approaches to layered defense, shifting resources "away from vulnerable platforms and weapons systems that are ill-suited to advanced threats" and redirecting investments "to cutting-edge technologies and capabilities that will determine our military and national security advantage in the future."[32]

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Strategic game changers

The case for directed energy capabilities

As the U.S. seeks to innovate, modernize, and upgrade its warfighting capabilities, directed energy (DE) weapons have emerged as persuasive, transformative technologies uniquely suited to addressing these prevailing threats. Unlike more traditional kinetic military systems, DE is "a focused beam of electro-magnetic energy that is used to enable or create military effects".[33]

Numerous DE solutions have been designed specifically for c-UAS base defenses, given the extent to which autonomous systems have become so prevalent on the battlefield. For instance, several electronic jamming solutions have been fielded that leverage a combination of radar target detection, electro-optical/infrared (EO/IR) tracking, and radio frequency (RF) countermeasures to detect, identify, track, disrupt and/or degrade the communications and control signals of airborne targets. Examples of these types of systems include: Silent Archer, produced by SRC[34], Inc; Anti-UAV Defense System (AUDS), produced by Liteye[35]; DroneSentry, produced by Droneshield[36]; Corian, produced by CACI[37]; and Titan, produced by Citadel Defense (a Bluehalo company)[38].

Alongside these RF-based counter-drone capabilities (which are ineffective against modern AI-enabled drones that do not require control systems), high-energy lasers (HEL) and high power microwaves (HPM) have emerged as even more critical features of a comprehensive and effective DE posture. Technological advancements in both areas extend their potential applications well beyond c-UAS missions to address a wider range of threats defining modern warfare.[39]

High-energy lasers (HEL)

Laser-based weapons systems involve narrow beams of light to focus energy precisely on a target to cause effects.

Chemical lasers – such as the Northrop Grumman-produced Chemical Oxygen Iodine Laser (COIL) deployed in the early 2010s on the Missile Defense Agency's Airborne Laser Test Bed (ALTB)[40] – are capable of reaching megawatt levels of power. However, these systems are typically extremely heavy (some weighing many tons), extremely large (some occupying several large shipping containers) and have limited magazine capacity. Each of these features fundamentally limits the range of military applications of these chemical-based lasers.[41]

Breakthroughs in solid-state and fiber-based lasers have resulted in far more favorable size, weight, and power (SWAP) and affordability characteristics, expanding the potential mission utility and platform deployment options of HELs to include: short-range air defense (SHORAD); c-UAS; and counter-rocket, artillery and mortar (c-RAM) missions.[42]

Multiple HEL prototyping efforts are currently being pursued by the U.S. DoD (see box on page 6). The specific characteristics of these

The High-Energy Laser Weapon System (HELWS).

HELs varies from system to system, but in general, laser-based capabilities have several commonalities and favorable performance attributes when compared to conventional kinetic weapons. These include:[43]

- **Speed of light target engagement:** DE has a distinct speed advantage over traditional kinetic munitions, with lasers able to initiate effects at range near instantaneously. To a laser, even a hypersonic weapon travelling at speeds in excess of Mach 5 would appear stationary.
- **Deep magazines and lower logistical requirements:** Many current HEL programs are fueled by electrical power. The number of shots they can fire and sustain is determined by a constant supply of power as opposed to a specific number of munitions. This removes one of the key logistical vulnerabilities of conventional kinetic weapons – the need to physically resupply a weapon and to store sufficient quantities of ammunition.
- **Favorable cost profile:** Lasers are cost effective and provide a far lower cost per shot than conventional offensive and defensive weapons. By way of example, in early November 2021, the U.S. Department of State (DoS) approved the sale to Saudi Arabia of up to 280 AIM-120C advanced medium range air-to-air missiles (AMRAAM) and related equipment at a cost of $650 million.[44] These systems have been used extensively by the Royal Saudi Air Force to counter the drone threat from Iranian-backed Houthi rebels in Yemen. Compared to the $2.32m price tag per missile in this case, the cost per shot for a laser weapon system is equivalent to the cost of the electrical power required to fire the shot – estimated to be just a few dollars. This provides a fiscally viable solution to the unsustainable and asymmetric cost curves associated with coping with the threats emanating from low-cost uncrewed and missile systems.
- **Precision strike:** HEL weapons are able to create precise effects at range, focusing their power on a specific target while (in theory) not creating collateral damage by impacting separate nearby objects.
- **Scalable effects:** Depending on their power levels, HELs can provide scalable response options, performing functions ranging from nonlethal and reversible jamming of electro-optic sensors, to burning holes or damaging material by increasing its temperature above its melting point, to igniting fires at range. In an environment marked by the expansion of diversity of threats – from traditional military threats to sub-threshold gray zone threats that blur the lines between military and non-military contingencies – the flexibility and scalability of response will be valuable to ensuring deterrence and containing escalation.

