Journal of Directed Energy **7**, Winter 2023, 163–182

Counter Directed Energy Weapons and the Defense of Naval Unmanned Aerial Vehicles

Bonnie Johnson,[1*] James Ansley,[2] Stephen Hakimipour,[2] Kyle Buffin,[3] Lisa Nguyen,[3] Victoria Couture,[4] and Eranga Gonaduwage[4]

[1]Naval Postgraduate School, Monterey, CA 93943,
[2]Naval Air Warfare Training Systems Division, Orlando, FL 32826,
[3]Naval Air Systems Command, Jacksonville, FL 32212,
[4]Naval Air Warfare Center Aircraft Division, Patuxent River, MD 20670

Advances in directed energy weapons (DEWs) technology are leading to fielded systems for the U.S. military and may also become threats as peer competitor nations are also developing these technologies for their militaries. U.S. military forces need to be prepared to operate in future threat environments that include DEWs. The Naval Postgraduate School is conducting counter directed energy weapons research to characterize directed energy threat environments and develop solution concepts for protecting naval assets against this developing problem space. The initial study focused specifically on high-energy lasers as the adversarial threat and on naval unmanned aerial vehicles (UAVs) as a type of military asset that would be particularly vulnerable in this threat environment. The study identified solution concepts for defending UAVs against adversarial high-energy lasers and developed an analytical tool for determining lethality effects over a range of threat scenario parameters.

KEYWORDS: directed energy weapons, high-energy lasers, counter directed energy weapons, unmanned aerial vehicles

1. Introduction

Technology advances in directed energy weapons (DEWs) present a new threat that is being exploited by peer competitor nations. The use of these weapons will impact U.S. naval tactics and necessitate new engineering solutions for naval assets to keep pace. As these threats may soon enter the littoral and maritime environments, it is essential to proactively plan for counter DEW (CDEW) methods, tactics, and capabilities. Preemptive measures are imperative to successfully defend against these powerful threats and protect naval assets.

Received September 17, 2020.
*Corresponding author email: bwjohnso@nps.edu.

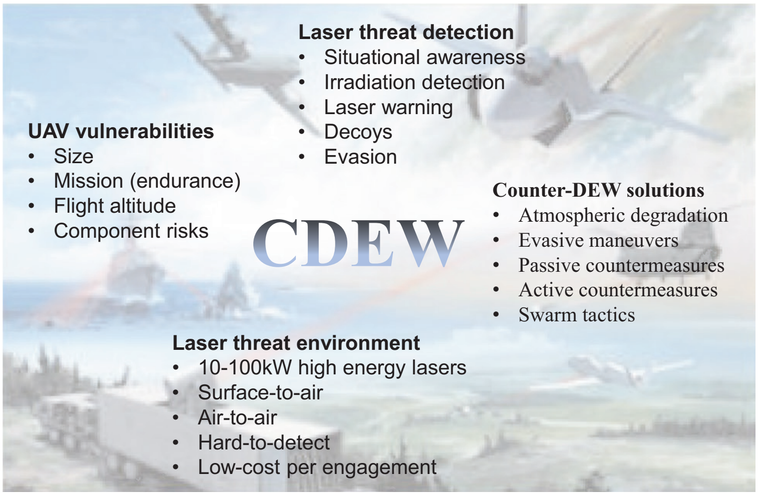

Fig. 1. Counter directed energy weapons (CDEW) operational view (adapted from Kiel[1]).

Naval unmanned aerial vehicles (UAVs) will be particularly vulnerable to adversarial DEW threats. They are generally made of lighter and thinner materials than manned aircraft, and their often forward-deployed missions will place them in close proximity to adversaries. Therefore, naval UAVs will be particularly susceptible to being targeted and damaged by adversarial DEW threats.

An operational view of a future DEW threat environment is depicted in Fig. 1, illustrating the potential for adversarial surface-to-air and even air-to-air high-energy laser (HEL) weapons to pose a threat to naval UAVs. The illustration indicates that the type, size, and mission of UAVs will affect how vulnerable they are to an HEL attack. The figure also lists some strategies and tactics, including the inherent limitations to HEL systems, atmospheric effects, countermeasures, evasive maneuvers, and swarm tactics, that support CDEW solutions for UAVs operating in these future environments. The first major challenge that will confront naval assets entering a DEW environment is the ability to detect a threat that may not occur until the asset is actively engaged by an adversarial DEW threat. DEW threat detection and warning are critical components of CDEW solution strategies.

