DIRECTED ENERGY FUTURES 2060

Visions for the next 40 years of U.S. Department of Defense Directed Energy technologies

This document was authored by the Office of the U.S. Air Force's Chief Scientist for Directed Energy, Air Force Research Laboratory, for the Office of the U.S. Secretary of Defense's Directed Energy Community of Interest. We are grateful for contributions from the U.S. Naval Research Lab, Office of Naval Research, U.S. Army Space and Missile Defense Command, Joint Intermediate Force Capabilities Office, other components of the Department of Defense, Los Alamos, Sandia and Lawrence Livermore National Laboratories, collaborators from industry, academia, and international partners affiliated with the North Atlantic Treaty Organization (NATO).

Approved for public release; distribution is unlimited. Public Affairs release approval # AFRL-2021-1152

Directed Energy Futures 2060

Table of Contents

Executive Summary

We maintain that we are approaching or have passed a tipping point for the criticality of Directed Energy (DE) capabilities as applied to the successful execution of military operations for the United States, Allies, and for the United States' rivals and potential adversaries. DE is a focused beam of electro-magnetic energy that is used to enable or create military effects, when used in conjunction with other military systems, including kinetic weapons. Specific examples of DE are lasers, radio frequency devices, high power microwave, millimeter wave, and particle beam technology used to create a military effect, e.g. deny, degrade, damage, destroy, or deceive.

A growing number of nations, are realizing the potential of DE for a variety of militarily relevant missions. At least 31 nations today have DE weapons for counter unmanned airborne system (c-UAS) missions, such as base defense. Other examples of pervasive DE technologies include pointer and illuminator lasers. Today both state and non-state-actors have used low-power lasers during operations: military, policing, during protests, and to imperil civil and military pilots. Counter sensor and counter electronic DE weapons are effective today from a variety of platforms (airborne, ground, and ship based), across various phases of war and intensities of conflict.

Recognizing the increasing military criticality of DE capabilities, we are moving aggressively to retain U.S. DE leadership. This increase in DE military significance is driven by convergence of trends in:

- The science and technology enabling greater DE performance and capabilities
- The characteristics and requirements of offensive and defensive operations across the battlespace, and
- The role and characteristics of information in maintaining military parity or dominance across the battlespace.

The increased criticality and competition of DE capabilities argues for a national strategy that guarantees U.S. DE military capabilities ensuring U.S. national interests and power.

Such a strategy must incorporate short-, mid- and long-term perspectives on the future of DE capabilities both generally and specifically as they apply to military operations. This report presents results from the first of a three-step effort to provide that long-term vision towards the development of this strategy. The other steps will be completed in subsequent workshops. The three steps are:

(1) Describe a range of possible Directed Energy future scenarios and explore the characteristics of those scenarios and their implications for national and military power.

(2) Understand the drivers and inflection points for those scenarios most advantageous and disadvantageous to the U.S with respect to national defense.

(3) Determine the minimum essential capabilities and actions required to implement a Directed Energy strategy meeting military needs.

For the first step, the DoD Directed Energy Community of Interest and the Air Force Research Laboratory Directed Energy Directorate, hosted a DE Futures 2060 Workshop in October 2019, to explore the status and role of directed energy capabilities 40 years into the future. The participants, comprised of DE experts from several agencies and services in the DoD, DoE, NATO, industry, and academia. The assembled experts assessed the historical and current state of DE technologies, and used those assessments to forecast DE technology, relevance, and proliferation into the future across a range of militarily relevant principles. They used an alternative futures analysis technique to develop a range of future scenarios and to explore how they relate to national power. This document summarizes and expands upon those discussions.

The workshop explored potential DE futures along three axes:

Advancements in DE systems performance

What performance can Directed Energy systems provide based on advances in DE science and technology?

Prevalence of DE capabilities

How widely and at what level are Directed Energy capabilities proliferated across nation states and other entities?

Military significance of DE enabled capabilities

What is the military utility of DE enabled capabilities in the execution or disruption of the kill chain, across domains and across the phases of conflict?

Along each of these axes or dimensions, the workshop participants defined three states bounding the potential futures for Directed Energy in 2060: optimistic, conservative, and pessimistic. These states were carefully developed to realistically span the range of possible future states, and to avoid the pitfall of wishful thinking as to the state along any axis.

Combinations of the states along the axes or dimension, produced 27 possible futures. A subset of these futures were developed in more detail to determine their implications to U.S. power and to the development of a national DE strategy. A sufficient number of the futures were examined to determine the full range of possible threats and opportunities for U.S. military power. The specific futures examined were:

Future 1 Prevalence, Technology, and Military Utility all Optimistic Case

Future 2 Prevalence, Technology, and Military Utility all Pessimistic Case

Future 3 Prevalence, Technology, and Military Utility all Conservative Case

Future 4 Technology, and Military Utility Optimistic Case, Prevalence Pessimistic Case

Future 5 Prevalence and Military Utility Optimistic Case, Technology Pessimistic Case

Future 6 Prevalence Conservative, Technology Optimistic Case, and Military Utility Pessimistic Case

Examination of these futures and their implications led to the following preliminary conclusions.

1. The U.S. and its close Allies increasingly rely on electromagnetic superiority to maintain operational communications and avoid detection. Therefore, we are approaching (or have passed) a tipping point in the criticality of directed energy capabilities to successful military operations for the U.S., Allies, peer competitors, and potential adversaries.
2. Our potential adversaries and rivals will increasingly challenge U.S. leadership in DE military capabilities.
3. This increased criticality and competition argues for a national Directed Energy strategy to ensure that the U.S. has the DE-enabled military capabilities required to protect our national interests in 2060.
4. The future state methodology ensures that an appropriate range of futures are considered that avoid the historic tendency for the DE community to overpromise in terms of the maturity of DE technology, and underperform as to the operational capability that DE can provide.

5. Even with a pessimistic estimate of the advance in DE science and technology, DE capabilities will have significant military utility in the battlespace of the future, due to the unique capabilities of DE systems in terms of precision, range, flexibility, scalability of effects, deep magazine, and active probing of the battlespace across all domains and phases of conflict. Today, DE weapons are used by all major military powers for a variety of effects.
6. The increase in military significance of DE systems depends on the ability to convert technological advances into operational capabilities. Technical challenges remain, that require research and development, as well as consideration for all elements of the DOTMILPF and life-cycle management.
7. Under conservative or optimistic projections of advances, DE capabilities will be a vital contributor to military operations within, and across all domains for the U.S. and its potential adversaries. Because the pace of conflict is forecast to quicken, certain counter-air operations of the future may only be possible with the speed advantages DE offers.
8. World-wide trends hint at a flatter economic and technological world in 2060. While the U.S. desires to retain its dominant position in DE operational application, science and technology, this position will be difficult to maintain with a large set of peer competitors.
9. For all futures examined, DE military applications will be sufficiently important that lagging behind peer competitors in areas of DE military capabilities risks the U.S. military's ability to project power and protect national interests.
10. The most probable, achievable state for the U.S. in 2060, is parity in DE science and technology and operational capabilities with the expanded set of peer competitors. The importance of assuring this parity is directly proportional to the level of proliferation of significant DE military capabilities and the level of increased performance, enabled by advances in DE science and technology, by those nations who lead in DE.
11. The key challenges in developing a strategy to assure those futures with the U.S. having at a minimum, parity with peer competitors are:
    a. Determining the breadth and focus of investments across the complex space of DE science and technologies with potential for military applications.
    b. Developing the human capital needed to perform the science and technology and engineering, required to transition the technology to operational capability.
    c. Ensuring the ability to adjust quickly to new advances or breakthroughs.
    d. The ability to rapidly convert those advances or breakthroughs into operational capabilities, ideally asymmetric capabilities, so as to match or outpace our competitors and potential rivals.

12. This first workshop and associated report provide a vision, valuable initial inputs for the refinement of the national strategy for Directed Energy, and argues strongly for continuation of the efforts, as critical inputs to national strategy development.

1. Introduction

Directed Energy (DE) is defined for military applications as the ability to project electromagnetic energy either broadly to provide information probing of the battlespace, or in a focused manner sufficient to produce a defensive or offensive effect at militarily relevant distances within the battlespace. The military significance of Directed Energy Weapons (DEWs) has long been recognized for ability to engage at the speed of light, propagating vast distances with precision. Other benefits include potentially deep magazines, meaning the capability to fire many shots without need to physically rearm the weapon, and low cost per shot. DE can also actively probe targets and threats, i.e. laser pointers (commonly called designators), laser and radiofrequency (RF) tracking, also called radar. The final benefit worth mentioning, is the ability to cause scalable and flexible effects, to include destructive, damaging, disruptive, non-lethal, deceptive, and unattributable effects.

Today in the early 2020s, world-wide DE already plays important military roles in counter-air defense, target identification, tracking, counter intelligence search & reconnaissance (ISR), and electronic warfare (EW). U.S. military thinking on electromagnetic spectrum operations defines DE in the context of electronic attack systems designed to disrupt or degrade an adversary's signals, deliver communications supporting cyperspace operations, or disable and destroy targets susceptible to high-energy electromagnetic radiation (U.S. Joint Chiefs' of Staff 2020). Today there are historical definitions that delineate DE and EW weapons which are otherwise similar in function and form. Because the historical definitions are unlikely to be important 40 years in the future, in this report we considered DE and EW weapons to be synonymous, especially with respect to applications of information superiority that reply upon electromagnetic spectrum superiority to accomplish military missions.

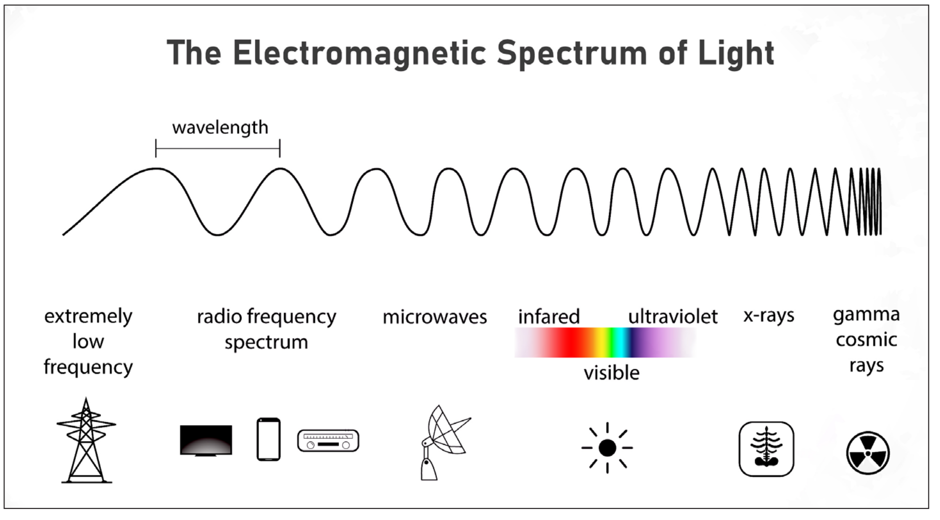


Figure 1: *The electromagnetic spectrum*

The electromagnetic spectrum of light (see Figure 1) spans frequencies , starting at a few Hertz (1Hz=1 oscillation of the electromagnetic field of light per second), the frequencies at which modern electrical infrastructure operate. The spectrum continues through radiofrequencies, microwaves, and millimeter waves, at which most modern communication systems operate, and then through the infrared, visible, and ultra-violet (UV) that are often referred to as the optical part of the spectrum. Finally, the most rapidly oscillating frequencies are X-rays and gamma rays.

Because most modern electrical and communication (e.g., cell phones, computers, radios) systems operate in the few Hz through optical frequency ranges, DE plays a vital role in the global technology of this and future eras. While the power of light is still considered mysterious by many people, and DE systems still considered the devices of science fiction, today DE systems commonly exploit the electromagnetic spectrum. They are of

[1] Light can be thought of as photons, particles of light, or an electromagnetic field that propagates time and space like a wave. The wavelength and frequency of light are related; wavelength is inversely proportional to frequency.

military and commercial utility, and pervasive in manufacturing and medical sectors of modern society. For example, in the early 2020s, specifically as of March 2021, the U.S. death toll from the COVID-19 pandemic has already surpassed the combined total number of American military service member lives lost during combat in World War I, II, and the Vietnam War. UV lights and other forms of light are standard equipment for sanitizing medical equipment and ventilation systems, helping to prevent spread of the disease.

Although DE is most certainly not a cure-all, there are other technologies on the horizon that make use of the power of light in perhaps surprising ways. For example quantum-information can be encoded on pulses of laser light, enabling higher security communications. In another example, there are projects underway in the U.S. (U.S.A.F. 2019, Mosher 2018) and in China (Rosenbaum 2019) that use DE to transport or "beam" power to remote and disadvantages locations.

Looking to anticipated future trends, it is our assessment that in a conservative forecast of the future, applications of electromagnetic spectrum dominance are likely to create significant *asymmetric military advantages*. A historical example of DE that also shows the flexibility DEWs provide to information superiority operations, is the example of illuminator lasers, also called designators, and colloquially laser pointers. These laser devices illustrate how DE can be used to create a *spectral asymmetric advantage* over one's adversaries. Countless military victories in Iraq and Afghanistan during the past 20 years, relied on infrared sensors and night vision goggles, used in conjunction with infrared laser illuminators to dominate adversaries on the ground and from the air. U.S. and Allied forces "owned the night" by domination of the infrared portion of the electromagnetic spectrum, in high intensity conflicts (Eason 2003).

DE is uniquely suited for several missions in a strategy for layered defenses and information superiority, by means of electromagnetic spectrum superiority. Notions of layered defense have long been a focus of U.S. military investment and are expected to increase, evolve, and solidify as offensive threats increase, evolve, and pose more risk. The challenges of electromagnetic spectrum superiority have been noted by the U.S.'s most senior leadership (U.S. Department of Defense 2013, President Obama 2010).

We argue that due to the convergence of trends in technology and the evolution of the battlefield, DE military capabilities have reached or passed a tipping point in their criticality to the successful execution of cross domain, military operations by the U.S., Allies, and current and potential rivals and adversaries. Recognizing this fact, these entities are challenging U.S. leadership in military DE capabilities.

This convergence of trends and increased competition, argues for a focused national strategy for Directed Energy to ensure U.S. leadership sufficient to protect our key national defense interests. Such a strategy must incorporate short-, mid- and long-term perspectives on the future of DE capabilities, generally and specifically, as they apply to military operations.

To provide this long-term perspective and to drive the development of the needed national DE strategy, the Office of the Secretary of Defense (OSD) Directed Energy Community of Interest and the Directed Energy Directorate of the Air Force Research Laboratory are executing a 3-step process. The 3 steps in this process are:

1. Describe a range of possible future Directed Energy scenarios and explore the characteristics of those scenarios and their implications for national and military power.
2. Understand the drivers and inflection points for those scenarios most advantageous and disadvantageous to the U.S. with respect to national defense.
3. Determine the minimum essential capabilities and actions required to implement a DE strategy meeting military needs.

Although we can only speculate about the future world of 2060 (see Appendix A for three fictional vignettes), the process we utilized follows one developed by NATO, and borrows from the Shell Oil Company's alternative futures analysis technique (Henchey 1978, Schwartz 1991, Bishop 2007, Rizzo 2018, NATO Strategic Analysis Branch 2017). Interestingly, the April 2020 issue of National Geographic adopted a similar methodology to future cast the world in 2070.

Future casting is part of the first step in a NATO Defense Planning Process (NDPP). To address the first step, a two-day workshop was conducted at Kirtland Air Force Base on 17 and 18 October, 2019. The participants in the workshop consisted of a wide range of DE experts from the DoD, DoE, NASA, NATO, industry, and academia (see Appendix B), each representing different sub-areas of expertise as well as various mission areas. The assembled experts shared a rich knowledge-base of the *historical* trends in DE, the *now* state of DE, and a *vision for the future.* Further steps in the futures planning process will be addressed in future workshops.

The first step in futures planning was completed in four parts. First, the group determined the key converging trends that have pushed the criticality of DE military capabilities past a tipping point. Identified trends include:

- Advances in the science, technology, performance, and capabilities of directed energy devices will be driven by military, industrial, and last but not least, commercial interests. For example, the semi-conductor industry is likely to drive advancements for DEWs.
- The characteristics and requirements of offensive and defensive operations across the battlespace and phases of conflict. Specifically, as the pace of war quickens, so must our ability to respond.
- The role and characteristics of information in maintaining military parity or dominance, across the battlespace. DE is critical for electromagnetic spectrum superiority, and will continue to be as information superiority will be vital in 2060.

Second, the group determined the key assumptions (see Appendix C) as to the geopolitical state of the world in 2060, which could impact DE capabilities and the range of nations that could possess them. These assumptions addressed the global distribution of wealth, power, and the nature of conflict and warfare in 2060.

Third, the workshop participants explored potential DE futures along three axes, named below, in the light of these trends and with the aforementioned assumptions:

Advancements in DE systems performance

What performance can DE systems provide based on advances in DE science and technology?

Prevalence of DE capabilities

How widely and at what level are DE capabilities proliferated across nation states and other entities?

Military significance of DE enabled capabilities

What is the military utility of DE enabled capabilities in the execution or disruption of the kill chain, across domains and the phases of conflict?

Along each of these axes or dimensions, workshop participants defined three states bounding the potential futures for Directed Energy in 2060: optimistic, conservative and pessimistic. These states were carefully developed to span a credible range of possible future states and avoid the pitfall of wishful thinking, for which the DE community is sometimes accused. The combinations of the states along these axes or dimensions produced 27 possible futures.

Fourth, the summit characterized a subset of these 27 futures to determine the implications for U.S. power and the development of a national DE strategy. The group examined enough of these futures to determine the range of threats and opportunities that the full range of possible futures poses to U.S. military power. Key observations and conclusions stem from the possible futures and the likely responses to them.

The remainder of this report captures the trends, assumptions, pessimistic, conservative, and optimistic future projections, future states determined by understanding the trends, and concludes with recommendations designed to achieve an optimistic future vision.

2. Trends

Using the three dimensions, Science and Technology (S&T) advancement, prevalence, and military utility, we discuss *historical* and *current day* (the early 2020s) trends affecting the *future* of Directed Energy out to 2060 as an element of national and military power.