> "A new revolution is coming in warfare, and it is coming at the speed of light. This revolution concerns the emergence of directed-energy weapons… Ultimately, directed energy weapons can be a game changer… capable of destroying ballistic missiles, hypersonic cruise missiles, hypersonic glide vehicles, and swarm drone and missile attacks."
>
> **LOUIS A. DEL MONTE, "WAR AT THE SPEED OF LIGHT", 2021**

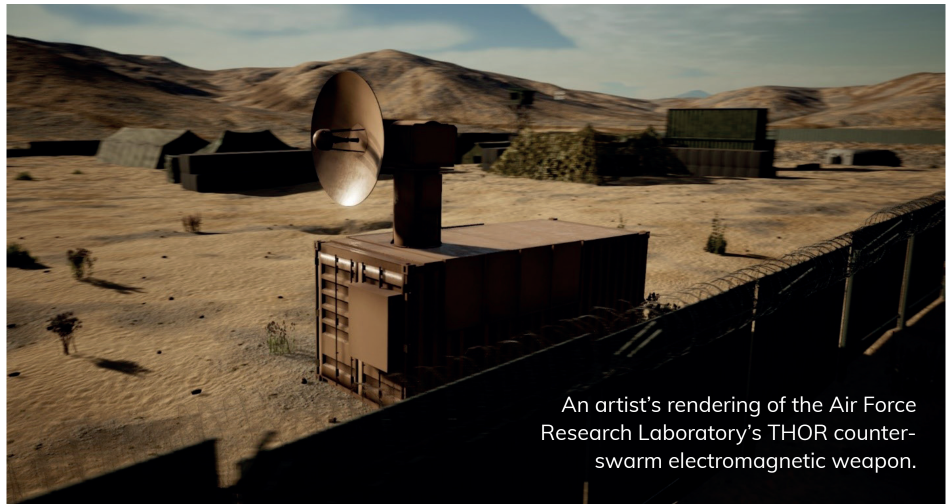
> **"HEL weapons are able to create precise effects at range, focusing their power on a specific target while (in theory) not creating collateral damage by impacting separate nearby objects"**

Notwithstanding these positive features, HEL weapons are susceptible to several performance and operational limitations.

First, laser-based capabilities are inherently restricted to line-of sight engagements and have no current applicability in over-the-horizon scenarios.

Second, poor atmospheric conditions and air turbulence can reduce the effectiveness, precision, and range of laser-based systems. While advances in adaptive optics – which adjust laser beams on a continuous basis in response to observed turbulence – can counteract the effects of atmospheric conditions, the extent to which lasers can be considered "all-weather" weapons remains questionable given that rain, fog, clouds, dust, sand, or other airborne particles can negatively affect their performance.

Third, laser-based DE weapons require seconds-long dwell time on a single target to cause effects, before they can be redirected to



An artist's rendering of the Air Force Research Laboratory's THOR counter-swarm electromagnetic weapon.