The Naval Postgraduate School (NPS) is conducting research to explore future adversarial DEW threat environments and identify solutions for protecting naval assets that will operate in these environments. This article presents the results of the initial study, which focused on the protection of naval UAVs against future adversarial HEL threats. The article begins with a description of what is publicly known about recent DEW systems being developed in foreign countries. Next, we present a characterization of future DEW threat environments, describing the types of possible attacks and the vulnerabilities of U.S. military systems that may operate in these environments. This is followed by a focus on naval UAVs and their vulnerabilities to DEW threats. Next, we explore some possible CDEW solutions for defending naval UAVs against DEW threats. The final section presents an analysis CDEW tool developed by NPS students that is intended for evaluating CDEW concepts based on the HEL threat, atmospheric conditions, and proximity of the naval asset to the threat.

2. Foreign Directed Energy Weapon Developments

Recent DEW developments by China and Russia are prompting the study of strategies and capabilities for countering these potential threats. Recent news reports show that China has been developing laser weapons ranging from low-powered tactical beam emitters to high-energy strategic weapons systems.[2] China's laser systems include (1) ground or vehicle-based systems with 10 kW of power that can destroy small fixed-wing aircraft, helicopters, and drones at low altitudes and short ranges (2 km); (2) larger 30-100kW vehicle-based systems with a larger range (4–25km); (3) a vehicle-based electro-optical system to support early warning, missile guidance, and lethal capabilities; and (4) individual low-power laser guns that can dazzle or blind an enemy from a short range. Recent reports indicate that China may be developing an airborne laser weapon system.[3]

President Vladimir Putin of Russia has openly discussed the development of new types of laser weapons, some of which are in service and capable of disarming targets with rapid precision.[4] One system is the Peresvet, which is believed to be capable of blinding enemy electro-optical devices and shooting down UAVs.[5] Reportedly, Russia is working on a combat laser complex to include aircraft-mounted lasers as part of an antisatellite complex and a ground vehicle-based HEL (mounted on massive low-bed wheeled trailers) for antimissile defense.[6] Figure 2 shows examples of laser systems being developed by China and Russia.

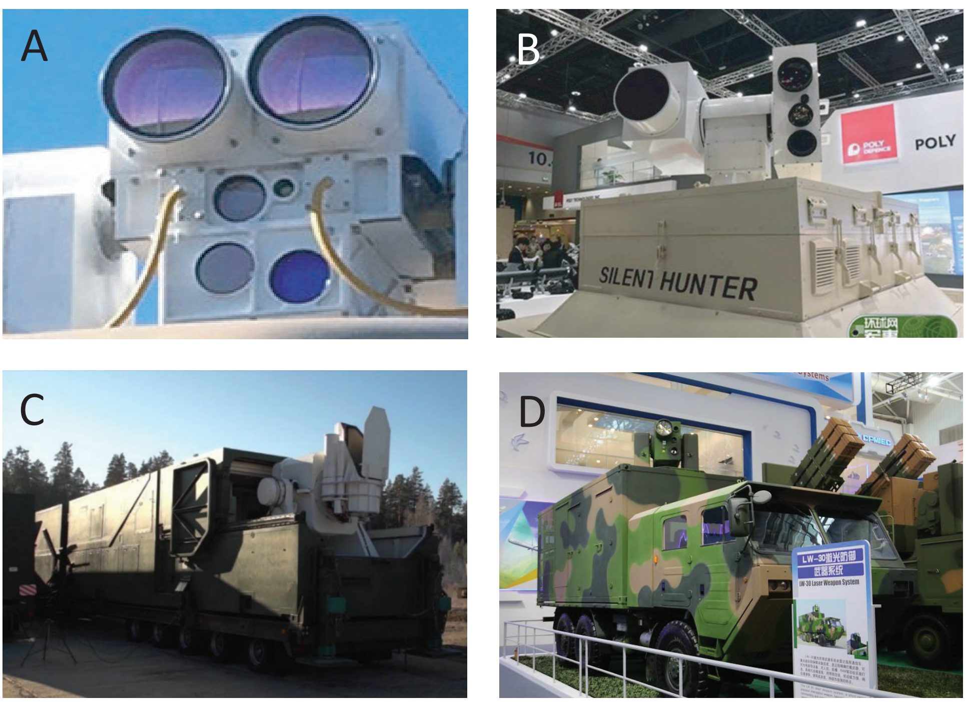

Fig. 2. Foreign DEW systems: (a) China's Guorong Vehicle-Mounted Anti-Drone System,[2] (b) China's High-Powered Silent Hunter,[7] (c) Russia's Peresvet Ground-Based Laser System,[4] and (d) China's LW-30 Anti-Drone and Anti-Aircraft System.[8]