These trends are discussed in greater detail, in six subsections according to the performance that DEWs enable.

1. Range and focus of military power – either broadly for information purposes or narrowly as required for defensive and offensive operations.
2. Scalability and flexibility of application of power within phases of conflict.
3. Precision applications for special operations.
4. Precision applications for non-lethal operations.
5. Speed of application of power within the battlespace – How fast can DE engage targets in a battlespace?
6. Platform considerations of size, weight, and power (SWAP) and affordability

In the following subsections, we discuss historical developments and current day status with specific, well-documented examples of DEW technology. We explore three technical areas: laser systems, high-power electromagnetics (HPEM), which includes radio, microwave, and millimeter-wave weapons, and the DE tech area of particle beams. Each is described with respect to the performance characteristics and expected trends forecast over the next 40 years.

2.1. Directed Energy Range and Focus of Military Power

Either broadly for information purposes or narrowly focused as required for defensive and offensive operations, the ability to project power with DE derives from the ability to create *effects* at range. For example, lasers can burn holes or otherwise *damage* material by increasing its temperature above its melting point. RF enables information dominance by *disrupting* communications as will be described in Sec. 2.2. Material *degrading* DE effects include counter-electronic and counter-sensor effects, both of which will be discussed in greater detail in
Sec. 2.2-2.3.

At range DE can be used to *destroy* or *degrade* material through absorption, which includes effects such as damaging sensors or the human eye, an offensive technique used by non-state actors today in operations, such as intermediate force actions that *deny* people access to point locations (see Sec. 2.4). Laser weapons can also cause *damage* by igniting fires.

Lasers 101:

Light amplification by stimulated emission for radiation devices, or lasers, were developed in the 1960s. They typically have unique frequencies in the infrared, visible, or ultra-violet parts of the electromagnetic spectrum. Lasers have proven useful for optical communications, industrial processing, and military DE applications.

All together Directed Energy Weapons cause all 5 of the well-known “D’s”— destroy, damage, degrade, deny, and deception— in addition to other strategic effects identified in the U.S. Joint Chiefs’ of Staff DoD Dictionary. In the rest of this section we will focus on the blunt effects of physical *damage* and *destruction* as a means to project military power at range.

The power of DE to burn holes in material by heating it to temperatures at which it melts or otherwise structurally breaks, is a power that is uniquely suited for lasers. For a few every day examples of high energy lasers that melt metal, consider welders and laser etchers. Both high-energy laser devices are common place equipment in industrial applications today. These laser devices are proliferated around the world. Lasers have found use in these applications because the physics of heating a hard material, such as metal to its melting point favors frequencies at which the material most effectively absorbs light. Those frequencies are typically in the UV, optical, and infrared parts of the spectrum, all of which, are suited to laser production. Laser light can be focused very tightly as well, literally focusing destructive energy on a potential target. And it has other unique characteristics, such as potential long-range characteristics that we will explain further throughout this document.

Historical and Current Examples of High Energy Laser Technology

Although today high-energy laser equipment is proliferated worldwide, the ability to create laser effects at vast ranges, for military purposes, is still limited. Today, for reasons that we will explain further, it is thought that two of the most militarily relevant use cases for high-energy laser weapons are i.) high-altitude (greater than 30,000 ft.) operations where the stand-off range between shooter and target is up to hundreds of kilometers, or ii.) ground- or sea-based defensive purposes.

In 2020, it is possible to build a 100's of kilowatt class laser weapon system that can create destructive effects at tactically relevant distances, which if deployed could enable certain offensive and defensive operations. By tactically relevant distances in this instance, we mean up to a few kilometers. Today, depending on laser energy level, hardness of the target material, and range between weapon and target, a laser weapon can create a destructive effect at tactically relevant distances by focusing precisely on a target for up to several seconds (Rehberg and Gunzinger 2018). The military utility of laser weapons has been proven through live fire testing, including for counter-air missions, the importance of which we will stress throughout this report, (88th Base Wing Public Affairs 2019, Chuter 2019, 88th Air Base Wing Public Affairs 2020, Altay, İbrahim, Ed. 2019, Lye 2020, GeoPolitics News 2020) and through mission-level weapons modeling and simulation.

Historically, and today, there are several well-known concepts for high energy laser weapons systems produced by the U.S., Allies, and potential rivals and adversaries world-wide. For example there are several airborne laser programs (Missile Defense Agency 2010, Mizokami, China's Airborne Laser Weapon Would Change Dogfighting Forever 2020, 88th Base Wing Public Affairs 2019, Mayfield 2019, S. Freedberg 2020) and space-based laser concepts (Missile Defense Agency 1997, Kornilov 1993). Both ground-based (Mizokami, U.S. Marines Have Started Testing Its Drone-Killing Laser Weapon 2019, 88th Air Base Wing Public Affairs 2020, S. Freedberg 2020, SRC, Inc. 2018, Ahval 2019, Altay, İbrahim, Ed. 2019, GeoPolitics News 2020) and ship-based (Lendon 2020, The Associated Press 2020, Chuter 2019, Cronin and Neuhard 2020) high energy laser weapon concepts have been demonstrated to a high technical readiness level (TRL) and maturity levels in specific mission areas, such as against small and relatively soft targets. Today these laser weapons cause destructive and damaging effects at militarily relevant ranges.

Furthermore, there is wide proliferation of laser weapon technology. As of 2020, at least 9 of the top 10 largest military powers in the world have publicly announced laser-based weapons programs. It is not clear if all of those programs specifically intend to cause mechanical failure of materials, or less lethal effects which we will discuss further in Secs 2.2-2.5. It is clear that many are counter UAS systems. There are publicly released videos of a Turkish Army ROKETSAN laser weapon system destroying small UASs (Altay, İbrahim, Ed. 2019). Although the first known successful counter-drone DE experiments were conducted by the U.S. under Project Delta, in 1973, reports indicate that in 2019, the Turkish military used a laser weapon to destroy a UAS during conflicts in Libya. If true, this is a first of its kind combat achievement (Ahval 2019).

[2] See Appendix D for description of scientific units of measurements for DE power, energy, frequency, and time.

[3] This topic will be addressed further in Sec. 2.5.

Figure 2: *From the top left clockwise, the U.S. Navy's Laser Weapons Demonstrator System, which was deployed on the USS Portland; The U.S. Air Force's Airborne Laser; The U.S. Air Force's High Energy Laser Weapons System, which was certified for use in combat Sept. 14th, 2020; The Turkish Army's ground based ROKETSAN Laser Weapon.*

From the perspective of proliferation and military utility of DE systems by 2060, in a conservative forecast— one where the U.S. and Allies are assumed to continue to be leaders in technology and military application of DEWs— it is reasonable to predict that all major military powers will also possess DE weapons. In the most optimistic case for the U.S. and its Allies, proliferation of the *highest energy laser* weapons will be limited to the U.S. and Allies.

Laser Proliferation Stat Shot 2010:

Today at least 9 of the 10 largest military powers have publicly announced laser-based weapon programs.

Future Trends and Challenges for Laser Weapon Technologies

To understand the future technical trends in lasers system development, one must consider the drivers behind laser technology in the last 40 years. Technical trends over the next 40 years will be driven by both military and commercial interests, in addition to the lessons learned from previous laser weapon programs. Some of the lessons learned from the U.S. Airborne Laser Program, which began about 40 years ago and used gas and chemical laser architectures, were i.) the logistical footprint of a laser can create operational challenges; ii.) maximum powers in the range of Megawatts can be attained; and iii.) control of the beam is vitally important and nontrivial to achieve with highly accurate pointing. The challenges of beam control include propagation of light through potentially turbulent atmospheres, compensation of mechanical jitter from the host platform (in this case, the airplane), and C4ISR integration. Today the U.S. Air Force continues development of a high energy laser on a tactical airborne platform (Insinna 2020).

The U.S. DE community has made significant progress toward addressing the lessons learned from early programs. Presently, the U.S. and Allied DE community uses a solid state and fiber optic laser architecture both because they learned the lessons about the logistical footprint of laser systems, and due to the industrial development and commercialization of fiber-optics and other solid-state laser technology. In fact, commercial development has revolutionized laser technology over the past 40 years. Solid state and fiber-optical approaches eliminate the need for large volumes of toxic chemicals in DE systems. Furthermore, fiber lasers can be combined to produce hundreds of kilowatts of power, with good beam quality (Anderson 2015), and have proven relevant in tactically suitable payload sizes, weights, and powers (SWAP).

Many of the trends in high energy laser technology development are driven by global commercial market forces. Over the next 40 years, solid state and fiber laser architectures will undoubtedly advance through continuous improvement in engineering processes with trillions of dollars of investment in international industries such as the communications, information, integrated photonics, and even commercial electronics industries. These industries are likely to drive the advancement of laser technology in the next 40 years, more than military applications will advance the technology. Fortunately, investments that are driven by militarily unique requirements appear likely to reap the benefits of industrial development such that even in a pessimistic view of the future, one can easily contemplate reduction in SWAP that would make airborne, space-based, and all domain DE missions more viable by 2060.

Conservatively, following trends of the past 40 years of development up until now, in the future, solid-state and fiber laser technology can be projected to achieve extremely high energy levels in the range of Megawatts over a second, high enough to reduce timelines for laser engagement to l*ess than 1s at tactical ranges* by 2060. Optimistically, 100's of Megawatt solid state laser systems could be possible. This technical trend is bolstered by current research in laser power scaling (Sherman 2019), to reduce dwell times and/or increase range of effects. For laser weapon technologies, these advancements represent an *inflection point* as they reduce the timescales of engagements significantly, enabling vital missions.

Once a sufficient amount of laser energy is created, the next challenge for laser weapons lies in the ability to propagate laser energy kilometers or farther distances, through the atmosphere, to targets at range. Trends in technology development over the next 40 years will be driven by solving such challenges. The challenge includes both tracking of moving targets at high levels of accuracy from moving platforms, and

Figure 3: *(Left) U.S. Air Force's Self-protect High-energy Laser Demonstrator (SHiELD) pod during flight tests in 2020; (Right) Concept drawing of advanced SHiELD-like system on a fighter of the future.*

being able to control the beam both accurately and precisely. Today, lasers weapons are powerful enough for missions against soft targets such as UASs (88th Air Base Wing Public Affairs 2020, Chuter 2019) and demonstrations of counter-missile applications (88th Base Wing Public Affairs 2019). State-of-the-art beam pointing from stabilized gimbal mounts permit hundreds of nanoradian precision pointing from stationary and slowly moving platforms, while tracking fast moving objects (Kwee 2007). Microradian accuracy is currently possible on large airborne platforms. In the future, by 2060, higher pointing accuracy, approaching 100s of nanoradians, could optimistically be possible on fast moving platforms.

Tech Reach Goals for 2060:

- **Gigawatt solid state laser**
- **Nanoradian laser beam-control accuracy and stability**
- **Miniaturization of laser systems**

Invention of solutions to technical challenges will drive future trends. For example, propagating laser energy through the atmosphere, becomes challenging in poor weather or turbulence. Turbulence causes both beam wander and brightness fluctuations in high energy lasers. Weather deleteriously effects all weapons, but poses particular problems for all optical and infrared sensors, many of which provide cues and tracking for command and control of weapon systems. Inventions over the next 40 years may prove the ability to overcome weather effects. As an example, current research focuses on ultra-short pulse lasers that promise to burn holes through fog (Rudenko 2020).

A technology that today compensates for the deleterious effects of atmospheric turbulence is adaptive optics, invented and developed nearly 40 years ago (Fugate 1991). Sophisticated adaptive optical systems can today compensate for moderate levels of turbulence and atmospheric distortions. Conceivable improvements in the engineering of optical systems, even in the most pessimistic case for technology advancement, will further improve efficiency in ability to put up to Megawatts of continuous wave laser energy on target at tactically relevant distances. Gigawatts or 100s of Megawatts of laser energy propagated at tactically relevant and longer distances, would be an optimistic technical outcome by 2060. In the atmosphere, power levels greater than a few Gigawatts would undoubtedly suffer from self-focusing effects (Nibbering, et al. 1997). U.S. DoD and Allied military utility studies have been conducted, and will continue to be conducted, to objectively determine, in conjunction with kinetic and cyber weaponry, to what degree of effectiveness DE capabilities can achieve *destructive* effects for specific missions and scenarios that include weather.

An easy way to avoid the issues of weather and atmospheric propagation is to deploy DEWs at high altitudes, where the earth's atmosphere is thinner. For this reason and others, high altitude military applications of DEWs will remain important concepts into the future.

Future trends in DEW technology will follow mission needs. The "holy grail" from a military utility perspective is a DE weapon system effective enough, favorable from a SWAP perspective, and affordable enough to provide a nuclear/missile umbrella. Although a concept often associated with science fiction, in fact ground and ship-based DE defense systems effectively act like point-localized force fields against small and relatively soft targets today. Airborne and space-based DE platforms could achieve a greater area defense and multipoint defenses, for a broader coverage missile umbrella. However, these concepts require significant technical advancement by 2060 to achieve the full range of power contemplated.

Albeit significant technical advancements are required in power, and range of power specifically, in the most optimistic case it should be physically possible to design a mission relevant concept of operations that permits nanoradian beam-control accuracy while tracking missiles up to hypersonic speeds, with a fast enough command and control loop and Megawatts of laser power (for more reading on this concept see Sec 2.5 and Appendix A: Vignette 1 and Vignette 3). By 2060 a sufficiently large fleet or constellation of high-altitude DEW systems could provide a missile defense umbrella, as part of a layered defense system, if such concepts prove affordable and necessary.

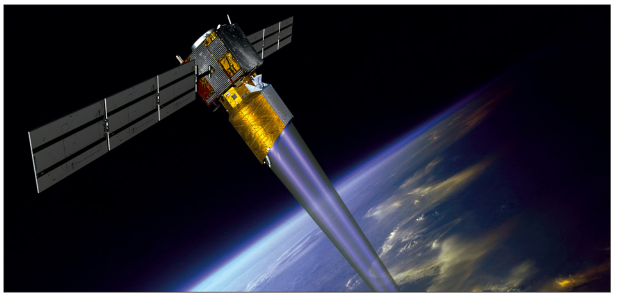


Figure 4: *Conceptual drawing of a space-based DE missile defense.*

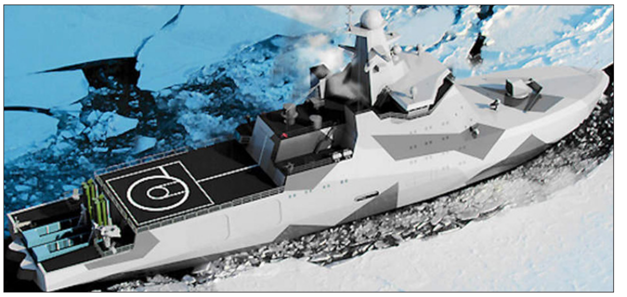


Figure 5: *Concept rendering of the Project 23550 Arctic patrol ship. This graphic is courtesy of the Russian Defense Ministry*

Future trends in range and focus of military power will be driven by new mission areas. Recently, the Arctic has become more contested and congested. The Russian Navy has therefore initiated Project 23550 to build laser weapons to melt ice, helping their ice breakers advance further and faster (Yurov 2020).

In conclusion, this section discussed historical and present-day trends, primarily through examples of laser weapon systems, which can cause the bluntest of effects— destruction and damage at range— thereby projecting military power. Challenges for all DEWs include applying these effects at long ranges. However, concepts of operations for militarily relevant ranges have already been demonstrated. Trends in solid state laser technology were identified as key drivers that will extend ranges at which DEWs will effectively project military power by 2060.

2.2. Directed Energy Scalability and Flexibility in Application of Power within Phases of Conflict

In addition to destructive effects described in Sec. 2.1, DE provides options for what many refer to as dialable or scalable effects. Associated with dialable effects is flexibility in application of power across the leading phases of conflict, from *shaping* of the battlespace, *deterring* aggression, and *domination* of the electromagnetic spectrum (U.S. Joint Chiefs' of Staff 2018). DEWs provide these options by causing *effects* in militarily relevant scenarios. Low levels of laser light, millimeter waves, microwaves, radiofrequencies, and particle beams can all be absorbed in materials through processes fundamentally different from hole burning described in Sec. 2.1, but with known and potentially devastating effects. These effects include:

- Causing *destructive* fires (even children know that one can fry an ant with a magnifying glass.)
- Counter informational and specifically, counter ISR missions such as jamming , dazzling, infrared and radar counter measures that *degrade, disrupt,* and *deceive* sensors and electronic systems that are highly susceptible to specific frequencies of light
- *Denial* by non-lethal repelling, long-distance hailing, and ground base defense missions (Office 2020)

[4] Jamming is defined in terms of electronic warfare as the ability to disrupt or degrade a radiofrequency signal by increasing noise background levels such that a signal, typically communication or tracking signals are rendered useless.

[5] Dazzling is a similar concept to jamming, but at optical and infrared wavelengths. In dazzling an optical or infrared signal is disrupted or degraded by increasing noise background levels such that an optical communication signal is disrupted or degraded, or temporarily blinding an electro-optical imaging system or the human eye.

- *Disruptive* and *destructive* offensive operations from airborne platforms (Mayfield 2019, Chen and Zhou 2019)
- *Disruptive* and *damaging* counter electronic effects for defensive counter-air missions and establishment of point defenses (Michel 2019, Mayfield 2019, Cohen 2019, Robinson-Avila 2019).

Today, DE weaponry provides scalable effects and flexibility in application of power during the *shaping* of the battlespace, for *deterring* aggression, and *dominating* adversaries within the phases of conflict.

Historical and Current Examples of High Power Electromagnetic (HPEM) Weapons

Both high and low power/energy *effects* of DEWs are well known today. There are many examples of effective technologies in the class of DEWs called High Power Electromagnetics (HPEM), which include millimeter wave devices, high power microwave (HPM), and radiofrequency devices. Additionally, devices frequently called electronic warfare (EW) jammers create counter-electronic effects at both tactically relevant distances, such as kilometers, and at closer ranges suitable for special operations or gray zone warfare.