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Overview of Major U.S. HEL and HPM programs

Each of the major U.S. military departments – the Air Force, Army, and Navy – are developing and testing a number of HEL technologies, with scaling of power capacity central to each of these programs. The lead time from prototype to full production and fielding of these programs is several years, and the DoD must adjust its requirements, acquisition, and budgeting processes to prioritize speed of delivery to the warfighter of proven technologies.

- High-Energy Laser Weapon System (HELWS): HELWS is a system designed by Raytheon to provide a mobile c-UAS capability for air base defense. Three prototypes have to date been delivered to the Air Force, with the system comprising a vehicle-mounted laser weapon and multispectral targeting system which can reportedly operate at distances of up to 3 km.[59]
- Self-Protect High-Energy Laser Demonstrator (SHiELD): SHiELD is a prototype system in development by AFRL, Boeing, Lockheed Martin, and Northrop Grumman designed to mount as an external pod on Air Force aircraft and provide defensive capabilities against air-to-air missiles (AAM) and surface-to-air missiles (SAM)[60]. After originally planning to conduct flight testing in 2021, that date has now been pushed back to 2024, with Air Force leadership now reassessing the technological maturity and utility of the system.[61]
- Multi-Mission High-Energy Laser (MMHEL): MMHEL is an Army technology demonstration effort consisting of a 50 kilowatt (kW) class solid-state laser system, agile beam control system, and supporting laser subsystems, integrated into a Stryker combat vehicle to provide short range air defense (SHORAD) support to the Army's maneuver brigades at reported average cost per shot of $30. Prototypes for the Army are expected in 2022.[62]
- High-Energy Laser Tactical Vehicle Demonstrator (HEL TVD): The HEL TVD, under development by Dynetics, Lockheed Martin, Rolls-Royce and MZA Associates, consists of a 100 kW class solid-state laser to be mounted on existing medium tactical vehicles to provide a counter-rocket, artillery, and mortar (c-RAM) capability to protect fixed sites, as well as to limited protection in mobile mode.[63] The Army is leveraging HEL TVD program developments to deliver four operational, 300 kW class Indirect Fire Protection Capability-High Energy Laser (IFPC-HEL) prototypes, with demonstrations against a variety of targets scheduled for 2022 and delivery to warfighters in fiscal year 2024.[64]
- High-Energy Laser with Integrated Optical-dazzler and Surveillance (HELIOS): The HELIOS, under development by Lockheed Martin, consists of a 60 kW high-energy laser (with scaled potential to 150 kW) and dazzler in an integrated weapon system, for use in c-UAS and counter-fast inshore attack craft (FIAC) operations.[65] Lockheed delivered the first HELIOS to the Navy in January 2021 ahead of a planned deployment of the system on US naval destroyers.[66]
- Indirect Fire Protection Capability-High Power Microwave (IFPC-HPM): The Army is developing IFPC-HPM to counter groups or swarms of UAS. According to the Army Directed Energy Strategy, IFPC-HPM is to be "paired with IFPC-HEL as part of a layered defense to protect fixed and semi-fixed sites."[67] In support of this program, from FY2022 the Army will partner with the Air Force by investing in the Tactical High Power Operational Responder (THOR) system, developed at the Air Force Research Laboratory (AFRL). The THOR prototype will undergo a series of risk reduction and system characterization efforts before its intended field testing in FY2024 and subsequent transition to a program of record in FY2025.[68]

address other targets. As a result, HELs are not yet suitable for addressing attacks involving multiple weapons simultaneously, such as UAS swarming operations.[45] DoD has noted that with increased power levels, target engagement could be decreased to millisecond timeframes, potentially enabling more rapid re-targeting. Efforts to scale the power capacity of HELs are therefore pivotal to current DoD HEL development programs. These efforts focus on fielding prototypes capable of increasing current power levels (of around 150 kilowatts) to megawatt levels that could feasibly position HEL weapons to engage and defeat ballistic and hypersonic systems, though even more powerful lasers could struggle to defeat hardened targets.[46]

Fourth, since laser-based weapons involve the application of a focused beam on a target at range, the potential exists for friendly systems (both military and civilian) to inadvertently be affected by HELs if they fail to correctly hit their intended targets.