3. Characterization of the DEW Threat Environment

Naval assets entering an environment with adversarial DEW systems face a range of possible threats in the form of bombardment by directed energy. DEW threat characteristics include wavelength (or frequency), power or intensity, beam width (narrowly focused to dispersed), propagation effects, beam characteristics (coherent, varied particles, electromagnetic radiation, pulses, etc.), and dwell time. HEL weapons require a period of time (referred to as the dwell time) to elapse while focusing a beam of light on a single spot to cause damage. The DEW threat characteristics, along with the characteristics and proximity of the target (human, aircraft, missile, sensor, electronic device, etc.) will determine the level of damage sustained—which can range from a hard kill to a soft kill. Hard kills structurally damage and often destroy targets, while soft kills disrupt functions while not entirely destroying systems. A DEW hard kill would burn through a target, resulting in a drone crashing, a human dying, or a missile exploding. A DEW soft kill might damage or destroy a UAV's sensor, communications link, or guidance system, while not outright destroying the UAV itself. DEW threats (shown in Fig. 3) include HELs, high-powered microwaves (HPM), high-powered radio frequency (HPRF), electromagnetic pulses (EMPs), and particle beams. These technologies vary in maturity, with EMP and particle beam systems being the least mature and, therefore, most futuristic. This study focused on HEL systems as the threat of interest.

The first challenge confronting naval assets entering a DEW threat environment is the ability to detect a DEW threat. The detection of an HEL threat may require being actively engaged by the HEL and may only be determined during the process of battle damage assessment. If an HEL soft kill is detected, it might be possible to implement a

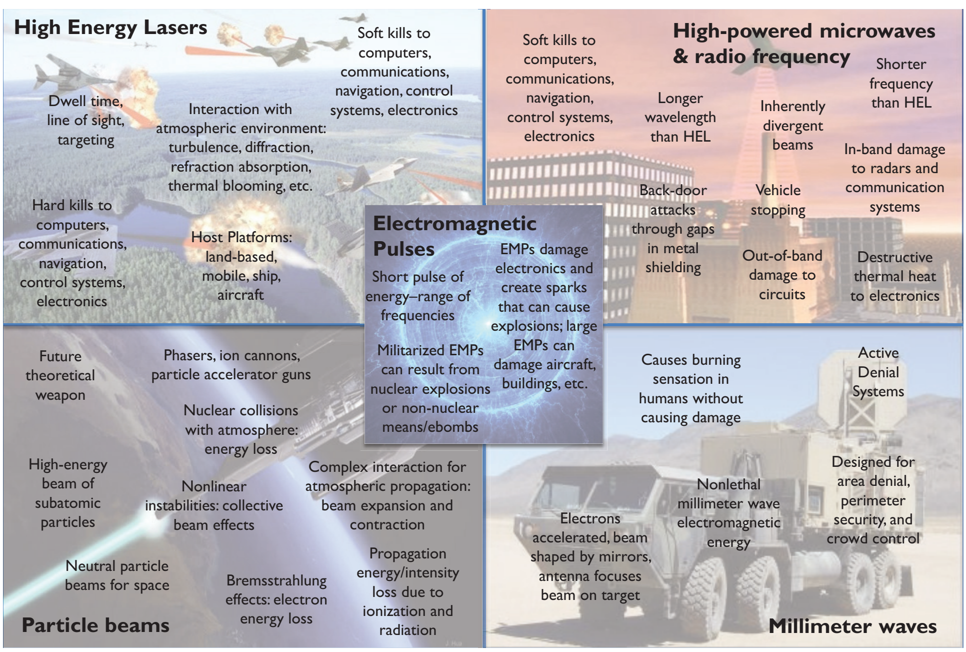

Fig. 3. Types of DEW threats.

countermeasure or evasion tactic. A laser detection and warning system would be very useful here. Intelligence on possible HEL systems would also provide critical information to aid in CDEW measures. Another possibility is the use of unmanned decoy systems that could venture into such environments ahead of time (before manned assets enter) to "test" the environment and detect HEL threats as expendable targets.

There are a range of possible destructive effects that adversarial HEL weapons can inflict on naval assets and missions. They can hinder military communications by damaging electronics, radars, computers, and satellites. They can decrease situational awareness by blinding or dazzling electro-optical sensors on ships, aircraft, and satellites. An HEL can potentially blind pilots and operators, either temporarily or with enough exposure—by causing permanent eye damage. HELs can attack and destroy drones, aircraft, helicopters, small boats, and missiles. Powerful HEL capabilities in the hands of adversaries can seriously impact the Navy's ability to operate in maritime and littoral regions.