Electromagnetic jammers are so widely proliferated and militarily useful that in 2020 they are considered standard equipment in the arsenals of all major military powers, including the U.S., NATO, Western European militaries, Russia, China, and several other military powers in Asia (Hamamah 2017). Russia and China have well known anti-access and area denial capabilities based on both kinetic and EW defenses (S. J. Freedberg 2019, Yeo 2020). Especially for non-lethal applications, such as electronic attack and electromagnetic spectral dominance, both of which play key roles in *shaping* and *dominating* the battlespace, these weapons are clearly militarily useful today.

While EW jammers can degrade a target's ability to operate, HPM weapons can degrade, damage, and effectively destroy a target. HPM has demonstrated *scalable* militarily relevant effects. When used in concepts of operations that benefit from *convergence of effects,* cyber, EW, HPM, and traditional, kinetic weaponry together provide *flexibility* and *scalability* in application of power across all phases of conflict.

High power microwave weapons are typically characterized as generating electromagnetic radiation of frequencies ranging from 300 Megahertz – 300 Gigahertz, and with peak power over 100 Megawatts (Chen and Zhou 2019). Electromagnetic energy absorbed in this range induces electric currents in electronic devices that may result in either a disruption or failure of the electronics, and in extreme cases, physical damage.

Research and development of HPMs began in the 1970's and has only accelerated with the proliferation of electronic systems. Almost every aspect of modern civilian and military daily operations incorporates

Radio and Microwaves 101:

Frequencies of light in the radio part of the electromagnetic spectrum are the backbone of our modern communication systems. Higher frequency, so called microwaves and millimeter waves have proven useful for a variety of military DE applications. These systems typically have an electrically driven source, which generates the radio or microwave frequency light, and an antenna that can steer and focus the beam on a target. Electromagnetic jamming in the radio frequencies are common-place military techniques that cause denial, degradation, and deception effects. Many modern electronic devices are susceptible to microwave frequency light; it damages those devices.

electronic systems: in almost every facility, including communications facilities and networks, control centers for power grids, cell phones, ATMs, and even household appliances. HPEM and RF DEWs that attack these pervasive electronic systems offer *flexibility* and *scalability* in a range of missions and from a range of platforms today.

Gigawatt vacuum-tube HPM systems have been demonstrated. At Gigawatts of power, an HPM device can break-down air which adversely effects the ability to propagate the directed energy long distances. The upshot is that for applications in the atmosphere, a breakthrough in the ability to generate more power is *not* necessarily needed. However, a technological breakthrough in the capability to propagate directed energy through the atmosphere could help achieve greater on-target power levels and increase effectiveness. High power vacuum-tube based technologies, are typically quite large. Hence, vacuum-tube based HPM systems are often ground- or ship-based systems with meters wide high-gain antennas that focus the DE at tactically-relevant ranges of effectiveness on the order of 1 km.

Although HPM counter-electronic effects are clearly demonstrated, surprisingly the actual modes of electronics failure are poorly understood at a basic physics level and are active areas of research in 2021 (Clarke 2019, Cui 2019, Dietz 2019, Lawrance 2017, Peng 2017). As researchers in these areas discover the physical mechanisms behind counter-electronic effects, it is possible that by 2060, more efficient uses of HPM and counter-HPM technology will also be discovered.

Figure 6: *(Starting clockwise from the top left) The U.S. Air Force's airborne microwave weapon system, also known as CHAMP, preparing for flight testing; Chinese GaoXin (GX) unique special missions aircraft, GX-3 and GX-7 are reported to be jammers (Yeo 2020); the transportable U.S. Air Force's counter UAS, base defense HPM, referred to as THOR; U.S. Army's Tactical Electronic Warfare System which may deploy to European and Pacific theaters soon (Pomerleau 2020).*

Other unique attributes of HPM that make it militarily useful in both high-intensity and lower-intensity phases of conflict lie in the fact that, unlike lasers or particle beams, in low doses, HPM based DE is *non-lethal* to humans. This is another reason that HPM remains useful for counter-electronic attack, which is of significant current-day and future military utility for both traditional and special operations. This subject of non-lethal DEW effects for intermediate force operations will be described further in Sec. 2.4.

Similar to other DE systems already described, HPM is militarily useful on a wide range of platforms today. Large (tactical vehicle sized), ground-mobile systems that have moderate power (on the order of 10's to 100's of MW) and longer pulse duration, with antennas on the order of a few meters in size have been demonstrated for defeat of IEDs, crowd control, vehicle stopping—ground and air— and maritime vessel stopping (Office 2020, Underwood 2017, Mizokami, High-Powered Microwave Ray Gun Can Stall Cars, Trucks 2018, U.S. Joint Intermediate Force Capabilities Office 2016, Rehberg and Gunzinger 2018, Robinson-Avila 2019, Cohen 2019, Underwood 2017). Today, as previously mentioned, ground-based, maritime, and airborne EW jammers are widely proliferated (Pomerleau 2020, Congressonal Research Service 2019, S. J. Freedberg 2019).

Larger, higher power ground-based HPM systems have also demonstrated longer range of effectiveness (10s of kilometers) for defense against aerial threats, e.g. missiles, with RF seekers. The extended ranges of such systems are achieved by designing them to operate at the same frequency as a missile RF seeker, i.e. the frequency at which the seeker is most vulnerable. Because RF seekers are very sensitive, a HPM weapon can effectively *damage* them. With a damaged seeker, missiles may fail to find or track an intended target, increasing the missile-targeting system probable circular error (i.e. CEP).

Compact versions of HPM technology, on the order of hundreds of pounds, with moderate gain antennas have been integrated into airborne platforms, missiles, and remotely piloted aircraft (Chen and Zhou 2019). The effective DE range of these airborne HPMs remains limited, ~100 meters, but they fly long distances to cause DE effects near their intended targets. Furthermore, one airborne HPM can fire multiple times, effecting multiple targets.

A perceived drawback to HPM is that the effects are often temporary. On the other hand, temporary or reversible effects offer *flexibility* for lower-grade effects, desirable during various phases and intensities of conflict. For example, if one were to temporarily disrupt an adversary's communications, ground troops can overtake a facility and recover adversary data. Another example is that one could send airborne HPM weapons ahead of an air strike package to disrupt an adversary's integrated air defenses (IADs), increasing the success of a subsequent air strike. Furthermore, in counter-missile and -UAS applications, damage can at times be permanent since the vehicles are often destroyed after falling to the ground.

HPEM Proliferation Stat Shot 2020:

31 independent nations have built 321 EW or HPM DEWs for counter UAS missions.

In 2020, driven by base defense needs, counter-UAS (c-UAS) DE weapon systems are proving highly militarily relevant for defeat of aerial threats. This includes c-UAS swarms, because the high power microwaves propagate in a conical beam that can be several degrees across or larger, simultaneously disrupting the electronic subsystems and effectively destroying multiple UASs in the beam (Robinson-Avila 2019, Cohen 2019). HPM and EW technologies have been so remarkably *successful* as counter UAS systems that a 2019 report issued by Bard College lists 321 EW- and HPM-based systems of 547 total known counter-drone systems, originating from 31 independent nations (Michel 2019). We predict that these technological demonstrations represent *inflection points* for DE technology, as they prove these systems have evident mission utility. Demonstrations to date are compelling, so much so that there is widening international adoption of DE for counter-air missions. These successes confirm the vision that DE is a game changing technology for counter-air missions (United States Air Force 2017). Furthermore, although not necessarily as imagined by science fiction, today, DEWs are effectively acting like counter-UAS force fields.

Today, the most mature and operationally relevant HPM (Robinson-Avila 2019) devices are built around vacuum-tube systems specifically designed and fabricated for high power applications. The output of an HPM system typically consists of a high intensity pulse of electromagnetic energy with a specific central frequency, a finite bandwidth around that central frequency, and a duty cycle. Vacuum-tube systems are designed to be narrow-band, with a central frequency known to be effective against a target of interest. Unfortunately, duty cycles of vacuum-tube systems are inherently low, on the order of a few pulses per second.

In other areas of electronics, semiconductors long ago replaced vacuum-tube based systems. Although in 2020, semiconductor HPM technology cannot deliver the robust power of vacuum-tube based technologies, semiconductor systems can be made relatively compact, for example contained within a small form factor (meters) and weighing on the order of tens to a few hundred pounds. Additionally, semiconductor technologies can have very high duty cycles and customizable waveforms. Today, semiconductor HPM systems typically have low to moderate gain antennas due to platform constraints. They are proven to be effective at defeating electronic systems at short ranges, on the order of 10s to100s of meters. Importantly, the fact that these systems are much smaller and lighter means that they can be integrated into more agile, smaller, mobile and airborne platforms that can attack closer to the target. This fact may lead to a competitive edge over conventional HPM systems in terms of military utility.

Solid-state HPM devices are also technologically important for *flexibility* of effects. Another promise of technological advancement using solid state systems is that they can be narrowband, mesoband, or ultra-wideband. Mesoband means that the frequency range of the transmitted energy is contained within a moderate to wide band of frequencies. Additionally, solid state amplifiers can produce narrowband through wideband pulses with waveforms that are tailorable in terms of intensity and duration, leading to sophisticated waveforms. Semiconductor-based systems have central frequencies that range from about 1 to 10s of GHz, based on their intended effects. Importantly, and unlike vacuum based technologies, duty cycles for solid state systems can be very high, on the order of 100's to 1000's of pulses per second. From a DEW perspective that may translate to a very deep magazine! If Gigawatt power levels can be attained in significantly smaller packages, development of solid-state HPM should help the U.S. and Allies build more efficient, more compact, and more frequency agile DEWs over the next 40 years.

Future trends and challenges for HPEM weapon technologies

Because EW and HPM are useful across all phases of conflict today, we can conservatively expect they will be militarily useful in all phases of conflict over the next 40 years. As with laser-based DEWs, high power microwave-based technologies are expected to reach both a high level of technological maturity and highly relevant military utility by 2060, in even a pessimistic prediction.

Tech Reach Goals for HPM in 2060:

- **Gigawatt power levels in semi conductor technologies**
- **Better fundamental understanding of HPM effects**
- **Miniaturization of HPM**

Research and development trends today point toward reducing acquisition and operating costs of HPM systems. Semiconductor and solid-state based systems are seen strategically as an important technology driver. Expected commercial advancements in electronics, along with advanced materials and manufacturing, are likely to drive these technologies significantly over the next 40 years. Optimistically, HPMs can be made affordable enough that the benefits of a deep-magazine, perhaps up to thousands of shots in less than a minute, and low-cost per shot will be realized. Therefore, one can conservatively expect that by 2060, DE will continue to be an effective and widely-proliferated class of weapons on a wide variety of platforms: air, space, naval and ground based. Applications of air- and space-based HPM platforms are currently the most technologically challenged because the sizes of typical vacuum-tube based high-powered microwave systems are typically quite large.

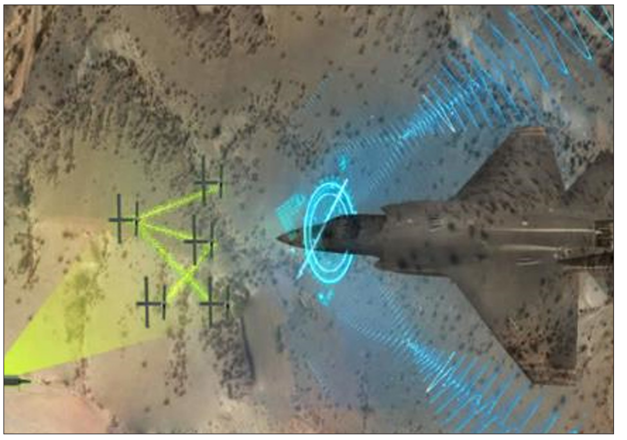


Figure 7: *Concepts for future electronic and counter electronic warfare rely on domination of the electromagnetic spectrum. Image courtesy of Raytheon. (Raytheon Technologies 2018)*

In 2020, all modern concepts for conducting joint operations and most service specific concepts of operations require control of the electromagnetic spectrum during all phases of conflict. For the directed energy community, electromagnetic spectrum superiority is a must-do mission and will likely drive trends in technology, military utility, and proliferation in 2060 and beyond.

Imperative mission needs for information operations (U.S. Joint Chiefs' of Staff 2014) in the future will drive trends in HPEM across all phases of conflict, including *domination of the battlespace.* The U.S. and Allies should continue to develop both defensive and offensive capabilities in all parts of the electromagnetic spectrum in order to *dominate* that battlespace. The backbone of 2020 information systems so fundamentally rely on radiofrequency and optical signals that freedom to operate in any modern warfighting concept requires DE weapons for electromagnetic spectrum superiority (Dayton 2016).

In 2020, concepts such as joint all domain command and control (JADC2) continue to be viewed as the best way to execute complex and coordinated missions of the future. *Domination* of the electromagnetic spectrum will be a key force enabler for those JADC2 missions. Although it is hard to imagine how technologically different the world of 2060 will be, we can conservatively predict, based on historical and current global technology trends that we will have a more internationally integrated communication system. Military applications that *disrupt* the power to, *degrade* performance of, or *destroy* key informational nodes will therefore be of great utility in 2060. DE will continue to be a key enabling technology for electromagnetic spectrum superiority missions, which are vital across all phases of conflict. These vital missions will drive HPEM trends over the next 40 years.

Highlighting the importance of electronics in 2020 modern society, this discussion also provides a compelling argument that the U.S. and Allies should address countermeasures to cyber and DE counter-electronic threats. Today those threats can come from peer competitors, rogue states, terrorists, and criminal organizations during all phases of conflict. We must guard against the DE equivalent of Pearl Harbors, Trojan Horses, and 9-11 style attacks over the next 40 years.

For future information, counter-sensor, and counter-electronic applications, considering all of the frequencies and wavelengths of DE discussed, it is an obvious conclusion that *frequency agility,* as part of information superiority operations will be vital by 2060 in order to operate in a contested and congested electromagnetic spectrum. Frequency agility means the ability to rapidly change the frequency composition of a DEW, either by tuning the frequency of a device, creating broad-band and tailored waveforms—where the frequency and energy composition of a DE beam varies as a function of time— or using another DEW device, in a complimentary manner. Additionally frequency agility can be used to defeat DE countermeasures and may be vital to retaining U.S. technological leadership in low-power DE missions, as well as high-power ones over the next 40 years.

To summarize, *flexibility* and *scalability* in application of power within the *phases of conflict* is an important concept for predicting the trends of military utility out to the year 2060. In this section we described DE usage in 2020 focusing on electronic warfare and high-power microwave weapons that demonstrate *scalability* of effects and *flexibility* as part of a broader layered defense strategy. This strategy includes conventional, cyber, and other weapons, to apply military power within the phases of conflict.

Counter-ISR, counter-electronic, c-UAS, non-lethal counter-personnel, and offensive and defensive informational DE missions are all described in this section. Based on the history of progress to date, one can expect that by 2060, several of these missions will continue to be important and evolve in an ever more electronic and connected world.

2.3. Precision of Directed Energy Weapons in special operations

Building on the concepts of Sec 2.2, precision of effects is important to certain missions including special operations. One of the remarkable characteristics of DE weapons is the ability to create a precise effect. For laser weapons that includes precisely boring a hole at range, effectively destroying or disabling a target, in addition to other effects. For example: igniting fires at range, and damaging or dazzling of a sensor. HPEM DEWs create precise effects in counter electronic attacks where they disrupt, deny, degrade, and in some cases damage or destroy equipment. By their very nature, DEWs that operate in non-visible portions of the electromagnetic spectrum are often non-attributable, or challenging to attribute, because the DE beam is invisible. Since they are precisely directed and ephemeral, even with infrared, microwave, or RF sensitive instruments, it is challenging to locate the source of the DE. With these characteristics, DEWs often find utility in special or covert operations.

A third example of DE weapons that we have not yet described in detail and are potentially useful for special operations are based on particle beam technology. Particle beam (PB) technologies generally fall into two sub-categories, electron or charged particle and neutral particle beams. PB concepts have the advantage that they penetrate into a material deeper than light can penetrate. Particle beam technology is known to create counter electronic effects, similar to HPM and RF technology. The characteristic of deeper penetration in materials, such as through metals that shield electronics against lasers, HPM, and RF, makes particle beams promisingly effective for applications where other DEWs are not.

Due to interactions with air, PBs do not propagate far within the earth's atmosphere. For this reason, as DEWs, particle beams are currently limited to either special operations where they can be used at close range or high-altitude operations.

As with all DEW technology, the desired end result is effects on a target. In the case of particle beams, gamma and X-rays are produced as secondary radiation which causes *destructive* effects in materials of military relevance. Also similar to other DE, particle beams see world-wide applications in medical and industrial processing, and from that perspective particle beams are today widely proliferated.

Historical and Current Examples of Particle Beams

PBs are unique because of their ability to penetrate into matter and deposit energy, frequently altering the material properties. This quality can be particularly useful when a target is shielded, such as for medical purposes, when trying to burn a deep tissue tumor, or for military purposes such as penetrating a missile airframe to disable the guidance electronics.

Charged beams consist of a collection of protons, electrons, or ions. Neutrons, photons in the X- and gamma-ray portions of the electromagnetic spectrum, and non-ionized atoms constitute neutral beams. X-rays and gamma rays are also generated as secondary effects of both electron and proton beams. Protons and ions being large and charged, typically do not travel far in matter, including the atmosphere. As such, their many military applications remain unexplored. Neutrally charged atoms share these same characteristics. Currently, then, the remaining particles – electrons, neutrons, and gamma or X-ray photons – are typically considered for military application (Berger 2017, Carron 2007).

Many technologies exist to accelerate electron and neutron particles up to militarily relevant energies, typically in the tens to thousands of Mega-electron volts (MeV), including RF and induction linear accelerators, neutron generators, synchrotrons, and free electron lasers, each with varying applicability to the battlefield.

The first PBs were created in cathode ray tubes in the late 19th century. High energy accelerators were not invented until the 1930s. Today, non-military applications of particle beams are most common in the field of medicine, where X-ray, gamma ray, proton, and atomic ion beams are used for cancer treatment (Trikanlinos 2009). Other non-military uses include ion implantation, industrial processing, and research (Feder 2010).

Particle Beams 101:

Technologies similar to HPM devices can also be used to create beams of particles. Particles, typically electrons or neutral particles, can be accelerated to nearly the speed of light. Although less developed than laser or HPM DEWs, particle beams have unique properties that could be weaponized, including for counter electronic attack, material degradation, and secondary radiation effects.