High power microwaves (HPM)

HPM weapons use electricity to generate short electromagnetic pulses at megawatt to gigawatt power levels with the intent of disrupting, degrading, or destroying electrical components of their targets.

HPMs benefit from all of the operational advantages associated with laser-based systems described above: speed of engagement, deep magazines, scalable effects, and favorable cost profiles. But critically, they suffer from none of the drawbacks and several additional characteristics enable an even broader range of HPM applications than is achievable with laser-based solutions.

- **Wide-area coverage:** The electromagnetic pulses of HPM systems transmit in a conical beam that can be several degrees across. This allows microwave-based weapons to disrupt the electronic components of any target that passes through the beam. HPM systems provide unique counter-swarm defensive capabilities as a result of this capacity to engage multiple targets simultaneously.[47]
- **Temporary or reversible effects:** Deploying HPM with variable and scalable power levels enables either a temporary or permanent disruption to targeted electronic systems. While temporary effects have at times been cited as perceived drawbacks of HPM systems, reversible effects do allow for greater operational flexibility depending on desired mission outcomes.[48]
- **Non-lethal applications:** At certain power and lower frequency levels, HPM enables a non-lethal, anti-personnel capability to restrict access to military and civilian high-value targets, such as bases, embassies, ports and other transportation infrastructure, and critical infrastructure sites.[49]

Range constraints, potential effects on unshielded military and commercial electronic systems in the beam range, and the potential for HPM to be rendered ineffective by hardening of

The High-Energy Laser Tactical Vehicle Demonstrator (HEL TVD).

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key components of targets, are key challenges that will need to be addressed as HPM continue to be tested and fielded.[50] However, as with HELs, technological advancements to achieve improved SWAP dynamics will ultimately determine the extent to which HPM systems can be deployed in a wide variety of tactical situations.

Currently, gigawatt-power HPMs are based on vacuum-tube systems, and several US military departments, the Air Force in particular, are developing and testing prototypes based on this technology. Several favorable demonstrations of these systems have been conducted in the past few years, but these solutions are large and heavy, limiting their air- and space-based applications. This currently restricts their use to ground- or ship-based systems where their large external antennas can be more easily employed.[51] Power-up times for these systems can also be considerable, while pulse rates of vacuum-based HPM systems are limited to a few pulses per second.

For instance, the Tactical High Power Operational Responder (THOR) is a counter-swarm electromagnetic weapon designed for short-range air defense. Under development by the Air Force Research Laboratory (AFRL) with support from several industry partners (including BAE Systems and Leidos), THOR requires a 20ft container for storage, is transported via military cargo aircraft, and needs approximately three hours to deploy and operate.[52]

Raytheon is developing a similarly-sized system – the Phaser HPM – under contract with AFRL, as well as a separate Counter-Electronic High Power Microwave Extended Range Air Base Defense (CHIMERA) system designed for UAS engagement at greater distances.[53]

The comparatively lower power capacity of semiconductor-based HPM relative to vacuum-tube technologies has until recently been considered a limiting factor for these types of capabilities. However, the use of more advanced materials in the manufacture of electronic components is leading to significant SWAP, affordability, and efficiency improvements.