HEL weapon systems are technologically advanced and inherently complex. They have a complex relationship with their external environment: Laser beams are highly affected by environmental and atmospheric conditions, and these conditions are themselves inherently complex and dynamic. Other factors contributing to this complex problem domain are the HEL's wavelength, the distance between the HEL and its target, and the target's characteristics (kinematics, material composition and thickness, etc.). Even slight changes in any of these factors can result in a much different amount of "power in the bucket" (amount of laser energy that reaches its spot on the target) and required dwell time. Table 1 lists the complex factors in the HEL threat problem domain and describes each factor's effect on the laser beam. The complexity of the HEL problem domain results in a significant degree of unpredictability in HEL weapon effectiveness.

All naval assets operating in a future DEW environment are vulnerable to HEL attacks. Currently, naval assets are not equipped with the ability to detect an HEL attack as it is occurring; nor do they have capabilities to counter or protect against such attacks. Hard kills present the most obvious and immediately devastating attacks; however, soft kills can have similarly debilitating results often from cascading failures or by compromising situational awareness. Adversarial HEL systems equipped with precision targeting, adaptive optics to overcome atmospheric obstacles, and enough power to cause hard kills require large power systems, sophisticated technology, and sizable host platforms. U.S. military intelligence, surveillance, and reconnaissance (ISR) assets have a better chance of spotting the larger, more sophisticated HEL systems. Lower-power adversarial HEL systems that are primarily capable of soft kills have a much smaller footprint, are cheaper, and may therefore be more ubiquitous in the future tactical environment. The small HEL systems will more easily escape our ISR detection. Even though they pose less of an immediate lethal threat, their ubiquity, obscurity, and stealthy kills present a significant threat to the Navy.

4. UAV Vulnerabilities in a DEW Environment

Naval UAVs will be highly vulnerable to future adversarial HEL threats based on their physical size, lightweight materials, components, and missions—taking them into hostile environments. Their proximity to threats, thin and lightweight structure, and flight kinematics make them especially susceptible to lethal HEL dwell times. HEL weapons can cause UAV soft kills or hard kills, resulting in a range of harmful effects from losing stability or power,

Table 1. Complex Factors Affecting HEL Weapon Effectiveness

Factors affecting HEL weapon effectiveness	Effect on laser beam
Water droplets, dust, aerosols (gas and solid particulates) acting as absorbers or scatterers	Molecules (particulates) absorb and scatter (deflect) laser beam photons and reduce the beam's energy.
Distance between HEL weapon and target	In general, there is an exponential laser power loss over distance. The Beer-Lambert Law provides an estimate of the laser beam exponential power loss over the distance traveled.
Changes in types and densities of molecules of atmospheric particulates depending on altitude	Changes in types and densities of molecules have different effects on laser beam power loss. The densities of water vapor, aerosols, and ozone change with altitude. Beyond the Earth's atmosphere where there is a vacuum, there are fewer obstructions.
HEL wavelength	Laser wavelength has a significant effect on how much or little the beam will be absorbed or scattered by atmospheric particulates.
Atmospheric turbulence	Turbulence occurs as the sun heats the atmospheric molecules, creating hotspots with varying temperature and density that act like lenses and bend (or refract) a laser beam, thus sending light in many directions. Turbulence also occurs due to wind shear, terrain-induced mechanical mixing, and heating from the Earth's surface.
Thermal blooming	Thermal blooming occurs as an HEL's output power and intensity increase to the point that the laser energy modifies the environment that it travels through. The laser beam changes the physical characteristics of the molecules and turns them into "lenses" that act as diverging lenses, causing the laser beam to disperse.
Line of sight	HEL weapons require a direct line of sight (LOS) to their targets that must be sustained for the required dwell time for a soft or hard kill. This may be hard to maintain if there are obstructions or if the target is moving.
Smoke, explosions	Smoke or other large particles act as aerosols that create multi-angle scattering and multipath distortion. The amount of laser absorption and scattering depends on the size and density of the particulates as well as the wavelength of the HEL weapon.

to losing sensor or communications, to crashing to the ground. Table 2 lists destructive effects that HEL weapons can have on UAVs.

UAVs support a variety of military missions including surveillance, communications, jamming, and deploying weapons. These missions are at risk for UAVs operating in DEW threat environments. HEL weapons can damage or destroy UAV components, leading to a variety of destructive effects. Figure 4 shows an example of UAV components. HEL damage

Table 2. Types of HEL Weapon Effects on UAVs

Types of HEL weapon effects on UAVs
Loss of functional control (loss of autonomous operations or remote control)
Loss of aerodynamical flight control
Loss of communication
Loss of stability
Structural distortions
Loss of power
Loss of sensors
Crash to the ground
Explosion

to any of the UAV's components is likely to lead to loss of mission effectiveness and loss of flight control.