In the 1980s, the United States made significant investments in charged and neutral particle beams as part of the Strategic Defense Initiative (SDI), colloquially known as "Star Wars". A significant portion of SDI investments were in the area of particle beam weapons to counter ballistic missiles. The Beam Experiments Aboard a Rocket (BEAR) project launched a neutral particle beam system onto a suborbital trajectory to test propagation theories as a part of that initiative (O'Shea 1990). High altitude applications, where the atmosphere is thinner, and space-based concepts for particle beam-based DEWs have been considered for militarily relevant use cases by both the U.S. and Soviet Union (Kornilov 1993, Whitney 2005, O'Shea 1990, Trevikthick 2019). These efforts typically focused on high-power beams, which created additional propagation challenges, and have proven to be a technology barrier at this time.

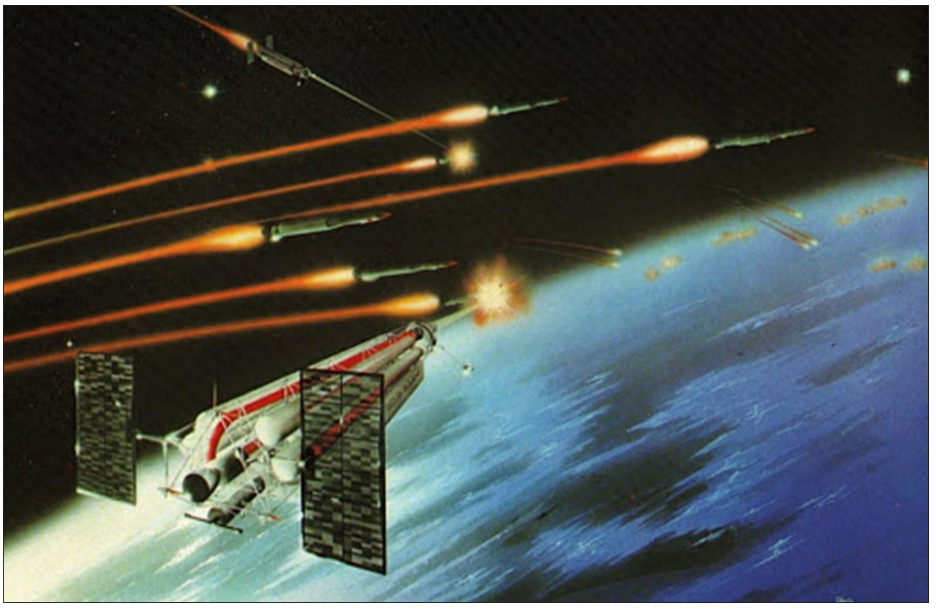


Figure 8: *Concept drawing of low-earth orbiting particle beam weapon, courtesy of Los Alamos National Laboratory via Aerospace Projects Review (Trevikthick 2019).*

Today, compared to other DEWs, particle beam weapons appear limited in military utility and proliferation. Many nations participate in the technical fields of particle physics, using particle accelerators, and the same underlying principles apply to generate particle beams for military purposes. However, many of the recent international trends in particle physics are toward larger and larger accelerators, which have less utility from a military perspective because of SWAP concerns. The particle beam community realizes that this trend cannot, however, continue. Promisingly, there is interesting research into using compact, 0.1- 4 m, linear particle accelerators (Chao 2013, Lewis 2019) for the production of radiation in the 1-100 GHz range, which, like HPM, could be used for counter-electronic purposes. Creation of efficient small particle devices, comprises a *technological inflection point* worthy of further research, as these low-SWAP devices would be of interest for air, space, short-ranged maritime and ground-based applications.

Future Trends and Challenges for PB Weapon Technologies

Despite investments spanning several decades, PB weapons are currently unproven and significant challenges to their adoption remain. Neutron and photon beam sources in SWAP-constrained packages are insufficient to generate militarily relevant effects.

In order to be militarily relevant by 2060, particle beams must propagate militarily relevant distances. Electron beams are currently considered to be the most likely to find military application, albeit that today, due to technological limitations, propagation can only be achieved poorly in the earth atmosphere. Militarily relevant systems are currently limited to less than a few hundred meters of effective range. Longer ranges are possible with higher energy electrons (~1 km at 1 GeV at sea level).

The International Plasma Sciences Committee issued a grand challenge in their 2020 decadal study to improve understanding of the interactions of lasers and particle beams, to include for the purposes of advancing national security (Committee on a Decadal Assessment of Plasma Science 2020). Optimistically, the response to this grand challenge will greatly improve propagation distances within the earth atmosphere through further research investments.

Other technical issues that will shape the future relevance of participle beams are that they generate ionizing radiation, meaning they pose significant risk to operators, bystanders, and enemy and friendly soldiers in the battlespace. As such, particle beam targets are conservatively anticipated to be limited to locations with carefully prescribed "keep out" zones. With these two challenges in mind, terrestrial and maritime particle beam applications are today thought to be possible, even in pessimistic forecasts, but limited to special applications where stand-off distances can be very short.

Particle Beam Tech Reach Goals for 2060:

- **Develop concepts to increase particle beam power projection**
- **Better fundamental understanding of particle beam effects**
- **Miniaturization of particle systems**

At altitudes above 30,000 feet, where human exposure is less likely and the atmosphere is thinner, the outlook for particle beams is much more positive, in conservative projections. Propagation ranges for electron beams above 30,000 feet extend from hundreds to thousands of meters even for small systems. As mentioned, high altitude applications and space-based concepts for particle beam-based DEWs have been developed. Challenges for these applications include SWAP vs. electron energy and range issues, particularly the weight of systems that need to be lofted to high altitudes for long periods of time.

The technological advancement most likely to be impactful for electron beam weapons in the future consists of increased acceleration gradients. State of the art accelerators today typically reach 50 MeV/m, but ongoing research into W-band RF linear accelerators promise to make 200-400 MeV/m gradients a reality in even conservative forecasts. Improvements in energy storage and conversion also conservatively promise to make electron beam weapons militarily feasible by improving their SWAP.

With conservatively projected SWAP improvements, the military utility of particle beam systems at or near sea level will increase with increasing range for both special and normal military operations. Still, risk of biohazard and associated policy issues will remain, and will limit applications. If advancements in SWAP are achieved, these technological improvements will make the most difference in high altitude applications. With lighter and more powerful PB systems, airborne systems may reach higher altitudes and can remain aloft for longer durations.

Should the described technological advancements be achieved, it is expected that the military utility of particle beams will increase significantly. As mentioned before, many nations participate in accelerator research, hence it is anticipated that, if driven by increasing military utility and technological capability, conservatively proliferation could rapidly increase. Pessimistically, proliferation could increase significantly. Proliferation of PB technology would pose a significant challenge, both legally and to U.S. security and military superiority in future engagements. Nevertheless, these examples illustrate how DEWs can be very precise and powerful in special and high-altitude operations, and why the U.S. should continue its investment in this area of research lest other nations take the lead.

2.4. Directed Energy Weapons for Intermediate Force Operations

A very useful characteristic of DE weapons, especially for gray-zone warfare and in low-intensity phases of war is the ability to create non-lethal effects. Prior sections discuss these *intermediate force* effects in terms of counter-material effects, informational effects, counter-personnel, and for scalable effects in low-intensity conflicts.

Notably, precision uses of DEWs for non-lethal operations rely on knowledge gained through rigorous scientific experimentation and understanding of the electromagnetic spectrum to produce *spectrally precise* effects. The human body, devices, vehicles, and structures are all composed of matter that is in some proportion either absorptive , reflective, or transparent to specific frequencies of light, the latter meaning that light may pass through with little or no effect. Exploiting frequency specific effects of absorption or transparency in matter, light can be used to generate *spectrally precise* militarily useful effects in specific electromagnetic spectrum frequency bands.

For example, low levels of RF and microwave frequencies of light find uses world-wide for television, radio, cellphones, wireless internet, satellite and other communication signals. Moreover, these specific frequencies of light are largely transparent to materials that make-up walls and other structural components, enabling their usage for communications inside buildings and vehicles. In addition to their military and everyday utility for communications, all of the devices that generate and receive these frequencies of communication can be deceived, disrupted by jamming, or more damaging counter-electronic effects. By exploiting the absorptive properties of human skin relative to millimeter waves, a higher frequency of HPEM than RF and microwaves, a non-lethal counter-personnel effect can be generated.

In another example, eye-safe, low-power infrared light can used for fiber optical communications or conversely to generate spectrally precise, deceptive false signals, dazzling, or damaging effects in infrared sensors. Because the human eye is insensitive to infrared light, at low-enough power levels it poses little danger of collateral-effects to the human eye. Alternatively, light in the higher frequency optical portion of the electromagnetic spectrum is strongly absorbed in the human eye and can be used for dazzling and non-lethal blinding.

Historical and Current Examples of DE Weapons for Intermediate Force Operations

As was mentioned previously, HPEM can be used for both counter electronic attacks, and, if used in the millimeter part of the spectrum, non-lethal counter personnel operations (Office 2020, U.S. Joint Intermediate Force Capabilities Office 2016). Human skin is chiefly composed of water, which strongly absorbs 95 GHz light. The Active Denial System (ADS) produces 95 GHz DE to non-lethally heat the topmost layer of human skin, acting to effectively deny people access to locations. People have described the physical effect of this DE as like facing a roaring fire. This *spectrally precise* effect can be thought of as creating a force field that repels crowds around an embassy, base, port, or other high value location.

[6] W-band frequencies range from 75 to 110 GHz in the microwave part of the electromagnetic spectrum

[7] This is known as Kirchoff's empirical law of spectroscopy.

The Active Denial System underwent extensive testing for effectiveness and human safety. It was also deployed to Afghanistan in 2010, but not used in conflict. The U.S. DoD Joint Intermediary Forces Directorate continues to support ADS, and concepts for application continue to be explored. Despite those efforts, the technology largely remains "on-the-shelf." Speculation about the reasons for not deploying ADS include simultaneously and perhaps perplexingly, concerns about both safety, in other words effectiveness, and lack of effectiveness of the technology. For these reasons, ADS is often considered as an example of how public acceptance of DE technology can limit the military utility of it.

Both today and in the future, this class of weapons offers unique options for security and special operations, low-level conflicts, and war in the gray-zone. The U.S., Russia, and China are all reported to have developed non-lethal ADS-like systems (Hambling 2012, Letzter 2014). Going into the future, whether or not the U.S. and Allies deploy this DE technology, it is quite possible that U.S. military members will face it in conflict.

Low-power optical wavelength laser light is used today as a non-lethal weapon for dazzling and blinding humans, which is a well-known but a policy-restricted military application in the U.S. Sadly, as the U.S. Federal Aviation Administration reports, lasers have been used for criminal purposes to blind pilots, endangering the innocent lives of the flying public (U.S. Federal Aviation Administration 2019).

Today, laser pointing, blinding, and dazzling are militarily useful during information operations, counter-optical and counter-infrared sensor attacks, protests, and policing operations (Cronin and Neuhard 2020, Taylor 2019). During recent protests in both Hong Kong and the nation of Chile, laser dazzlers have been used by both police and protesters.

Moreover, because optical and infrared sensors are susceptible to low levels of laser light, laser illuminator weapons can achieve disruptive and damaging effects as counter-situational awareness tactics, depending on the degree of effect required at a defined stand-off distance. These militarily relevant and widely proliferated examples of DEWs are available for ground, naval, airborne, and space-based purposes today.

Future Trends in DE Weapons for non-lethal operations

Spectrally precise effects across a wide range of non-lethal operations, power, and posture for acceptance of non-lethal risks remain key considerations for the U.S. and Allied nations to achieve the full promise of DEW technology for non-lethal operations. Continued effects research and development is needed to support public acceptance of intermediate force DEWs at specific power-levels and frequencies. As discussed in prior sections, there are paths to successful deployment of DEWs by the U.S. and Allies, even in pessimistic future projections. However, policy limits applications at many frequencies and

Figure 9: *(left to right) A Chinese non-lethal counter personnel system (credit Top81 via IHS Janes); The U.S. Joint Intermediate Forces Directorate Active Denial System, a counter-personnel millimeter wave system; Russian counter-personnel system (Hambling 2012).*

power levels. Any policy must guide acceptable application of DEWs for non-lethal and all intermediate force applications, both today and in the conceivable future. Resolution of DE policy and acceptance issues represent an *inflection point:* if these issues can be resolved, the U.S. and Allies should continue to develop new technologies and militarily relevant capabilities, and if not, DE technologies are destined to be either stuck "on-the-shelf" or limited to niche military applications as they are today.

Figure 10: *Imagery of Hong Kong protestors and police using dazzler lasers on 12 June 2019, published by Longsheep on reddit.com*

The lamentable trend in proliferation of small lasers, even to non-state actors and criminals, is an illustrative one. It is a tragedy that, internationally, the flying public's lives are imperiled by Class IV lasers that can easily damage the human eye, and can be purchased on the internet for less than $200. Small cheap lasers are a "poster child" for why by 2060, and hopefully sooner, better global policies on trade of DE technologies are needed. Fortunately, countermeasures to these widely available lasers can easily be implemented, albeit at increased cost. Optimistically, the U.S. and its Allies will suffer little imposed cost while strategically imposing cost on adversaries.

In summary, today DE power levels are intense enough to generate effects through many non-lethal intermediate force operations that rely on exploitation of *spectrally precise effects.* By 2060, in conservative projections of the future we expect increases in range as power levels increase and there is tighter integration into missions that offer greater flexibility and scalability. Policies regarding usage of DEWs must be developed to guide DEW usage for military operations.

2.5. Speed of application of power within the battlespace – How fast can DE engage targets in battlespace?

In the 5th century B.C.E., Sun Tzu stated: "What is of greatest importance in war is extraordinary speed: one cannot afford to neglect opportunity." Since extraordinary speed has been important in warfare for the past 2025 years, it is a safe prediction that speed will continue to be important over the next 40 years.

In fact, the promise of greater future military power enabled by speed in a higher paced future conflict is likely to be more important in 2060. Other technology areas, including hypersonic vehicles, material and other advances in computing and electronics, advanced sensing, and autonomy, are likely to increase the pace of future conflict. Important challenges of today will remain and could be amplified in a high-paced future conflict. For example, consider the startling challenge of creating or maintaining the ability to engage multiple high-speed targets, within a targeting cycle, or within the Observe, Orient, Decide, Act (OODA) loop of an adversary's targeting cycle, in a much more automated and advanced future battlespace.

One of the greatest promises of DE is that nothing travels faster than light. Compared with traditional munitions, DEWs have a significant speed advantage.

Historical and Current Examples of DEWs and Speed of Light Effects

Historical and current day examples that have been briefly mentioned but bear revisiting in the context of nearly speed of light effects include laser, HPEM, and particle beam technologies. DE weapons of sufficient power/energy levels initiate effects at a distance, at the speed of light (or for PBs, up to 99% the speed of light). However, the actual effects of DEWs may be realized over longer timescales, thus we will analyze nuances of timescales for a sensor-shooter system. To illustrate this, we discuss the stressing case for high-speed of warfare, the tactical timelines for information operations and the timelines for space-borne and airborne vehicles, where the fastest speeds are required. At the speed of light, a stand-off range of 1 km equates to initial target engagement[3] microseconds after the shot. But this analysis alone is potentially very misleading, because DE and all weaponry require time to find, fix, track, target, *engage,* and assess (F2T2EA), according to the standard definition of the targeting cycle, all of which typically require longer periods of time.

Numerous examples of militarily relevant informational, counter-sensor, counter-electronics, and non-lethal effects have been described in prior sections, all of which are relevant examples of the power of DEWs to rapidly engage targets in the battlespace. Although the DEW begins target *engagement* at the speed of light, typically the described DEWs require micro to millisecond engagement times before creating a desired military effect. In general, the time before effects occur depends on power, range, and hardness of the target.

With current day electronic and computing technology, realistically a targeting cycle can at best be closed on millisecond timescales. That is assuming that the find, fix, track, target (F2T2) portion of the cycle happens at electronic speeds, i.e. milliseconds, and the time required to achieve DE effects is also milliseconds after initial target *engagement.* Under normal circumstances however, this would be extremely optimistic. Today, anywhere that human interaction is required, targeting cycles may be limited by human reaction times which are at best milliseconds to seconds long. Therefore, when you add it all up, finding, fixing, tracking, and targeting typically happens today over seconds-short timescales at fastest. For a concrete example, consider that the requirement for the targeting cycle for an intercontinental ballistic missile intercept is on the order of tens of minutes (Becker 2017).

Counter-air missions, to include counter-hypersonic ones, are a significant and potentially existential challenge in all warfighting domains. In Sec. 2.3, particle beam DEWs and effects were described that could counter missiles on millisecond timescales, if SWAP and propagation issues were resolved. In-band laser or HPEM counter missile systems described in Sec. 2.2, are effective today at tens of kilometers, on millisecond to second timescales, depending on power, range, and hardness of the target. Although it is fortunate that these systems are possible today because they offer ability to reduce the effectiveness of missiles, there are a few practical drawbacks to using these DEWs as they require a priori knowledge of the missile seeker spectral sensitivity, they often require large platforms due to SWAP concerns, and if counter DE technologies were incorporated into seekers, the DEW effects could be rendered useless. Hence, especially when attempting to counter a missile, users often desire a blunter or otherwise more reliable effect.

In Sec. 2.1, it was described that with the 2020 class of high-energy solid-state lasers, typically in the hundreds of kilowatts range, several seconds may be required to create blunt damage effects at tactical distances, i.e. structural failure in metal or other hardened materials. As laser power scales up, the necessary engagement times to create effects tend to decrease. Predicted to be possible in 2060, with optimistic advancement of solid-state laser technology, hundreds of Megawatt-power lasers can close the gap in total *engagement* time down to millisecond timescales, which would enable high energy laser DEWs to engage as fast as, or faster, than kinetic effectors.

[8] For the purposes of this discussion engagement begins after the steps of finding, fixing, tracking, targeting and concludes when DE effects are achieved. The total engagement time for DEWs is the time that passes during propagation of the engagement distance plus the time required to deposit energy and achieve desired effects.