In examining DE technology advances over the next 40 years, the AFRL has pointed specifically to the performance gains made possible by the transition from silicon to gallium-nitride (GaN)-based electronic components[54], since GaN sustains higher voltages at lower temperatures, conducts current faster, loses less energy, and can perform in more robust operating environments.[55]

These potential SWAP improvements have led to the emergence of innovate new capabilities that are smaller, lighter, demonstrate greater power density, can be deployed on more agile, mobile, and airborne platforms, and are able to achieve pulse rates orders of magnitude in excess of those obtained from vacuum-based capabilities.[56]

For instance, technology company Epirus has developed and successfully tested a GaN-based semiconductor directed-energy microwave – Leonidas[57] (see box below) and is planning the release in 2022 of its Leonidas Pod, a compact, portable counter-electronics and offensive HPM that can be vehicle or drone mounted. Lockheed Martin has also developed a compact, airborne tube-launched and re-usable HPM interceptor for c-UAS and counter-swarm missions known as Morfius.[58]

Technology spotlight High power microwaves

Breakthroughs in semiconductor-based HPMs – built on electronic components developed with energy efficient and robust advanced materials – have enabled the development and successful fielding of operator-safe solutions with far more favorable size, weight, and power (SWAP) characteristics, allowing them to be deployed on more agile, mobile, and airborne platforms.

Technology overview: Epirus, a California-based technology company, has developed Leonidas, a portable counter-electronics system that uses solid-state gallium nitride (GaN) software-defined HPM to disable multiple electronic threats across a wide area or neutralize a single system in more restricted environments.

Several system characteristics appear to distinguish Leonidas among other competing capabilities. First, testing data indicates that Leonidas is able to deliver power and performance at far greater levels than current vacuum-tube market offerings. Second, its precise pulse spectral content avoids interference with other electronic systems (such as airport radar systems or Wi-Fi networks). Third, Leonidas has a significantly lighter and smaller system footprint, enabling improved maneuverability as well as the ability to be vehicle-mounted or rapidly-towed into the field. And finally, the system uses waveforms similar to more traditional consumer microwave or cellular products that do not emit ionizing radiation and therefore enable a high degree of operator safety.

Proven capabilities: Leonidas has achieved a 100% success rate in three public capability demonstrations. In February 2021, the company hosted the first solid-state HPM counter-swarm demonstration, followed in May with a demonstration of its capability to defeat fixed-wing and mixed drone swarms. In a mid-October advanced capabilities demonstration, an upgraded Leonidas system was successfully tested against various red team scenarios to showcase its expanded electronic defeat, fixed-wing swarm defeat, and precision strike capabilities.

Solution adoption: General Dynamics Land Systems (GDLS) and Epirus announced a strategic teaming agreement in October 2021 to integrate Leonidas into the U.S. Army's Stryker and other manned and autonomous ground combat vehicles for enhanced mobile short range air defense (SHORAD) capabilities.[69]

CREDIT: COURTESY OF EPIRUS

The innovation adoption challenge

Unlocking the potential of emerging directed energy capabilities

"Too many small companies doing defense work have become casualties in the 'valley of death' rather than billion-dollar unicorns. The reason there are not more success stories is not a mystery: the US government did not create the necessary incentives. It did not buy what worked best in large quantities."

CHRISTIAN BROSE, "THE KILL CHAIN", 2020

The threat landscape is clear and immediate. Proven directed energy technologies exist today that can provide the U.S. with a competitive edge over China, Russia, and other potential adversaries. And yet, a clear disconnect exists between the successful development of capability prototypes and the DoD's ability to support the production of these solutions at scale, or to distribute them to the warfighter in a meaningful timeframe.

The challenge? Put simply, existing DoD requirements, acquisition, and budgeting processes do not adequately support the development, testing and fielding of technology innovations. While these legacy processes have enabled the DoD to plan for and predict potential technical risks and schedule and/or cost over-runs associated with major defense acquisition programs, the inflexible nature of these procedures has also stifled rapid, agile innovation and subsequent adoption of emerging capabilities.[70]

This reality has led Dr. Eric Schmidt – former chief executive officer at Google and former chairman of the Defense Innovation Board (DIB) – to conclude: "DoD does not have an innovation problem; it has an innovation adoption problem."[71]