The type of damage that a UAV will sustain depends on which of its components is targeted by the HEL weapon. Table 3 lists major UAV components and describes the associated HEL damage effects that could incur. The aircraft's body and chassis are likely to be the first components to sustain damage effects. Depending on the body's protective material coating, it may delay some destructive intrusion into the UAV's internal components. Other external components that may be damaged or destroyed include UAV sensors, communication datalinks, and gimbal systems. Sensor may be supporting data acquisition for the UAV's flight itself or to support surveillance missions. Sensors often have a high susceptibility to HEL attacks, as the laser can dazzle or blind sensors, damage electronics, interfere with calibration, or affect sensor controls and data processing. Likewise, HEL attacks can take out datalink electronics and antenna hardware, preventing controllers from communicating with UAV by leaving them unable to receive data or send commands. A UAV's primary computer and avionics are integrated into all of its components. If an HEL is able to damage the computer, which is likely to be located deep inside the UAV body, a wide range of adverse effects will occur, rendering the UAV completely disabled. HEL damage to flight-control systems and propulsion systems will cause the UAV to lose aerodynamic stability, possibly leading to a crash. Finally, an HEL

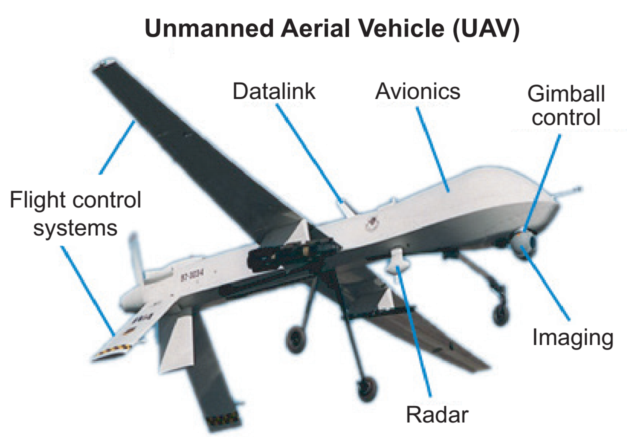

Fig. 4. Components of unmanned aerial vehicles (UAVs).

Table 3. HEL Weapon Effects on UAV Components

UAV component affected by HEL	Possible HEL damage effects
Body and/or chassis	Loss of designed reflectivity and/or radar signature, loss of designed dwell time delay, destructive intrusion into internal components
Sensors (radar, imaging)	Loss of mission-critical sensors, loss of sensor calibration, loss of flight-control critical sensors (can be caused by an HEL's extreme heat)
Communications datalink	Loss of signal from operator, loss of critical data from external signals, loss of flight control from lack of operator input
Primary computer and avionics	Loss of system interoperability, loss of flight control, loss of mission
Flight control systems	Loss of stability, flight control, pitch, altitude; can result in crash
Propulsion systems (actuators, motors)	Loss of flight due to an uncontrollable or inoperable propulsion system, locked actuators, or locked controls
Power supply/fuel cell	Loss of power for critical systems, loss of flight control, explosion

attack on a UAV's power supply could cause loss of power, loss of flight control, or even an explosion.

UAVs can be classified according to their size. Table 4 categorizes UAVs (also referred to as unmanned aerial systems (UASs) according to groups based on their weight (MGTOW = maximum gross takeoff weight), which also roughly corresponds to normal operating altitude (AGL = height above ground, FL = flight level corresponding to air pressure), speed, and mission. This general classification was used to study HEL effects on different types of UAVs based on their size and mission, which also affects their proximity to potential HEL threat systems during operations.

The U.S. Navy is making significant investments in UAV programs to support three different missions: long-dwell stand-off ISR, penetrating surveillance and strike, and tactical missions.[10] Four representative naval UAVs (shown in Fig. 5) were chosen based on their varying sizes and missions as examples for HEL vulnerability evaluation.

The four representative UAVs were (a) a large Group 5 broad area maritime surveillance (BAMS), (b) a large Group 5 combat UAV, (c) a rotary-wing Group 4 ISR and fire support UAV, and (d) a small Group 2 ISR UAV. The large BAMS UAV (Fig. 5a) has a mission of supporting manned maritime surveillance ISR platforms, by providing additional surveillance data including video footage and imagery of targets of interest.[11] The large combat UAV (Fig. 5b) provides strike fighter missions and is capable of carrier launches and aerial refueling. The large combat UAV is a low-observable, fast-moving, and semi-autonomous UAV. The Group 4 ISR and fire support UAV (Fig. 5c) is a rotary-wing helicopter UAV designed to support ISR, situational awareness, aerial fire support, antisubmarine warfare, and precision over-the-horizon targeting missions. It is a UAV designed for endurance (longer flight times), longer ranges, slower speed, and medium altitude. The small Group 2 ISR UAV has