Compare for instance, the potentially several-millisecond DEW engagement timescales with those of a hypersonic vehicle, where at Mach-5 the vehicle covers 1 km in a little more than 1/2 a second. Promisingly, millisecond engagement timescales are *2 orders of magnitude faster* than the time of flight of a hypersonic missile!

Therefore, a tactical hypersonic intercept could be possible, if the targeting loop can be closed fast enough, with the constraint that seconds to minutes long targeting timescales may limit effectiveness of missile intercepts at tactical ranges. DEW effects data on real or surrogate targets are required to solidify the assumptions about effectiveness timescales in these order of magnitude estimations. Experimentation to collect such data are underway, and should be continued as threats evolve.

At longer ranges, for example intercontinental missile ranges, the time required to close the F2T2EA loop is longer, on the order of tens of minutes. Mid-course engagement from a pre-positioned DEW, space-based or high altitude, could therefore be effective on intercontinental ballistic missile timescales. For long to medium range cruise missiles today, which travel near Mach-5 over hundreds of kilometers distance, flight times are on the order of a few minutes. Finding, fixing, tracking, and targeting of missiles may also take minutes, necessitating a rapid engagement. Thus, a pre-positioned DEW, airborne or space-based, could be effective on fast enough timescales to permit mid-to-long range cruise missile intercepts. Ground or ship-based DEWs, for base-defense missions may also be effective if they can close the targeting loop fast enough.

Future Trends for DEWs and Speed of Light Effects

Future trends in DEWs will be driven by military needs for high speed effects. This includes both for informational, counter-sensor, counter-material, and non-lethal effects, when rapid reaction times are not necessarily critical, and counter-air effects when they are.

As analysis in this section demonstrated, at tactical engagement distances, closing the F2T2EA loop in less than a fraction of a second will be required to effectively counter tactical hypersonic missiles. An optimistic goal by 2060 would be to reduce targeting and engagement latencies for DEW systems, at tactical distances, to milliseconds for space, air, ground, and maritime based weapons performing counter-air-missions. Reduction to millisecond timescales could permit multiple DEW intercepts, which may be necessary in future conflict scenarios where multiple targets are likely.

Longer range defense, where missile flight times may be minutes, do not require such short latencies. Unfortunately, at longer distances, DE beams suffer from divergence. Consequentially, longer distances require longer dwell times to create effects, and this argues for higher power/energy DE systems that can put sufficient energy on target to cause rapid effects. Still, in conservative and even pessimistic predictions, concepts of operations can be conceived that appropriately pre-position weapons in order to counter missiles. For pre-positioned weapon concepts, the technical challenges to resolve are reduction in SWAP and achieving affordable and reliable CONOPs.

Pessimistically, the goal of reducing latency in targeting could be achieved by 2060, because in 2020, many of the foundational capabilities required for these types of missions are already proven. Electronics and computing, especially with anticipated advances in autonomy, are likely to quicken and be more efficient by 2060. Conservatively we expect that with advances in electronics and computing, targeting on millisecond timescales will be possible by 2060. These future trends in electronics and computing speed will be driven by both commercial and military needs. Optimistically, with advances in computing and higher-bandwidth electronics, microsecond or shorter timescales could be realized.

Low-energy DEW effects can be achieved today with particle beams, HPEM, and lasers. Each of these technologies have SWAP challenges and some are power limited. For those reasons, although closing the targeting cycle is forecast to be conservatively achievable, an optimistic DE future is required for DEWs to be militarily relevant in tactical missile defense. The achievement of much higher energy solid state lasers is therefore an *inflection point* for DEW technology, enabling critical missions in 2060. Reduction of SWAP in particle beam and HPEM systems, such that airborne and space borne applications allow pre-positioned CONOPs, could be another *inflection point.* With the development of solid-state sources, HPEM SWAP reductions are expected, as was described in Sec. 2.2. SWAP reducing technologies were also described in Sec. 2.3, with regard to particle beams.

Figure 11: *Art of autonomous DEW battles. In the future battles may happen at a pace faster than humans can think.*

Amplifying a concept discussed briefly in Sec. 2.2, for future information, counter-sensor, and counter-electronic applications of power within a battlespace, with all of the frequencies and wavelengths of DE discussed, it is an obvious conclusion that *frequency agility* is also an important concept. In fact this concept will be a vital enabler of information superiority operations by 2060, in order to operate in a contested and congested electromagnetic spectrum.

Interestingly, the concept of frequency agility is also one of importance when considering the ability to engage multiple targets across the battlespace. One can predict that in the future, and perhaps even by 2060, the pace of battles may be measured on millisecond timescales, which by some estimates is faster than a human can think. Today the technology exists in research labs to conduct the DE version of a Rock'em Sock'em robot battle, where "Red" closed loop DE weapon and sensor systems battle "Blue" closed loop DE weapon and sensor systems. Both systems can autonomously and rapidly vary tactics, *agilely switching frequencies,* to create a variety of *spectrally precise* effects, all while defending against, and attempting to overcome each other's attack. These simulated battles are waged at speeds on the order of milliseconds, enabled by autonomous sensing and decision making.

In this section, the ability to rapidly generate deceptive, denying, degrading, damaging, and destructive effects in the battlespace is explored, in the context of a simple analysis of how fast DE effects can reasonably be achieved. Additionally, this analysis investigates how fast effects must be achieved to realize the full power of DE for counter-air defense missions, in an optimistic future.

Today, DE power levels are intense enough to generate millisecond timescale effects in many informational, non-lethal, and counter-air operations. By 2060, we optimistically expect increases in range and effectiveness to increase as well.

DEWs are adequate today for providing near speed of light effects in the battlespace for many missions. Going forward over the next 40 years, flexibility of effects in the electromagnetic spectrum will rely on operations at a variety of power levels and a variety of frequencies. Furthermore, the ability to agilely change frequencies and modes of effect are a natural extension of DEW military power which promises to enable electronic warfare at millisecond timescales.

2.6. Platform considerations of size, weight, power, and affordability

Military utility of DEWs across a wide range of missions and platforms requires that they meet size, weight, and power requirements (SWAP) in addition to affordability and considerations of Doctrine, Organization, Training, Materiel, Leadership and education, Personnel, and Facilities (DOTMILPF).

As has been described already, today DE finds use in several militarily relevant applications. Specific examples consist of DE illuminators and electromagnetic jammers widely accepted as essential components of both how the U.S., Allies, and near peer competitors apply military power across all phases of conflict today. These DE technologies are integrated into a variety of military platforms and have achieved acceptable SWAP characteristics. As we have already described, technology trends over the next

Figure 12: *U.S. Army concept drawings of counter-swarming UAS strikers.*

40 years will continue to push directed energy weapon SWAP reduction in several ways.

As with any military technology, adoption of DE technology remains likely if the technology can either accomplish a unique and necessary function that enables a mission, or if within the considerations of DOTMILPF, when compared with alternative approaches DE enables a more affordable solution. For this reason, today most discussions of cost of DEWs revolve around the ability to achieve the promise of a deep magazine and low cost per shot. Neglecting non-recurring engineering costs, for the systems of today, in 2020, we have achieved those balances in several areas. Pointers, jammers, dazzlers provide unique capabilities in affordable, SWAP acceptable packages. Mobile weapons for shooting down soft targets and denying ISR collection are already proving more effective than many alternatives (Michel 2019).

Take for example counter-UAS capabilities; net guns, shotguns, are effective at 10s of meters ranges, but less effective than c-UAS DE systems at ranges nearing 1 kilometer. Missiles or UASs can achieve c-UAS effects at long ranges, but are expensive compared with the favorable cost per shot that c-UAS DE systems provide. Counter-UAS DEWs also provide the unique capability to defeat swarms in a single or few shots—achieving low-cost per shot and deep magazine effects.

Given the state of DEWs today, we conservatively predict that DEWs will be able to achieve lower cost per shot and deeper magazine than alternatives for several specific missions by 2060. The ground and maritime base defense mission areas are already nearing that tipping point.

Table 1: Summary of DE Missions & Military Utility in 2020 (black font, black stars) and conservative forecast in 2060 (blue italic font, blue stars). One star represents one of the five "D" effects.

Missions/operations enabled:		Information Superiority	Non-Lethal Effects	Counter Electronic/Sensor	Counter Air
Range and Focus of Power	DEW Effects	Deny Degrade Damage Deceive	Deny Degrade Damage Deceive	Deny Degrade Damage *Destroy* *Deceive*	Deny Degrade Damage *Destroy* *Deceive*
Scalability and Flexibility in application of Power					
Speed of Application of Power					
Precision applications					
SWAP Suitability for Platforms		Ground, Naval, Air, *Space*	Ground, Naval, Air, *Space*	Ground, Naval, *Air, Space*	Ground, *Naval, Air, Space*
Relative Military Utility Assessment		★★★★	★★★★	★★★☆☆	★★★☆☆

Table 1 summarizes the DE missions and operations enabled, and a general description of military utility in 2020 on a variety of platforms suitable for five physical warfighting domains, ground-based, naval, air, and space. Relative military utility is assessed according to 2020 ability to create military effects for a specific mission or type of operation, in a SWAP suitable platform, as has been described in this section. Conservative forecasts for those characteristics in 2060 are also assessed.

Future Trends for DEWs in SWAP and Affordability

The commercial laser, communications, electronics, and semi-conductor industries have been technology drivers for the past 50 years, and we can expect that those industries will continue to drive trends toward smaller packaging and better electronic efficiency. These commercial forces will drive trends in SWAP and affordability more than military applications.

While it is challenging to contemplate all of the myriad ways technologies will be different in 40 years, we can reliably predict that militaries will follow important technological trends that develop in the rest of the world's biggest markets. The information sector of the U.S. economy, reliant on the current semi-conductor architecture, in 2020 is expected by many to be a huge growth area and is closely monitored today (Lerman, et al. 2020). One could argue that the information and consumer electronics industries underlie most, if not all, of the other contributors to the U.S.'s GDP defined by world-leading economics analysts (The Deloitte Network 2019). Thus, technology drivers in electronics and communications will be primarily influenced by investments made by commercial industry, which is estimated to be in the trillions of dollars. The U.S. investment in all of military equipment and operations in 2020 is $740 Billion dollars, less than 1% of which is invested in electronics, communications, EW and DE research. We conservatively can expect therefore that the technological trends over the next 40 years in electronics, communications, EW, and DE will be driven by investments from the commercial sector.

One can expect that commercial industry will drive toward specific goals for better power efficiency, more affordable, smaller, more integrated package sizes, and faster rates, driven by desires to decrease costs and raise profits. If these commercial drivers result in new technology architectures, DE technology will follow suit.

The U.S. Military and its Allies should therefore invest in development of electronics and electro-optical systems to meet specialized needs that satisfy uniquely military requirements. For example, military applications often require higher power or higher energy devices. Hence, investments by militaries should focus on those aspects of electronic and photonic devices, while leveraging commercial and industrial technology trends in both electronics and photonics over the next 40 years to reduce SWAP and cost.

Breakthroughs are also expected in several areas e.g. material, manufacturing, and component-level breakthroughs that can result in further reduction of system size and weight while increasing power output. Specifically, current research in solid state switches, batteries, and capacitors, key HPEM system components, will conservatively evolve and could lead to breakthroughs in HPEM effectiveness.

Another potentially exciting development is in Gallium-nitride, a material dubbed "the next silicon" because it shows promise for replacing silicon, the current backbone of electronics (A. Chen 2019). It is reported that Gallium-nitride sustains higher voltages, conducts current faster, and more efficiently. These improvements all hint at significant SWAP, affordability, and efficiency improvements in all electronic devices in an optimistic future for DE.

In summary, over the next 40 years commercial and military interests are expected to drive SWAP and affordability for many aspects of DEWs. This conclusion is supported by historical precedent, current investment levels, and the promise of breakthrough technologies in the future.

3. Future States

The futures states analysis that we performed is conducted in the context of DE 1.) Prevalence, 2.) Science and Technology advancements, and 3.) Military relevance/utility. The trends analysis assumes the three categories to be mutually independent. Global Prevalence captures who world-wide is projected to utilize DE for military applications: Pessimistically, the U.S. and Allies do not have access to the most effective DE technology, while unfortunately others do; Conservatively the U.S., Allies, peer-competitors, rogue states, terrorist and criminal organizations have access to DEWs, as is the case today in 2020; Optimistically the U.S. and Allies *only* would have access to the most effective DE technology in 2060. Definitions of the S&T Advancement category are: Pessimistically, DEWs are no more advanced than they are today; Conservatively, incremental continuous improvement in DE tech will progress towards goals stated in Sec. 2; Optimistically, either by incremental engineering advancement or tech breakthroughs, the stated tech goals will be achieved. Military utility/relevance in 2060, pessimistically, will be roughly the same as today, niche applications and useful for informational and counter-informational operations; Conservatively, DE-enabled missions will grow; Optimistically, DEWs will be of great military utility because they enable important missions that could not otherwise be accomplished, and/or DE technology significantly reduces cost and/or complexity over alternative approaches in 2060.

Given the background and stated pessimistic, conservative, and optimistic trends in DE discussed in Sec. 2, we now describe seven future states. These seven future states bookend the forecasted Global Prevalence of DEWs/Science & Technology Advancement (S&T)/Military Relevance.

1. Positive DE US futures

a. Big Dog – Prevalence: Optimistic/ S&T: Optimistic/Relevance: Optimistic

i. Summary description: Major advances are made across DE enabling technologies and translate into military capabilities that have a major impact on military operations across the kill chain, within and across domains and across all phases of conflict. Within this future the US & Allies maintain a significant lead over all rivals and potential adversaries in DE enabling technologies, and in converting those technologies into required military, operational capabilities.

ii. Challenges: With such a high level of military significance for DE enabled capabilities peer competitors vigorously pursue matching if not exceeding US DE capabilities. The U.S. is hard pressed to maintain a technological lead across the wide area of DE technologies and capabilities relevant to military applications. Any such lead remains intrinsically fragile in time and as to military advantage.

b. DE niche world - Prevalence: Optimistic/S&T: Pessimistic/Relevance: Optimistic

i. Summary Description: Only moderate progress in advancing DE technology is achieved, but that sufficiently produces significant areas of important military capabilities. These military capabilities have specific applications within the kill chain, across domains and phases of conflict. The U.S. retains a significant advantage in S&T and in operational capabilities in niche areas over rivals and adversaries.

ii. Challenges: The U.S. advantage in S&T and operational capabilities is continually challenged by U.S. rivals and potential adversaries. The advantage is difficult to maintain in a flatter technical and economic world of accelerating technological change. The U.S. must guard against technological surprise across the broad areas of potential DE military application.

c. Prevalence: Optimistic/ S&T: Optimistic/ Relevance: Pessimistic

This future can manifest in two states.

<u>Triumph of counter-DE</u>

i Summary Description: Nations make great progress broadly across DE technologies, but technological progress enabling DE offensive and defensive application are outstripped by technologies defending or defeating such applications. Although only the U.S. and its allies have DE capabilities, counter-DE capabilities proliferate widely among the U.S.'s rivals and potential adversaries. The principal military value of DE lies in providing information services to drive the kill chain. These provide capabilities across the kill chain, domains and phases of conflict.

ii. Challenges: In this future there is parity between counter-DE offensive and defensive applications and in the defense of DE information capabilities against attack. There is an on-going “arms race” between DE defense and DE offensive/ defensive applications. The US finds difficulty maintaining parity in a flatter world, where peers possess similar economic power and the ability to rapidly advance technologically. A breakthrough by the US or its rival and potential adversaries could provide a significant military advantage.

Pacifist Utopia

i. Summary Description: Great progress is made in DE S&T but there is world-wide consensus against its military application akin to restriction on tactical use of nuclear weapons. As such, advances in DE S&T and capabilities are limited to scientific and commercial applications or information dominance military applications.

ii. Challenges: With technologically capable DEWs the U.S. and its Allies still remain at risk from non-state actors who are unconstrained by international agreements on the military use of DE technologies. At a minimum this requires that military systems are protected against the worst effects of potential applications of DE capabilities.

2. Competitive DE US Futures

a. Crowded DE battle-field - Prevalence: Conservative/ S&T: Conservative/ Relevance: Conservative

i. Summary Description: In this future a broad spectrum of actors achieves significant and sweeping advances in DE technology: the U.S., Allies, rivals, and potential adversaries. The U.S. maintains parity in DE technology and in its military applications for information dominance and offensive and defensive operations. Significant military applications apply to the kill chain, across domains and across the phases of conflict.

ii. Challenges: This is a highly multi-polar DE future. In an economically and technologically flatter world, the U.S. is continually challenged militarily to maintain parity in DE technology and operational applications. An ongoing DE “arms race” exists based on the common recognition by the U.S., its rivals and potential adversaries of the significant military advantage that superiority in DE military capabilities can provide. All parties are challenged to have a sufficiently broad S&T and development program to maintain parity, and guard against DE technological and operational surprise.

b. Failed Promise - Prevalence: Pessimistic/ S&T: Pessimistic/ Relevance: Pessimistic

i. Summary Description: This is a future of only modest advances in DE science and technology and only modest increases in DE military capabilities. While DE has military applications, they tend to be niche applications with limited importance across the kill chain, across domains and across the phases of conflict. Despite an overall lack of technological progress and military utility the U.S. is not a leader in DE technology or in DE military applications.

ii. Challenges: In this future the U.S. becomes disadvantaged compared to its rivals and potential adversaries in developing and deploying DE military capabilities. This could be because the U.S. determined that other S&T and operational investments produce greater return in overall military capabilities within limited national manpower and fiscal resources. Or it could be due to an underestimate of the value of DE's niche, military applications. In either case, in this future, the U.S. & Allies run the risk of having to play catch up if there are DE S&T breakthroughs that increase the military utility of DE enabled capabilities.

3. Negative DE US futures

a. **Missed Boat/Odd Man Out - Prevalence: Pessimistic/ S&T: Optimistic/ Relevance: Optimistic**

i. Summary Description: This is the worst-case DE future for the U.S. In this future, major advances occur across a plethora of DE S&T, and are converted into important military capabilities by a number of U.S.'s rivals and potential adversaries across the kill chain, domains and phases of conflict. The U.S. lags these rivals and potential adversaries. This is the result either of a conscious U.S. decision to invest in other areas that provide equivalent or superior military capabilities or a failure to predict the military utility of DE and invest in the S&T and the development of DE capabilities.

ii. Challenges: Unless other technologies pursued have produced offsetting or superior military capabilities, in this future the U.S. sits at significant, military disadvantage compared to its rival and potential adversaries. If this is not the case, the U.S. faces the challenge to catch-up in the S&T and military capabilities. In a technologically and economically flat world, catching up is highly difficult.