The DoD has made some progress towards addressing this challenge and overcome barriers to entry for new market participants and solutions. For instance, various organizational units have emerged that focus exclusively on streamlining procurement processes and developing new mechanisms to support technological breakthroughs. These include: the Defense Innovation Unit (DIU), which focuses on accelerating the adoption of leading commercial technology throughout the military and growing the national security innovation base; the Air Force's AFWERX and Special Operations Command SOFWERX (both designed to support collaboration, innovation, prototyping and exploration between industry and government stakeholders); and the National Security Innovation Network (NSIN) which aims to build networks of innovators to generate new solutions to solve national security problems. These 'innovation hubs' have enhanced the DoD's ability to understand and engage with less conventional technology companies, identify promising new commercial solutions, and support the rapid prototyping of these capabilities.[72]

The DoD's budgeting and acquisition priorities are also evolving to ensure it can meet the strategic challenges posed by increasingly capable adversaries. An Adaptive Acquisition Framework (AAF) has been developed which seeks to provide several acquisition pathways tailored to the type of capability being acquired.[73] Meanwhile, in its budget request for fiscal year (FY) 2022 released in May 2021, the DoD highlighted the need to innovate at speed and scale, requiring rapid experimentation and fielding of new capabilities, divestment of legacy systems that no longer match the threat landscape, and smart investments in the future.[74]

"DoD does not have an innovation problem; it has an innovation adoption problem"

These efforts notwithstanding, unlocking the full potential of new directed energy technologies requires more action in several key areas of acquisition, innovation and adoption:

Simplifying the requirements process

The current requirements process – involving extensive and often years-long studies designed to ensure the DoD has a comprehensive understanding of its needs prior to committing budget dollars – is the single greatest barrier to rapid technological advancement.[75]

Directed energy weapons have at times been described as "only five years away for the past twenty-five years"[76] – a reflection in part of a protracted requirements process that is misaligned with the speed of technological evolution and with underlying commercial drivers that require companies to realize more immediate financial returns on their investments. A simplified requirements process is a prerequisite to an acquisition framework with more favorable parameters for potential participants.[77]

Increasing innovation funding

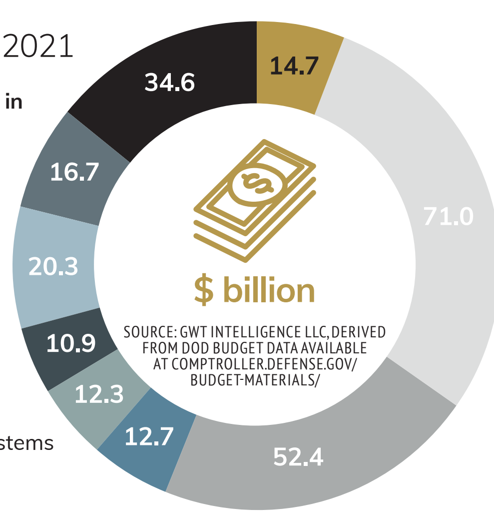
On the surface, the FY 2022 budget request affirmed the DoD's commitment to innovating and modernizing, with a research, development, test and evaluation (RDT&E) budget totaling $112 billion – the most ever requested by the DoD and an increase of more than 5% over the prior year.[78]

However, funding for RDT&E – amounting to around 15% of total DoD spending – has been relatively static for some time,[79] and funding for science and technology (S&T), at $14.7 billion or 2% of the total budget, is well below the 3.4% minimum threshold previously recommended by the Defense Science Board.[80] As such, DoD spending is actually lagging and insufficient to support innovation advancements.