Table 4. UAV Categories[9]

UAS groups	Maximum weight (lb) (MGTOW)	Normal operating alititude (ft)	Speed (kts)	Representative UAS	
Group 1	0–20	< 1200 AGL	100	Raven (RQ-11), WASP	
Group 2	21–55	< 3500 AGL	< 250	ScanEagle	
Group 3	< 1320	< FL 180		Shadow (RQ-7B), Tier II / STUAS	
Group 4	>1320		Any airspeed	Fire Scout (MQ-8B, RQ-8B) Predator (MQ-1A/B) Sky Warrior ERMP (MQ-1C)	
Group 5		> FL 180		Reaper (MQ-9A) Global Hawk (RQ-4) BAMS (RQ-4N)	

a mission of providing persistent ISR, targeting, and force protection in support of tactical operations[12] with a long range, long endurance, slow speed, and medium altitude.

The four UAVs were evaluated based on their vulnerability to potential future HEL threats. The UAVs were evaluated based on their mission, normal operating altitude, average proximity or range to the HEL threat, their speed, endurance, material, maneuverability, and fuel type. This quantitative evaluation assigned a low to high ranking of HEL susceptibility, assigning a color based on the level of risk. Table 5 shows the quantitative comparative evaluation. The size of the UAV contributes to its vulnerability—the larger the size, the greater the surface area—creating a greater opportunity for an HEL to inflict damage. A UAV's mission can contribute to its HEL vulnerability. As an example, an aircraft conducting routine surveillance during peacetime operations will have lower risk of encountering HEL threats than those in contested battle zones. A UAV's operating altitude and range

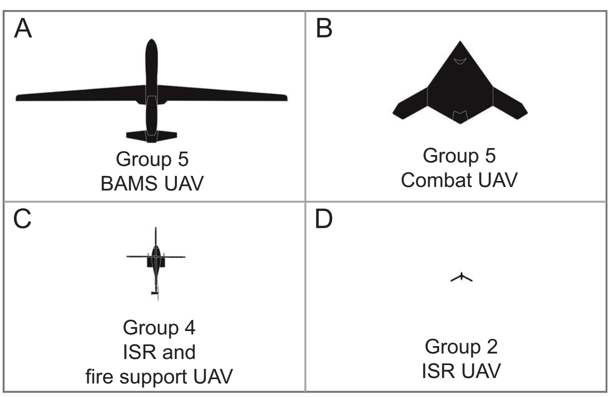

Fig. 5. UAV Examples11: (a) Group 5 BAMS UAV, (b) Group 5 Combat UAV, (c) Group 4 ISR and Fire Support UAV, (d) Group 2 ISR UAV.

Table 5. Evaluation of HEL Vulnerability of Example Naval UAVs

	BAMS UAV	Combat UAV	ISR and fire support UAV	Small IRS UAV
Size	Largest (Group 5)	Largest (Group 5)	Large (Group 4)	Small (Group 2)
Mission	Broad area ISR	Strike fighter ops	ISR, aerial fire support, antisubmarine Warfare, precision targeting for over the horizon strike	ISR, target acquisition, Force protection
Normal operating altitude	Higher altitude > FL 180 (FL = flight level)	Higher altitude > FL 180	Medium altitude < FL 180	Lower altitude < 3,500 AGL (above ground level)
Average proximity	Very long range to HEL threat	Long range to HEL threat	Medium range to HEL threat	Shorter range to HEL threat
Average speed	Fast	Fast (note: stealth design makes it hard to detect and track)	Medium	Slow
Endurance	Long	Medium	Medium	Long
Material/ thickness	Aluminum and composite/thicker	Composite/thicker	Composite/medium thickness	Composite/thin
Maneuverability	Large footprint for launch and recovery: runway	Stealth incorporated into design and maneuverability	Small footprint for launch and recovery: vertical takeoff/landing	Small footprint for launch and recovery: catapult-launched
Fuel type	Heavy fuel	Heavy fuel	Heavy fuel	Gasoline/ heavy fuel

Low vulnerability; Medium-low vulnerability; Medium-high vulnerability; High vulnerability

(proximity of the UAV from the HEL threat) are linked with the atmospheric conditions that the HEL laser beam must traverse to make contact with the UAV. With a higher altitude and greater range from the HEL, the UAV is less likely to be harmed, as the laser beam would have to penetrate through more of the atmosphere. A UAV's speed contributes to its ability to flee from the HEL's beam coverage and out of harm's way. A UAV's endurance, or longevity of flight, may dictate the likelihood and duration of it operating in an HEL threat environment. A UAV's material may arguably be one of the most significant properties determining its HEL vulnerability. The material may be susceptible to damage from an HEL or may be reflective of laser beams. The material susceptibility is a complex factor and is highly dependent on the wavelength and properties of the specific HEL laser as well as the thickness of the material. A UAV's maneuverability will make it more or less capable of dodging the laser or at least preventing the threat locking on an area for the required dwell time. A UAV's fuel type can contribute to its lethality—if the fuel is combustible, this presents a vulnerability as lasing may cause an explosion.