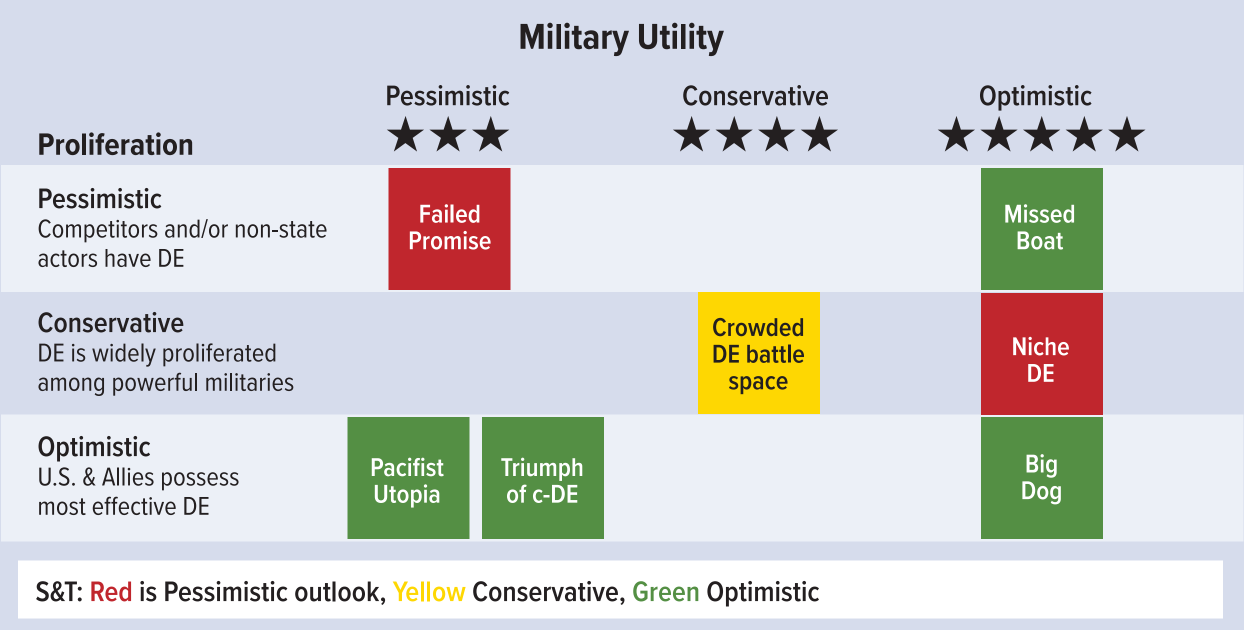


Figure 13: DE Alternative Futures

Figure 13 is a graphical representation of the DE alternative futures states analyzed. Military Utility from current day, 2020 capability (see Table 1), through conservative and optimistic trends in 2060 are shown along horizontal axis. Proliferation trends are shown along the vertical axis. Colors represent Science and Technology advancements of DE technology in alternative futures. Green represents optimistic technology advancement. Yellow, conservative S&T advancement, consistent with constant engineering improvement on the technology of today. Red represents a pessimistic outlook, either none or only slight technological advancement over today.

4. Recommendations and Conclusions

Predictions of the future are fraught with peril; one could be wrong. Still it is worthwhile to organize thoughts around a vision for the next 40 years. Furthermore, the military must function to protect and defend which requires planning for future conflicts. It is not a certainty that U.S. servicemen and women will be members of the most technologically sophisticated military in future conflicts. DEWs are currently being rapidly developed and proliferated around the world, and DE is globally considered to be a game-changing military technology. The impact DEW technologies will actually have over the next 40 years is still to be seen. This report only seeks to organize thoughts around a realistic vision for DEW technologies in 2060. Data gathered for this report shows that both in the past, today, and likely into the future, 2060, DEW proliferation will be driven by the requirements for three capabilities which will be needed to face enduring challenges:

- Information superiority operations that promise control of the electromagnetic spectrum. Electromagnetic spectrum superiority in a conflict requires EW or DE weaponry.
- Capability to project military power faster, at longer stand-off ranges, and efficiently, as part of an integrated layered defense which includes command and control, ISR, cyber, and kinetic weapons.
- Unique, intermediate force, special operations, and potentially space-based missions that require flexibility, scalability, and precision effects across all domains and phases of conflict.

Today, we believe that we retain at least parity with peer-competitors. Low-power DE technology is currently available to anyone, world-wide, with means to buy it: the U.S. and Allies, peer-competitors, rogue nations, criminal organizations and terrorists. In the most probable future, the U.S. and Allies will continue to play a major role in the advancement of DE for military purposes. Fortunately, today the U.S. has close collaborations with Allied DE scientists, developers, military operators, and strategists. We plan to continue to partner internationally with our Allies in DE development, further strengthening our collective military power and investment. Unfortunately, in the most probable future from a proliferation perspective, the U.S. and Allies will not be the only ones who wield DEWs. The key question is, to what degree peer-competitors, rogue nations, terrorists, and criminal organizations will possess competitive DE capabilities?

Over the next 40 years, we predict that even in a pessimistic case, the technology barriers for development of high-energy, high-power, operationalized DEWs will be steep, and investment in DE is the key to the U.S. and Allies retaining leadership in these tech areas. Regrettably, historical trends have shown that with significant investment and technical knowledge, DEWs can be created or purchased by any organization world-wide, and therefore policies must be developed to maximize our ability to access technical talent and the most advanced equipment: electronics, sensors, optical and RF components, and DE-unique materials, some of which require advanced manufacturing. A lesson that one must cautiously observe from the Cold War is that technological and military investment can drive national costs to unacceptable levels, and as threats to national power continue to evolve over the next 40 years, there must be continued assessment of DE's value.

This report highlights with factual references to international developments that include ground based, air based, field demonstrations, naval deployments, and highlights several examples of how *DE is used in operations today.* The military utility of DE in 2020 is apparent. Given that, a question that this report seeks to answer is where should the U.S. DE community, in co-operation with our Allies, invest in DE technology and development to achieve an optimistic future in 2060— one that will continue to bring value to the U.S. military? Our recommendations are thus:

- The U.S. should choose appropriate investments that will maintain *electromagnetic spectrum* and *information superiority.* DE and EW are a key technologies in that regard. From laser illumination, designation, laser and RF tracking, communications, jamming, and counter-ISR, DE devices are key to future information superiority. Continued investment is needed to establish spectrum superiority in future conflicts, across a variety of intensities and frequencies in the electromagnetic spectrum and with advanced concepts such as *frequency agility.*

- The U.S. and Allies should continue to develop *concepts for information operations* that use electromagnetic spectrum superiority to *create asymmetric advantages.*
- The U.S. DE community should request revision of Joint Doctrine Publication 3-13 to include DE as an offensive and defensive information operational capability. In Joint Doctrine Publications 3-85, the distinctions between DE and EW should be clarified, and eliminated where redundant, in order to align the joint services behind concepts of operation.
- The U.S. and Allies should continue to *investigate* and *discover* new applications of DE technology. Investments should be made in areas where missions make sense: such as information operations, high-altitude long-range strike, tactical forward strike missions, and tactical air, space, ground, and ship-based defense missions.
- For self-protection, such as aircraft, naval, and base defense, where today research into DE systems have fundamental speed, efficiency, and potentially cost advantages over traditional kinetic technologies, to include counter-ISR and counter-electronic attack today; *research* and *development* is needed to continually improve high-power/energy DE technology lethality and effects research, as the Allied DE community strives for counter-air technology of the future.
- For the national defense, the "holy grail" mission is a nuclear and/or conventional missile umbrella employing a layered defense concept that includes traditional weapons, DEWs, advanced C4ISR. This mission is increasingly important as concepts for swarms of UASs gain traction and missile technologies advance. Speed, reach, and low-cost per shot are advantages in point defenses that DEWs have demonstrated today; the DE community should strive for both more effective DEWs that realize the benefits of rapid engagement, and concepts of operations that address operational challenges in an affordable architecture.
- Focusing on proliferation and military utility, even in a pessimistic technological future, furtherance of today's *non-lethal* and *non-kinetic kill* intermediate force capabilities will continue. Moreover, it is anticipated that peer-competitors, rogue nations, terrorist and criminal organizations will continue to possess similar DEWs that can degrade, disrupt, deny, damage, and even destroy equipment. Therefore, the U.S. should invest in technologies to at least maintain parity in DE areas, which includes counter measures to shore up known vulnerabilities in case of either a high-end conflict or a 9/11, terrorist style, DE attack.
- Driven by trillion-dollar commercial forces— the aerospace, information, and consumer electronics industries— electronics and photonics will continue to advance during the next 40 years. The DE community should leverage these industries, and reap the benefits of that external investment to overcome many of the engineering challenges in the areas of affordability and SWAP.
- In addition to leveraging advancements by others, the U.S. and Allied militaries should continue investment in areas where DE technology is driven by *militarily unique* requirements, several of which are discussed throughout this document.
- The U.S. and Allied militaries should continually evaluate what technologies to limit for classification purposes, exportation controls, and supply chain issues. We plan to study this problem in more depth, to supply specific details to policy makers in future U.S. DE Community of Interest reports.
- The U.S. and Allied nations should continue to invest in education, facilities, and institutions in order to retain DE leadership.

The DE Futures Workshop established that thoughts on the subjects of base defense, a nuclear/missile umbrella, electromagnetic spectrum superiority, and the feasibility of various DE concepts are widely varied. However, it is clear that internationally, today DE technology supports and enables important military missions. Moreover, it will likely continue to be an important enabler, world-wide, for militarily relevant missions. Policy and affordability were also discussed by the assembled experts as limiting issues in the development of these DE concepts.

We are at or near a critical tipping point in DE technology. The pessimistic, conservative, and optimistic alternative futures for DE military utility, proliferation, and technology advancement are described in this report, based on understanding of historical trends, knowledge of the current state of DE, other advanced technology areas, and predictions about major technology drivers over the next 40 years.

5. References

88th Air Base Wing Public Affairs. "AFRL gives warfighters new weapons system." *Washington Headquarters Services,* April 6, 2020: https://www.whs.mil/News/News-Display/Article/2138161/afrl-gives-warfighters-new-weapons-system/.

88th Base Wing Public Affairs. "Air Force Research Laboratory completes successful shoot down of air-launched missiles." *Wright-Patterson AFB Press Release,* May 3, 2019: https://www.wpafb.af.mil/News/Article-Display/Article/1834836/air-force-research-laboratory-completes-successful-shoot-down-of-air-launched-m/.

Ahval. "Turkish laser shoots down enemy drone in Libya, making military history." *Ahval,* 2019: Ahvalnews.com.

Altay, İbrahim, Ed. ""Turkey's Rocketsan unveils directed-energy weapon Alka against drones". Daily Sabah. 8 May 2019." *Daily Sabah,* May 2019: https://www.dailysabah.com/defense/2019/05/08/turkeys-roketsan-unveils-directed-energy-weapon-alka-against-drones.

Anderson, B., Flores, A., Holten, R., Dajani, I. "Comparison of phase modulation schemes for coherently combined fiber amplifiers." *Optics Express,* 2015.

Becker, Rachel. "Could the U.S. stop a nuclear missile attack?" *The Verge,* 2017: https://www.theverge.com/2017/5/30/15713966/ballistic-missile-attack-department-of-defense-pentagon-north-korea.

Berger, M. J., Coursey, J. S., Zucker, M. A., Chang, J. *Stopping-Power & range tables for Electrons, Protons, and Helium Ions.* National Institutes For Science and Technology, Physical Measurement Laboratory, 2017.

Bishop, P., Hines, A., Collins, T. "The Current State of Scenario Development: An Overview of Techniques." *Foresight,* 9(1), 2007: 5-25.

Carron, N. J. *An introduction to the Passage of Energetic Particles through Matter.* Boca Raton: Taylor & Francis Group, 2007.

Chao, Alexander Wu, Mess, Karl Hubert, Tigner, Maury, Zimmerman, Frank. *Handbook of Accelerator Physics & Engineering 2nd Ed.* World Scientific Publishing Co. Pte. Ltd., 2013.

Chen, Angela. "Gallium nitride is the silicon of the future." *The Verge,* Feb 12, 2019: https://www.theverge.com/2018/11/1/18051974/gallium-nitride-anker-material-silicon-semiconductor-energy.

Chen, K.,, and Xiaodong Zhou. ""Development of high power microwave technology"." *Proceedings of 2019 IEEE 3rd Information Technology, Networking, Electronic and Automation Control Conference,* 2019: 2148-2152.

Chuter, Andrew. "UK shoots for new laser weapons against drones, missiles." *Defense News,* July 9, 2019: https://www.defensenews.com/global/europe/2019/07/09/uk-shoots-for-new-laser-weapons-against-drones-missiles/.

Clarke, T.J., Guillette, D.S. "Modelling radio-Frequency Effects on a Microcontroller." *Proceedings of ICEAA Conference.* Granada, Spain, 2019.

Cohen, Rachel S. “Mircowave Weapons Moving Toward Operational Use.” *Air Force Magazine,* March 20, 2019: https://www.airforcemag.com/microwave-weapons-moving-toward-operational-use/.

Committee on a Decadal Assessment of Plasma Science. Plasma Science: *Enabling Technology, Sustainability, Security, and Exploration.* The National Academies of Sciences, Engineering, and Medicine, 2020.

Congressonal Research Service. *Defense Primer: Electronic Warfare.* https://fas.org/sgp/crs/natsec/IF11118.pdf: Federation of American Scientists, 2019.

Cronin, Patrick M., and Ryan D. Neuhard. “Countering China’s Laser Offensive.” *The Diplomat,* April 2, 2020.

Cui, Y., Darmody, C., Goldsman, N. “Nano & Micro Scale Device-level EMI Induced Vulnerability: Simulations and Experiments.” *4th Annual UCoE review.* Albuquerque, NM, 2019.

Dayton, Alan. “Winning the Invisible Fight: The Need for Spectrum Superiority.” *Defense360, a project of the Center for Strategic and International Studies,* Dec 21, 2016: https://defense360.csis.org/winning-the-invisible-fight-the-need-for-spectrum-superiority/.

Dietz, D. “Stochastic Proagation Delay through a CMOS Inverter as a Consequence of Stochasic Power Supply Voltage, Part I: Model Formulation.” *IEEE Transactions on Electromagnetic Compatibility* 61 (2019): 226-232.

Eason, G. “Weapons that won the war.” *BBC News,* 2003: http://news.bbc.co.uk/2/hi/middle_east/2950403.stm.

EurAsian Times. “US Super-Carrier Annihilator: Russia Test-Fires One of the Fastest Anti-Ship Missiles on the Planet.” *EurAsian Times,* November 27, 2020.

Feder, T. “Accelerator school travels university circuit.” *Physics Today,* 63 (2), 2010: 20-22.

Freedberg, Sydney. “Lockheed Aims For Laser On Fighter By 2025.” *BreakingDefense.com,* September 17, 2020: https://breakingdefense.com/2020/09/lockheed-aims-for-laser-on-fighter-by-2025/.

Freedberg, Sydney J. Jr. *Who’ll Fix EW? Task Force Gropes for Answers.* https://breakingdefense.com/2019/12/wholl-fix-ew-task-force-gropes-for-answers/: Breaking Defense, 2019.

Fugate, R.Q., Fried, D.L., Ameer, G.A., Boeke, B.R., Browne, S.L., Roberts, P.H., Ruane, R.E., Tyler, G.A., Wopat, L.M. “Measurement of atmospheric wave distortion using scattered light from a laser guide-star.” *Nature,* September 12, 1991: 144–146.

Geopolitics News. “Russian laser weapon shot down an Israeli drone over Syria during combat tests.” *Geopolitics News,* 2020.

GeoPolitics News. “Russian laser weapon shot down an Israeli drone over Syria during combat tests.” *GeoPolitical News,* 2020: https://geopolitics.news/middle-east/russian-laser-weapon-shot-down-an-israeli-drone-over-syria-during-combat-test/.

Hamamah, F, Wan Ahmad, W. F., Gomes, C., Mohd Isa, M. Homan, M. J. “High Power Microwave Devices: Development Since 1880.” *2017 IEEE Asia Pacific Microwave Conference.* Kuala Lumapar, Malaysia, 2017.

Hambling, D. “Why Russia will be the first to use the Pain Ray: Analysis.” *Popular Mechanics,* 2012: https://www.popularmechanics.com/military/weapons/a7804/why-russia-will-be-the-first-to-use-the-pain-ray-9833954/.

Henchey, N. “Making Sense of Futures Studies.” *Alternatives, vol. 7, no. 2,* 1978: 24-28.

Insinna, V. “US Air Force delays timeline for testing a laser on a fighter jet.” *Defense News,* 2020: https://www.defensenews.com/air/2020/06/30/us-air-force-delays-timeline-for-testing-a-laser-on-a-fighter-jet/.

Kornilov, Yuri. “Unknown Polyus.” *Zelmya I Vselennaya, 4, 18, reprinted in English in Science and Technology, Central Eurasia, JPRS Reports* USP-93-001, 1993.

Kwee, Patrick, Seifert, Frank, Wilke, Benno, & Danzmann, Karsten. “Laser beam quality and pointing measurment with an optical resonator.” *The Review of Scientific Instruments* 78, 2007.

Lawrance, J., Landavazo, M., McConaha, J. *Investigation of Frequency Dependence of Upset Threshold in a Typical X86 ATX Desktop Computer.* Air Force Reseach Laboratory Technical Report, DTIC AD1063445, 2017.

Lawrence Livermore National Laboratory. “National Ignition Facility & Photon Science FAQ.” 2020: lasers.llnl.gov.

Lendon, Brad. “The US successfully tested a laser weapon that can destroy aircraft mid-flight.” *CNN,* May 23, 2020: https://www.cnn.com/2020/05/22/asia/us-navy-lwsd-laser-intl-hnk-scli/index.html.