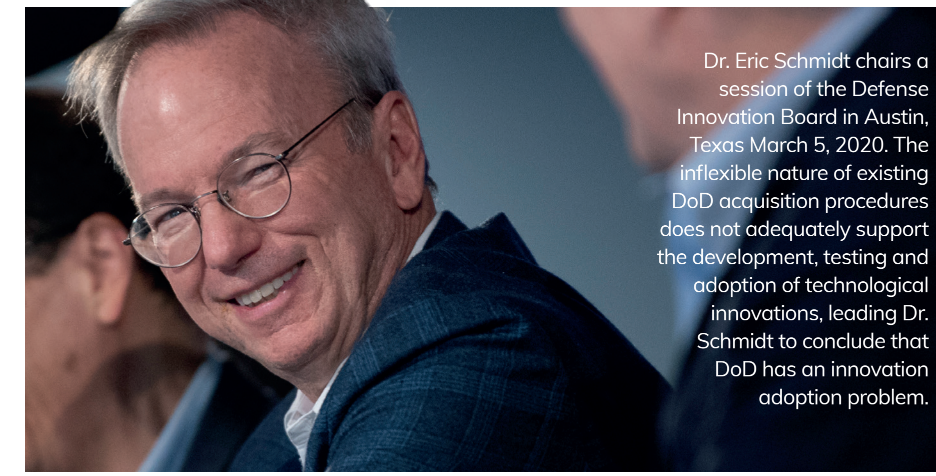
Alongside top-line funding growth, better incentives are needed to encourage the development of new capabilities to address pressing military problems.[81] One approach is for the DoD to: communicate more publicly its 'big technology bets'; back these initiatives with substantial funding; encourage more competition among commercial vendors for prototype contracts; and actively pick winners and provide funding for proven solutions. This approach could be further supported by the allocation of 'bridging funds' by the DoD to support the continued development and refinement of capabilities, and to support commercial entities as they transition from prototype to full production contracts.[82]

DoD FY22 budget request May 2021

While the DoD FY22 budget request released in May 2021 highlighted the need to innovate at speed and scale, funding for science and technology remains well below the minimum threshold recommended by the Defense Science Board.



- RDT&E S&T
- Aircraft
- Ground systems
- Missiles & munitions
- Shipbuilding & maritime systems
- Mission support
- C4I systems
- Missile defense
- Space-based systems


Dr. Eric Schmidt chairs a session of the Defense Innovation Board in Austin, Texas March 5, 2020. The inflexible nature of existing DoD acquisition procedures does not adequately support the development, testing and adoption of technological innovations, leading Dr. Schmidt to conclude that DoD has an innovation adoption problem.

Fit-for-purpose contracting mechanisms

Closely connected to funding incentives is the development of appropriate commercial acquisition frameworks that better support rapid prototyping and experimentation. Critical elements of these mechanisms are: speed to market of new capabilities; exploiting commercial terms and conditions for prototype contracts that enable vendors to retain intellectual property; and minimizing opportunity costs by simplifying the administrative burden on companies responding to open tenders.[83]

While existing non-standard acquisition approaches, such as Other Transaction Authority (OTA) arrangements, serve as interim solutions, a more fundamental reexamination of 'one-size-fits-all' contracting approaches is needed to create a more flexible and tailored process that promotes differentiation in the way the DoD procures major weapons programs versus more agile emerging capabilities.[84]

A capabilities-focused budget

More flexible funding and spending authority approaches focused on capabilities as opposed to defined program of record vendors would afford the DoD greater agility to shift vendors as technologies evolve. A value-based 'portfolio management' approach – one that positions defense decision-makers to pivot and reallocate funding as required on emerging capabilities (without exceeding top-line budget thresholds) – would incentivize commercial entities to continue to evolve their solutions to best respond to operational needs. Defense officials, in turn, would have greater latitude to select technologies based on performance and mission utility.[85]

Transforming the way DoD does business and engages with non-traditional commercial suppliers will be a major determining factor in the U.S.' ability to keep pace with evolving threats and adversarial capabilities. As the DoD explores its options to budget for and acquire innovative DE and other advanced capabilities more expeditiously, it should also emphasize the building of a more technology-knowledgeable workforce. In particular, these efforts should encourage and incentivize a procurement and acquisition decision-making process prioritizing the rapid and flexible adoption of emerging technologies.[86]

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