A large BAMS UAV, as shown in Fig. 5(a) and in Table 5, has a relatively long flight duration, thereby maximizing its broad area surveillance mission. Its large size and flight endurance present a vulnerability for being detected and targeted by HEL weapons. It operates at a high altitude where it is "not visible with the naked eye."[13] Its high altitude allows it to operate at a fairly lengthy distance from ground-based HELs. This protects the UAV, requiring a long dwell time and high energy for an HEL system to cause damage. A BAMS UAV is most vulnerable during launch and recovery, as these actions require a sizable logistic footprint for this large UAV.

A large combat UAV, as shown in Fig. 5(b) and in Table 5, will likely operate in a future DEW threat environment, given its tactical use in hostile areas. Unlike the BAMS, the combat UAV has a less predictable flight pattern, giving it an advantage against HEL threats. A combat UAV is capable of aerial refueling, thereby presenting a vulnerability if the refueling occurs within range of an adversarial HEL weapon. A large combat UAV has several advantages as well—it is built with a high reflectivity material, it is designed for stealth, and it can reach subsonic speeds. Thus, it would be difficult for adversaries to detect and target these types of UAVs. And if an HEL threat is detected, this type of combat UAV could quickly speed up and leave the area.

A rotary-wing ISR and fire support UAV, as shown in Fig. 5(c) and in Table 5, has some advantages and disadvantages in terms of its susceptibility to an HEL threat. It flies at a lower altitude to conduct its ISR missions and is smaller and lighter than the large BAMS and combat UAVs. The Group 4 rotary-wing UAV would generally be much closer to potential HEL threats, putting it at higher risk. However, the atmospheric conditions at the lower altitudes may offer some natural protection. This type of UAV uses liquid combustible fuel, which presents a vulnerability if targeted by an HEL weapon. Also, this type of UAV's rotor presents a single point of failure versus fixed-wing UAVs; however, the constant movement of the shaft may provide some protection from HEL damage.

A relatively small Group 2 ISR UAV, as shown in Fig. 5(d) and in Table 5, is vulnerable to HEL threats based on its lighter weight, slower speed, low operating altitude, and long endurance. These types of UAVs are likely to operate in closer proximity to potential HEL threats. Their small size and lightweight materials make them more susceptible to being irradiated and destroyed with shorter laser beam dwell times. However, their small size makes them harder for the enemy to detect and track.

5. CDEW Solutions for UAVs

A primary objective of this study was to identify and categorize CDEW solutions to provide an engineering framework for the development and future implementation of these solutions. A review of CDEW research projects revealed that a variety of technologies are currently being developed to protect military assets against future DEW threats. These approaches include target hardening such as reflective coatings and the use of materials with improved thermal properties and exotic metamaterials that can potentially bend electromagnetic waves around a target.[14] Laser warning systems are being developed to identify HEL threats. Concepts for strategic approaches include evasive maneuvers, deployment of decoys or obscurants, and swarm attacks. Table 6 identifies five categories of CDEW solution approaches that can be applied to UAVs: atmospheric operations, UAV payloads for HEL threat identification and warning, UAV payloads for active countermeasures, UAV shielding, and UAV maneuvers

Table 6. Five Categories of CDEW Solutions for UAVs

CDEW solutions for UAVs		
1	Atmospheric CDEW operations	Exploiting atmospheric conditions that reduce threat HEL effectiveness to passively protect UAVs.
2	UAV payloads for HEL threat identification and warning	Integrating payloads onboard UAVs to perform laser threat identification and laser warning.
3	UAV payloads for 6ctive countermeasures	Integrating payloads onboard UAVs to deploy active countermeasures for protection against HEL threats.
4	UAV shielding	Coating UAVs with materials that can reflect, conduct, or radiate the heat away from the beam, or be ablated by the laser beam.
5	UAV maneuvers and swarm tactics	Using UAV tactics such as maneuvers to prevent laser LOS or dwell time; or the use of swarms that include UAV decoys.

and swam tactics. Three of the types of CDEW solutions (atmospheric operations, active countermeasure payloads, and UAV maneuvers and swarm tactics) must be implemented during operations. For these approaches, the decision to implement them are made in real time and are based on the operational situation. Three of the CDEW solutions (HEL threat identification payloads, active countermeasure payloads, and shielding) require engineered solutions that are implemented during the design and development phases of the UAVs. They require that CDEW payloads or specialized shielding materials be engineered into the UAVs prior to deployment and operations. When possible, the use of multiple CDEW solutions, from more than one of the five categories, can be combined to offer greater protection.