Lerman, Rachel, Reed Albergotti, Elizabeth Dwoskin, and and Kelly, Heather. “Big Tech is worth even more the day after congressional grilling.” *The Washington Post,* July 30, 2020: https://www.washingtonpost.com/technology/2020/07/30/amazon-apple-facebook-google-earnings/.

Letzter, R. “China’s New Long-Range Weapon Causes Pain From Afar.” *Popular Science,* 2014: https://www.popsci.com/chinas-got-pain-beam/.

Lewis, S.M., Dolgashev, V.A., Haase, A.A., Nanni, E.A., Othman, M.A.K., Sy, A.V., Tantawi, S.G., Kim, D., Simakov, E.I. “Design of a High Gradient THz-Driven Electron Gun.” *International Particle Accelerator Conference 2019.* Melbourne, Australia, 2019.

Lye, Harry. “U.S. Navy deploys ODIN counter UAS laser.” *Naval Technology,com,* Feb 24, 2020: https://www.naval-technology.com/news/us-navy-deploys-odin-counter-uas-laser/.

Mayfield, Mandy. “Services Report Progress on Directed Energy Programs.” *Joint Intermediate Force Capabilities Office,* June 19, 2019: https://jnlwp.defense.gov/Press-Room/In-The-News/Article/1927276/services-report-progress-on-directed-energy-programs/.

Michel, Arthur Holland. *Counter-Drone Systems, 2nd Ed.* Annandale-on-Hudson, NY: The Center for the Study of the Drone, 2019.

Missile Defense Agency. *Airborne Laser Test Bed Successful in Lethal Intercept Experiment.* Fort Belvoir: MDA News Release, 2010.

Missile Defense Agency. *Opening Remarks by Lt. Gen. Lester L. Lyles, USAF Before the Subcommittee on Strategic Forces, Committee on Armed Services.* MDA, 1997.

Mizokami, Kyle. “China’s Airborne Laser Weapon Would Change Dogfighting Forever.” *Popular Mechanics,* January 13, 2020: https://www.popularmechanics.com/military/aviation/a30502725/china-airborne-laser/.

“High-Powered Microwave Ray Gun Can Stall Cars, Trucks.” *Popular Mechanics,* April 26, 2018: https://www.popularmechanics.com/military/weapons/a20063831/high-powered-microwave-ray-gun-can-stall-cars-trucks/.

“U.S. Marines Have Started Testing Its Drone-Killing Laser Weapon.” *Popular Mechanics,* June 21, 2019: https://www.popularmechanics.com/military/research/a28120435/laser-weapon-claws/.

Mosher, D. “A startup is developing a 100-gigawatt laser to propel a probe to another star system. That may be powerful enough to ‘ignite an entire city.’.” *Business Insider,* 2018: https://www.businessinsider.com/breakthrough-starshot-laser-beam-power-2018-12.

NATO Strategic Analysis Branch. “Strategic Foresight Analysis 2017.” *NATO Press,* 2017.

Nibbering, E. T. J., G. Grillon, M. A. Franco, B. S. Prade, and A. Mysyrowicz. “Determination of the inertial contribution to the nonlinear refractive index of air, N2, and O2 by use of unfocused high-intensity femtosecond laser pulses.” *Journal of the Optical Society of America B., 14 (3),* 1997: 650-660.

Office, U.S. Joint Non-Lethal Capabilities. *Active Denial Technology.* https://jnlwp.defense.gov/Press-Room/Fact-Sheets/Article-View-Fact-sheets/Article/577989/active-denial-technology/: U.S. Department of Defense, 2020.

O'Shea, P. G., Butler, T. A., Lynch, M. T., McKenna, K. F., Pongratz, M. B., Zuagg, T. J. "A Linear Accelerator in Space -- The Beam Experiment Aboard Rocket." 1990 *Linear Accelerator Conference.* Albuquerque, NM, 1990.

Peng, Z., Shao, Y., Gao, H., Lin, S.,. "High-Fidelity, High-Performance Computational Algorithms for Intrasystem Electromagnetic Interference Analysis of IC and Electronics." *IEEE Transactions on Components, Packaging and Manufacuturing Technology* 7, no. 6 (2017): 653-668.

Pomerleau, Mark. *Soldiers in Europe Could Soon Have a New System to Disrupt Signals.* https://www.c4isrnet.com/electronic-warfare/2020/06/29/soldiers-in-europe-could-soon-have-a-new-system-to-disrupt-signals/: C4ISRNET, 2020.

President Obama. "Unleashing the Wireless Broadband Revolution." 2010.

Raytheon Technologies. *Winning the future battlespace.* https://www.raytheon.com/news/feature/future_battlespace, Raytheon Technologies, 2018.

Rehberg, C., and Gunzinger, M. *Air and Missile Denese At a Crossroads: New Concepts and Technologies to Defend America's Overseas Bases.* Center for Strategic and Budgetary Assessments, 2018.

Rehberg, Carl, and Mark Gunzinger. "Air and Missile Defense at a Crossroads: New concepts and technologies to defend America's overseas bases." *the Center for Strategic and Budgetary Assessments,* 2018.

Rizzo, G. "Strategic and Corporate Foresight." *National Conference for Leadership Development, Italian Air Staff,* 2018.

Robinson-Avila, Kevin. "New THOR hammers drones with microwaves." *Albuquerque Journal,* June 21, 2019.

Rosenbaum, Eric, Russo, Donovan. "China plans a solar power play in space that NASA abandoned decades ago." *CNBC,* 2019: https://www.cnbc.com/2019/03/15/china-plans-a-solar-power-play-in-space-that-nasa-abandoned-long-ago.html.

Rudenko, A., Rosenow, P., Hasson, V., Moloney, J. "Plasma-free water droplet shattering by long-wave infrared ultrashort pulses for efficient fog clearning." *Optica 7,* 2020: 115-122.

Schwartz, P. *The Art of the Long View: Planning for the Future in an Uncertain World, 1st Ed.* Double Day Business, 1991.

Sherman, J. "New Laser Scaling Plan sets directed-energy efforts, FY-19 contracts." *Inside Defense,* Apr 2019: https://insidedefense.com/daily-news/new-laser-scaling-plan-sets-directed-energy-efforts-fy-19-contracts.

SRC, Inc. "AN/VLQ-12 CREW DUKE: The most widely deployed counter-IED system protecting our warfighters today." Product Info Sheet, 2018.

Taylor, Alan. "The Lasers of Discontent." *The Atlantic,* November 19, 2019: https://www.theatlantic.com/photo/2019/11/photos-lasers-discontent/602263/.

The Associated Press. "China rejects report it fired laser at US Navy plane." *ABC News,* March 7, 2020: https://abcnews.go.com/US/wireStory/china-refutes-report-ship-fired-laser-us-navy-69447697.

The Deloitte Network. *Changing the lens: GDP from the industry viewpoint.* Article, https://www2.deloitte.com/us/en/insights/economy/spotlight/economics-insights-analysis-07-2019.html#:~:text=Services%20has%20been%2C%20by%20far,industry%20by%20contribution%20to%20GDP.: Deloitte Touche Tohmatsu Limited, 2019, https://www2.deloitte.com/us/en/insights/economy/spotlight/economics-insights-analysis-07-2019.html#:~:text=Services%20has%20been%2C%20by%20far,industry%20by%20contribution%20to%20GDP.

Trevikthick, J. "Budget Docs Show Pentagon Aims to Loft Particle Beam Anti-Missile Weapon into Space in Four Years." *The Drive,* 2019: https://www.thedrive.com/the-war-zone/27039/budget-docs-show-pentagon-aims-to-loft-particle-beam-anti-missile-weapon-into-space-in-four-years.

Trikanlinos, T.A., Terasawa, T., Ip, S., Raman, G., Lau, J. "Particle Beam Radiation Therapies for Cancer." *[Internet]. Rockville (MD): Agency for Healthcare Research and Quality,* 2009.

U.S. Department of Defense. *Electromagentic Spectrum Strategy -- a call to action.* Washington D.C.: Deputy Secretary of Defense, 2013.

U.S. Federal Aviation Administration. "Laser Incidents." December 5, 2019: https://www.faa.gov/about/initiatives/lasers/laws/.

U.S. Joint Chiefs' of Staff. "Information Operations 3-13." 2014.

—. "Joint Electromagnetic Spectrum Operations 3-85." 2020.

—. "Joint Operations 3-0." October 1, 2018.

U.S. Joint Intermediate Force Capabilities Office. *Non-Lethal Weapon Requirements.* https://jnlwp.defense.gov/Press-Room/Fact-Sheets/Article-View-Fact-sheets/Article/577999/non-lethal-weapon-requirements/: U.S. Department of Defense Non-Lethal Weapons Program, 2016.

U.S.A.F. "U.S.A.F. develop space based solar power beaming capability." *Airforce Technology,* 2019: https://www.airforce-technology.com/news/usaf-northrop-solar-power-beaming/.

Underwood, Kimberly. "Army Takes On Microwave Weapon." *SIGNAL,* December 1, 2017: https://www.afcea.org/content/army-takes-microwave-weapon.

United States Air Force. *Air Force Directed Energy Weapon Flight Plan.* USAF, 2017.

Whitney, Roy, Douglas, David, Neil, George. "Airborne megawatt class free-electron laser for defense and security." *Proc. SPIE 5792, Laser Source and System Technology for Defense and Security.* https://doi.org/10.1117/12.603906: U.S. Department of Energy, Office of Scientific and Technical information, 2005.

Yeo, Mike. "China's unique special missions aircraft." *Defense ReviewAsia,* March 31, 2020: https://defencereviewasia.com/online-feature-chinas-unique-special-missions-aircraft/.

Yurov, Dmitri. "Laser Armed Nuclear Icebreakers: What Russia has in store for the Arctic." *Sputnick International,* November 2, 2020: https://sputniknews.com/military/201707171055615670-russia-nuclear-laser-icebreakers-prospects/.

6. Appendices

Appendix A: Future States Vignettes

The following three futures vignettes are science fiction. Described in these vignettes are three imagined scenarios that highlight aspects of DE and other advanced technology advancement, proliferation, and military utility. After each fictional vignette is a short analysis that describes connections to the main body of the DE Futures report and future states.

Vignette 1: DE defends resources in space

12 September 2060

Abundant Harvest Asteroid Corporation had just planted the flag on Asteroid 5982, a giant hunk of nickel and chromium and several other precious metals orbiting the sun in the asteroid belt just past Mars. It was the farthest yet that any corporation had laid claim to an asteroid. They remained emboldened by the burgeoning commerce of Mars, which despite many NASA missions never showed definitive signs of life, that is until it was colonized. It was colonized primarily in the southern hemisphere, near enough to the southern polar ice cap, where each colony had an outpost to gather water, and still at a low enough latitude that the daily temperature ranges were closer to conditions on Earth. Without the wind chill of course, which could be blistering in the desert mares where the U.S. began their first colony.

China and their economic partners had a colony two mares over, both in the southwest hemisphere of Mars, both in the northern reaches of the Planum Australe. Abundant Harvest Asteroid Corporation was the english name for the Chinese state-sponsored mining corporation, as registered with the U.N. "Committee on the Commercialization of Space."

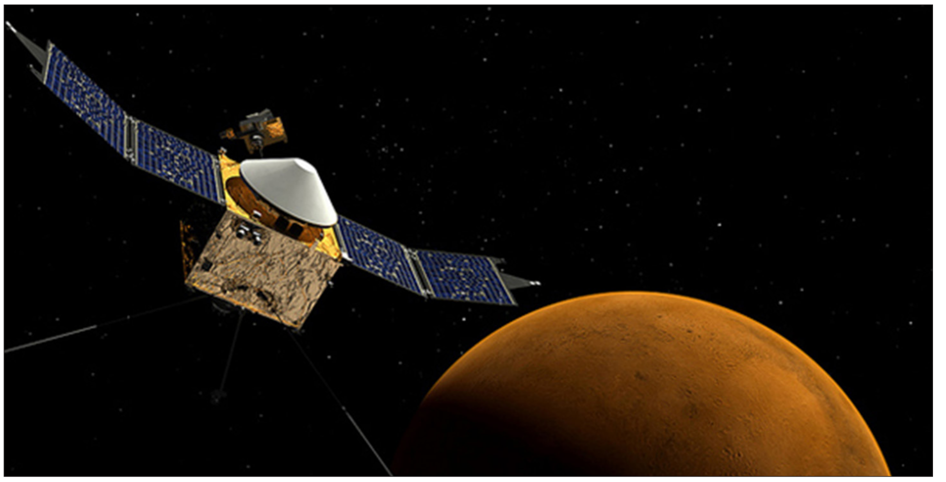


Figure 14: *Concept drawing of NASA's Mars Orbiter*

While colonization of the moon remained very limited, primarily to support space tourism, there was wealth to be gathered in the asteroids, rich resources of metals that in turn drove the skyrocketing space mining industry. Like the line made famous by the Looney Tune's wild west prospector Yosemite Sam, "There's gold in them thar hills." The hills in this case are asteroids and it's not just gold but billions of tons of other valuable metals too. Metals such as iron, cobalt, and nickel in addition to precious metals, such as gold and platinum. The U.S.-European Union and their trading partners, and China and their partners, known as the Allied Asians, strip mined the asteroids, and were cultivating bustling mining towns on Mars.

Under guidance from the U.N., a system of claims governed ownership of an asteroid to strip it of its resources. However, it basically came down to whoever first prospects a claim, claimed the entire asteroid.

Unlike the prospectors of the old wild west, who rode horses and trains and worked with a pickaxe and shovel, the prospectors on Mars were multinational conglomerates who sent robotic mining spacecraft to harvest the distant mother loads buried inside asteroids. Internationally, scientists identified which asteroids could be profitable for metals. And which ones were loose piles of rubble only valuable when mined for oxygen, silicon, magnesium, calcium and other elements.

With their assertion of a claim over Asteroid 5982, the Abundant Harvest Asteroid Company had just beaten the U.S.-backed company Deep Space Resources to their planned next business venture, in addition to one-upping the U.S. and their Allies.

13 September 2060

"Commander, we must send them a message," demanded Neil Cover, the CEO of Deep Space Resources.

"I'm sorry Mr. Cover, but the U.S. Space Force is not here to be some sort of Martian Sheriff, this is a competitive commercial environment and Abundant Harvest has not broken international laws," explained General Alighieri, the commander of the small military base that was adjoined with the US-EU mining boomtown. "You will have to try to get to the next asteroid faster. Speed up your plans to go to 6107."

"But their military is building a blockade around significant parts of the asteroid belt, including the orbit to 6107. Why can't you help us to maintain our claims? We pay our taxes, do something." pled Neil Cover.

Gen. Alighieri knew Neil had a point. The Allied Asian Armed Forces (AAAF) were acting like a security detail for the Abundant Harvest miners, establishing what they referred to as shipping lanes, yet amounted to a blockade of small agile and potentially weaponized spacecraft. Still Gen. Alighieri lacked authority to be the security staff for U.S. mining corporations. She wasn't the Sherriff who could gather the leaders of international mining conglomerates to have a good old-fashioned shoot out at the Martian version of the OK Corral. The U.N. guidelines for the free and fair usage of space permitted establishment of shipping lanes.

U.N. guidelines also permitted the U.S. to pursue its own strategy for the defense of its citizen's interests in deep space. Because they had a technological edge over peer competitors in the area of directed energy, they developed a concept of deterrence, by very publicly placing two laser weapons in orbit around Mars, purely for defensive purposes. The two weapon systems continuously covered the asteroid belt. Without an atmosphere and in the frozen depths of space near Mars, 2 Gigawatt lasers, produced by beam combining nearly 200 independently generated laser beams into a 2 Megajoule, 1s blast of power were a technical possibility. Such powerful laser weapons are only possible in laboratories on Earth— working in space had benefits.

"Neil, I know that this means taking on risk, but if you go for Asteroid 6107, or any asteroid in the belt and they try to block you or take any hostile action, we will protect you. Beyond that maybe you should hire your own space security staff. We aren't China. You own your company and that is a good thing! That's why you are digging billions of dollars of profit yearly out of those asteroids. While you pay taxes, you also breathe our air, drink our water, and benefit from our power grid. And yes, if a foreign power makes an aggressive move toward you, we have your six. But we are not your security staff. The code of combat in space only allows us to respond proportionally with aggression to anyone who is actually trying to hurt you or your property."

Because time is money, Neil Cover continued with his planned launch that night. The Deep Space Resources RQ-12 rocket launched carrying a robotic mining craft off the Martian planes, propelling it on a trajectory toward Asteroid 6107.

14 September 2060

Twenty-four hours later the Deep Space Resources RQ-12 was within 1,000 kilometers of the PLA Space Force Vessel 20 that established the farthest end of a supply chain corridor. As the Deep Space Resources craft followed a trajectory toward Asteroid 6107 it would cross paths with Vessel 20 in what was collectively called the 9th Sector of the asteroid belt.

"Are you watching them?" demanded Cover.

Gen. Alighieri stared at Neil Cover, her eyes flashed with anger as in the middle of her control room a holographic projection visualized the 9th sector including the Deep Space Resources craft, Vessel 20, and several nearby asteroids. She looked Neil in the eyes, her gaze turning from red hot to ice cold. She could have him thrown out of her command room, instead she tilted her head slightly to the left and stated icily, "I see the same projection you see Mr. Cover."

"Ma'am," Neil corrected himself. He didn't mean to be rude. Tensions were high and he was a ball of nerves.

A radio dispatch came through from the AAAF spacecraft, "U.S. command center please be aware, we will be conducting routine waste ejection. This is a flight safety warning to avoid the 9th sector of the belt for the next 15 minutes.

"Are they throwing their garbage at us?" Neil cover screamed, as simultaneously rubble, leftovers after mining a nearby asteroid tumbled out of the aft airlock of Vessel 20.

"Mr. Cover if you cannot control yourself, you will be removed from my command center," asserted Gen. Alighieri.

"Orbit analysts," she requested, "please give us the conjunction distance and the risk of collision."

"Initial orbits indicate that it will all miss the Deep Space Resources craft by at least 5 kilometers," the Chief Orbital Analyst reported. "It's a shot across the bow."

"Ok two can play at that game, weaponeers do you have the aim points to execute COA 3?" Gen Alighieri requested of her team.

They had planned for an event like this. Course of action, or COA number 1 was to attempt to destroy all of the space debris with the gigawatt laser. Blasting the debris was no problem. The danger was that even a very small piece of debris moving at orbital velocities could shred the Deep Space Resources space craft. The success of COA 1 depended on accurately sensing millimeter sized pieces of debris, then aiming the laser well enough to divert the debris in a predictable way, all while not causing a worse debris problem.

COA 2 was to fire upon the Allied Asian vessel with the Gigawatt laser weapon, which might destroy the ship. The spacecraft cannot outrun a laser, in deep space there is nowhere to hide, it was a sitting duck. Even if it took a few seconds to burn through the hardened hull of the space craft, the laser would eventually destroy the ship and set a terrifying precedent for future conflicts.

COA 3 involved a secondary, highly classified payload, an ultrashort pulse laser weapon, still high energy but much lower peak power, than the main Gigawatt laser. The ultrashort pulsed laser energy was compressed into a few femtoseconds, and far more efficient at drilling small but deep holes.

The CONOP of COA 3 was to aim the pulse at the aft airlock on the PLA vessel, where they knew no people would be harmed. The weaponeer confirmed aim points and the pulse was unleashed upon Gen. Alighieri's command, "Fire!"

The airlock lost pressure. Vessel 20 wobbled as pilots attempted to stabilize it. While she could have destroyed the AAAF vessel, a small pin-prick hole drilled into a section of the spacecraft where they stored excess mining debris was escalation of aggression in proportion to the AAAF's actions.

"AAAF Vessel 20, you appear to be unsteady. Have you lost control after your waste dump?" Commander Alighieri asked in a deadpan tone to mask the sarcasm with which she asked for their status. She smiled, took a deep breath, and hung up. "See Mr. Cover, you have nothing to worry about."

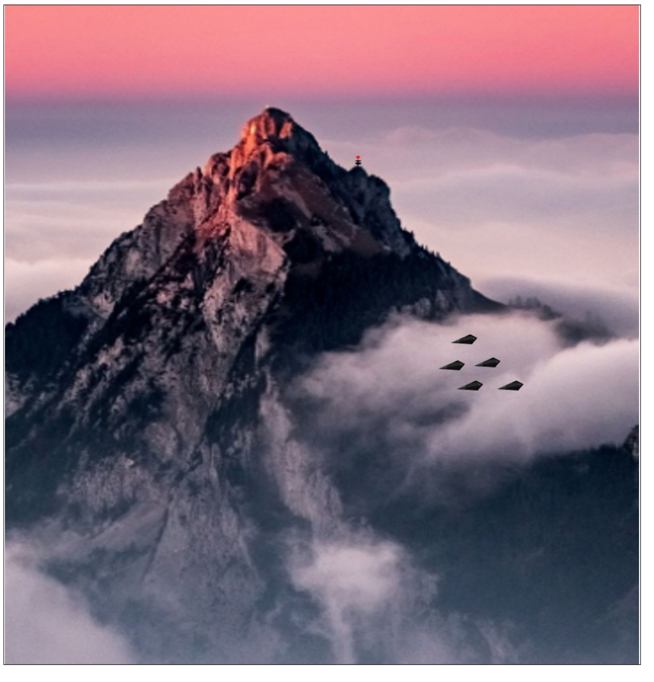
Analysis: This vignette highlights a few aspects of future states where the U.S. continues to develop DE technology and other technologies at an optimistic rate (Lawrence Livermore National Laboratory 2020). Additionally, this presents an optimistic view on proliferation of DE weapons which are available to the U.S. but not to peer adversaries. Military utility DE trends are consistent with a conservative or optimistic case, as it is widely recognized that lasers could be more effective in space than in terrestrial applications assuming SWAP concerns are resolved. The vignette also highlights aspects of the speed and focus of power of DEWs. Because the U.S. is presumed to have DEW advantages over peer competitors, with conservative to optimistic forecasts of military utility, this is an example of the Big Dog scenario.

Vignette 2: Ultra-small particle device disables C2 systems

15 March 2060

From a bunker control room dug into the Chang Chenmo Kangri, a peak in the Himalaya Range 14' north of the 34th parallel, PLA UAS pilots were suppressing fire from the Indian Armed Forces, 40 km away at the front lines of an incursion of PLA Expeditionary Rangers that were establishing a presence on India's sovereign territory.

Daily, Chinese UAVs had been penetrating lands they disputed from the bunker dug deeply into a Himalayan mountain on the Chinese claimed side of the two nations' shared border. What was different today is that they were absolutely mopping up the floor with the Indian Army, permitting the PLA expeditionary forces to advance.



If India lost this battle, they would be pushed by their larger, richer neighbor to the north, well beyond the 1970 boundary. They would concede all claim to Pangong Lake.

Fortunately, the Indian Minister of Defense had one ace in the hole: A cyber backdoor to the TigerStar brand network switches that were installed in the server room of the underground Chinese bunker.

Calls for help were pouring into the Republic of India's "pentagon," the Secretariat Building in New Delhi. It was time to deploy the clandestine weapon they had spent millions to create a sophisticated web of supply chain relationships that facilitated planting it inside the bunker control room.

The secret weapon was an ultra-small particle device stowed away on the network switch circuitry. When deployed the particle beam device would physically destroy electronics at an atomic and molecular level.

The effort it took to create this device was tremendous. However, research and development of the ultra-small particle source was an old idea, developed in 2025. The development required integration of the particle device into a chip. Inconspicuous placement on the TigerStar network switch circuit board was the master stroke, performed after years of cooperation between India's Ministry of Defense engineers and intelligence wing. Extensive espionage had identified the network switches as an exploitable weak link in the PLA command and control centers. Clandestine operations were executed to plant the device on the network switch circuit board, knowing it was a key entry point to the PLA defense supply chain.

Once deployed, the physical destruction of electronics in the network switches would bring the command and control center to its knees. Of course, the network switches would be promptly replaced with new ones, but that might take days. That was enough time for India to turn the tide in the battle!

17 March 2060

The Chinese bunker control room dug into Chang Chenmo Kangri was humming again, networks were back up, operations were resuming cautiously. The PLA suffered a great loss to their UAS fleet, it wasn't possible to resume expeditions across the Indian Border until reinforcements were sent. The chief of engineering for the PLA's control centers had arrived on the 23rd and was about to reveal what his investigation had determined as the root cause of the failed network switches, the root cause that resulted in a lost battle, lost lives, and equipment.

System administrators at the control center crowded into the classified conference room with the command and control center's most senior leaders. They all knew the network switches failed, but why was still a mystery. They were about to hear the results of the official investigation.

"Network analysis found a cyber backdoor command sent on the 22nd of March, that caused the network switches to fail," stated the Chief Engineer, "It is puzzling that all three switches suddenly failed in an irreversible way. They could not be reset as was protocol. It is as if the switches were physically damaged but there are no signs of forced entry or electrical overload."

Since they had never seen computer chips physically break like they had, it took another 3 months of investigation before the PLA realized that every TigerStar brand network switch in their inventory had an ultra-small directed energy weapon installed on it.

Analysis: In this vignette, DE is assumed to be conservatively proliferated. The U.S. does not factor in this vignette based on the idea of escalation of real-world events at the disputed border between China and India. The assumed advancements of DE S&T are modest by 2020 standards; small particle devices are possible today. The military utility can be assumed to be conservative or more useful, because this is a special operations scenario, plausible today. Therefore, this is an example of the Crowded DE Battlespace or DE Niche World futures.

Vignette 3: Failure to defend homeland against advanced missile strikes

Figure 15: *Image of Zircon hypersonic anti-ship missile reportedly test-fired in October 2020 (EurAsian Times 2020).*

2 February 2060

"President Blumm has been assassinated," read the words on the display. "He died in a hypersonic missile strike on the Hexagon at 9:01AM. The Secretary of Defense, Leo Steinbeck was also killed in the missile strike. Defense officials stated they attempted to warn the President when the early missile warning detection systems first saw the launch of two missiles from ships in the North Atlantic Ocean, but they could not evacuate the President in time. It is believed that the Russian Free Armed Forces (RFAF) are behind the assassination."

Dr. Sabina Flagg read these words in horror. Her nightmare scenario had happened.

She even had an appointment this afternoon to speak with the President about this nightmare scenario. Just yesterday she had explained the odd signals she has seen in data from the Northern Greenland Radar Station to the Chief Scientist of the Air Force who referred it immediately to the Secretary of the Air Force, who made a call and arranged for her to have a conversation with Secretary Steinbeck.

Dr. Sabina Flagg was the world's second leading scientist in hypersonics. The first was Dr. Andrey Medved, who had recently made an important discovery. Dr. Sabina Flagg's alarming discovery in the beeps and squeaks of the radar signals, used to monitor Russia's missile testing range, was that Dr. Medved had succeeded in developing a hypersonic missile that exceeded Mach 10. Sabina wanted desperately to warn the President and had been glad for the appointment. Now she only wished she could have warned him in time.

1 February 2060

"A missile with that great of velocity could be used to destroy a target before the early warning system could notify them," Dr. Flagg explained to Secretary Steinbeck in the Hexagon's main command and control center.

Displays glowed on the walls showing maps, live video from around the world, lists of assets and their status scrolled as the third world war progressed minute to minute. Top military officers and their staff watched battles unfold, commanding and controlling forces.

"That's impossible," retorted Sec. Steinbeck, "The fastest hypersonics are Mach 8 and the missile warning system provides initial warnings within seconds. Worst case scenario we close the tracking and targeting loop in less than 2 minutes."

"Sir, that *was* true." Dr. Flagg explained, "I believe Dr. Andrey Medved, of the Russian Aeronautics Academy has made a technological leap forward. His invention of the 4 stage CODA engine, in theory permits Mach 10+ velocity missiles."

"In theory? Does anyone understand that we are trying to fight a war here? Why should we care about a Russian Academy science project?" growled Sec. Steinbeck, looking to his staff in exasperation.

For the past two months Sec. Steinbeck had been leading the struggle to contain the RFAF as they mobilized on Europe. First occupying its former lands under the USSR, the RFAF were now advancing into other areas. The U.S. had only officially joined the fight recently. President Blumm announced the war, then began sheltering, moving every few days from bunker to bunker. There had been no strikes yet on U.S. soil, but with the declaration of war they expected attacks could begin.

"Ma'am, artillery has a long history. David killed Goliath with his sling. In 333 B.C.E., with trebuchets, Alexander the Great's engineers broke the walls of Tyre. In 1415, Henry the 5th won the Battle of Agincourt against superior French numbers, because King Henry effectively used his long bows. For thousands of years people have built projectiles that go farther, faster, and are more destructive. I happen to be a bit of an expert in this subject," boasted Mary Jackson, one of Sec. Steinbeck's top advisors. "The fastest hypersonic missiles are Mach 8; we haven't reliably achieved faster ones in the past 30 years. And all of the intelligence we gather tells us no one else has either. Why should we believe this?"

"Ma'am, Sir," she addressed both Ms. Jackson and Sec. Steinbeck, "I'm the world's foremost scientist in hypersonics. I follow the development of new technologies, especially those of Russia's top expert Dr. Andrey Medved. Seven years ago, he developed a theory for the 4 stage CODA engine, and since then I have been following his research and intelligence on RFAF testing. Radar data from 2 days ago, has led me to conclude that Medved was successful. He developed a Mach 10+ hypersonic missile."

"If what you say is true, seems you are the world's second foremost scientist in hypersonics," quipped Mary Jackson. "However, Sir, if Dr. Flagg is correct, a weapon like this could be used to decapitate the heads of government. Our early warning systems might fail to close the targeting loop fast enough to provide warnings. And timely intercept would be challenging under the best of circumstances."

"What could stop it?" Sec. Steinbeck asked.

"Nothing we have is fast enough, we don't have interceptors that could react fast enough. Our long-range targeting cycle is about a minute, which is fast enough for a Mach 8 missile intercept…" Mary Jackson trailed off pensively, "Perhaps if we had built a directed energy defense system."

"I thought we had DE systems protecting all of our major installations?" asked Sec. Steinbeck.

"Correct Sir, but they are all short-range," Mary continued, "We would need forward deployed DE weapons. We would have to detect a missile during launch, autonomously target it, and destroy it all within a minute. We don't have anything like that."

The Secretary of Defense, considered all of the information he was receiving. "Well I happen to be meeting with the POTUS here tomorrow morning, 0900. I'll mention this new weapon to him." He turned to Mary, "Will you please get in touch with Mr. Blumm's Chief of Staff, for an urgent appointment with us and Dr. Flagg."

Analysis: This vignette highlights a few aspects of future states where the U.S. continues to develop DE technology at a pessimistic pace. Furthermore, in this vignette the U.S. lags behind peer competitors in hypersonic missile technology, here the fictional CODA engine. Military utility and proliferation of DE trends are consistent with either the pessimistic or conservative cases. The vignette also highlights aspects of how speed in all areas of future warfare promises to increase the pace of conflict, such as hypersonics and autonomy. Because the U.S. no longer possesses the most technologically advanced weapons, it is assumed to have "Missed the Boat." This scenario could also be a DE Niche World Future, which we consider to be the most likely forecast of DE military utility and proliferation based on today's state of the art.

Appendix B: Participating Organizations

Air Force Materiel Command

Air Force Office of Scientific Research

Air Force Research Lab **(Co-Host)**

Air Force Space Command

Army Space and Missile Defense Command

Defense Health Agency

Directed Energy Professionals Society
Joint Non-Lethal Weapons Directorate
Joint Directed Energy Transition Office
Los Alamos National Lab
Lawrence Livermore National Lab
Naval Research Lab
North Atlantic Treaty Organization (NATO)
Office of Naval Research
Office of Secretary of Defense - Directed Energy Community of Interest (Host)
Office of Undersecretary for Defense – Research & Engineering
Pennsylvania State University
Purdue University
Sandia National Lab
The Aerospace Corporation
The MITRE Corporation
The Leonardo Company
United States Space Force
University of New Mexico
University of Missouri

Appendix C: 2060 Assumptions

In addition to considering specific trends affecting DE tech, military relevance, and proliferation, defining DE futures requires assumption as to the larger global state of the world in 2060. We make the following assumptions as to overall global economic, political, and national defense to the year 2060.

Economic Assumptions

- A tripling to quadrupling of global gross domestic product (GDP) with an annual average growth rate of 3%-4% over the period to 2060.
- U.S. economy doubling with an annual average growth rate of 2% over the period to 2060.
- U.S. portion of global GDP decreases from current 22% to between 10% and 15%.
- Large, developed economies experience similar or lower growth rates relative to the U.S.
- Chinese and Indian economies significantly exceed U.S in size but lag in per capita GDP.
- World population increases 30% to near 10 billion, primarily in developing nations.
- Top economies are China, India, United States, Indonesia, Brazil, Russia, Mexico, Japan, Germany, and the United Kingdom.
- Global economy is more integrated and driven by automation, artificial intelligence, robotics, and additive manufacturing.
- The growing economy increases demand and competition for natural resources.

Political Assumptions

- Global political power is distributed across a wide range of nations driven by increases in overall global wealth and a more evenly distributed technical base and world economy.
- U.S. remains a first-tier power, but with its political power diminished relative to other first-tier nations.
- Tiering of nations by level of power continues with narrowed differences between and within tiers.
- Europe and North America continue to control a disproportionate percentage of global power relative to their populations.
- U.S. is not the preeminent world power by multiple measures.
- Wider distribution of power increases potential for competition and conflict.
- Premium on flexible partnerships and alliances to support shifting national needs, priorities, and changing geopolitical balance.

National Defense Assumptions

- The continuation of great power competition.
- A highly multi-polar world with a significant number of nations and alliances having equivalent economic power and technical infrastructure but diverse and divergent interests.
- Conflicts increasingly integrated across the air, land, sea, cyber, and space domains and extending globally and across cislunar space.
- The cyber domain is critical to military operations. Foreign competitors increasingly seek cyber capabilities to target systems and infrastructure.
- Conflicts occur at greater speeds and range across an ever increasingly diverse set of integrated and flexible platforms and systems.
- Technical advantages between major powers has narrowed or disappeared.
- Success is driven more by resources, logistics, and successful alliances rather than by technological advantage.
- There may be a wide range of conflicts involving a wider set of countries with significant military power.
- Increased global competition leads to an increased number of conflicts.

Appendix D: Acronym List

AI Artificial Intelligence

C2 Command and control

C4ISR Command, Control, Communications, Computer, Intelligence, Surveillance, and Reconnaissance

c-UAS Counter Unmanned Aircaft System

CEP Probable Circular Error

CONOPs Concept of Operations

DE Directed Energy

DEW Directed Energy Weapon

DoD Department of Defense

DOTMILPF Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, Facilities

EW Electronic Warfare

HPM High Power Microwaves

HPEM High Power Electromagnetics

GDP Gross Domestic Product

JADC2 Joint All Domain Command and Control

LASER Light Amplification by Stimulated Emission Radiation – commonly referred to as a laser

OSD Office of Secretary of Defense

NASA National Aeronautics and Space Administration

NATO North Atlantic Treaty Organization

NDPP NATO Defense Planning Process

S&T Science and Technology

SI The international system of units

SWAP Size, Weight, and Power

TRL Technical Readiness Level

U.S. United States of America

UAS Unmanned Aircraft System

Appendix E: Description of Units of Measurement

Throughout the document we discuss lengths in units of meters and kilometers, which are commonplace. Less commonplace in everyday language are the units of measurement that describe relevant timescales, frequencies, energy, and power levels. The energy of a photon, measured in units of Joules (J), is proportional to the frequency of the light measured in Hertz. The constant of proportionality is related to Plank's constant, $h=6.626x10^{34}$ Joule-seconds. Hertz (Hz) are the frequency of oscillation of the electromagnetic field of light per seconds (1Hz=1/s). Power levels are described in Watts (W) and are defined as the rate of energy per time (1W=1J/s).

Time, frequency, power, and energy described in this document range over several orders of magnitude defined in subsequent Table. Examples: $1GHz=10^9Hz$; $1MW=10^6W$; and $1ns=10^{-9}s$.

Prefix (symbol)	Magnitude
femto (f)	10^{15}
pico (p)	10^{12}
nano (n)	10^{9}
micro (µ)	10^{6}
milli (m)	10^{3}
base unit	1
Kilo (k)	10^{3}
Mega (M)	10^{6}
Giga (G)	10^{9}