5.1 Atmospheric CDEW operations

HEL weapons are severely limited by weather and atmospheric conditions. These limitations can be exploited as a method of protecting UAVs. Certain weather conditions, such as rain, fog, haze, smoke or ash from fire, dust, and smog from pollution, can act as a natural obscurant for UAVs. These atmospheric conditions can cause extinction, an effect where molecules and aerosol particles absorb and scatter laser beams.[15] Similar effects can degrade a laser beam encountering fog, haze, or rain.[16] Optical turbulence from fluctuating atmospheric pressure and temperature effects can cause a laser beam to wander, jitter, bend, or diverge, which increases its spot size and reduces its concentrated power.[15] Thermal blooming is caused by the interaction of very-high-energy laser beams (>100 kW) with the atmosphere (the laser heats the air), causing the beam to diverge and weakening its irradiance on the target.[15] Table 7 lists atmospheric conditions that affect laser beams and have potential as CDEW solutions.

These atmospheric conditions can be used as countermeasures, offering protection for UAVs from HEL threats. In order to use atmospheric extinction as a CDEW solution, UAVs could conduct operations in cloud cover, dust storms, and polluted areas, and during mist or rainfall. These natural conditions offer the greatest probability of absorbing and scattering HEL laser beams. Operating UAVs at the greatest distance from the HEL threat or at the altitude with the highest density of maximizing the operating range from the HEL threat offers natural protection.

Table 7. Atmospheric CDEW Operations for Defense of UAVs

Atmospheric condition	Effect on laser beam	UAV countermeasure strategy
Rain, fog, haze, fire, dust, ash, pollution	Extinction, molecular and aerosol absorption, beam scattering, loss of energy, increase in required dwell time.	Launch missions during high extinction conditions.
Turbulence	Divergence: breaks laser beam apart, increasing spot size and reducing concentrated power.	Exploit this by calculating temperatures at the operational environment.
Thermal blooming	Heating of air molecules along the beam path creates divergent lenses and unfocused beam.	Use flight patterns (i.e., head-on approaches) to increase the likelihood of stagnation zones along the beam path.

Implementing atmospheric CDEW operations for protecting UAVs against HEL threats requires knowledge in three areas: (1) knowledge of the threat, (2) knowledge of the weather conditions, and (3) knowledge of the UAVs and their missions. The more that is known about the HEL location, type, and capabilities of the laser(s), and expected power, the more accurate the estimate of atmospheric protection will be. Knowledge of the weather conditions can come from weather predictions and real-time sensors measuring effects. Finally, understanding the UAV missions and how these can be accomplished based on where they need to operate and for how long, including possible alternate routes, is an input to determining UAV operations that can best exploit atmospheric CDEW protections. Figure 6 shows a concept for supporting human decision makers with automated decision aids to determine atmospheric CDEW operations for UAV missions.

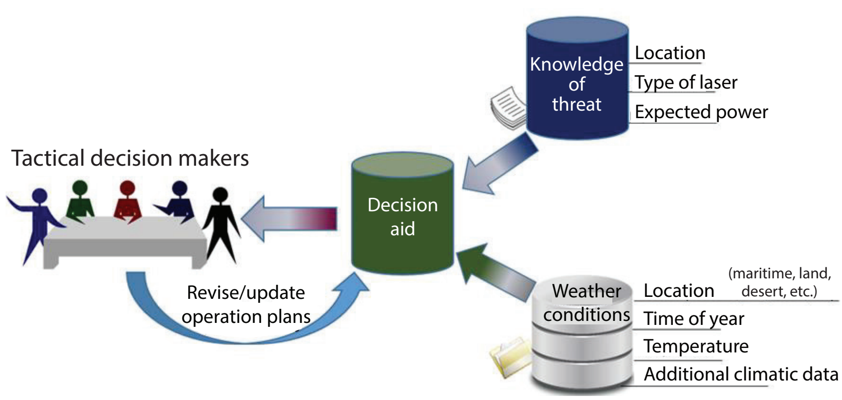

Fig. 6. Concept for a decision aid to support atmospheric CDEW operations.

5.2 UAV payloads for identification and warning

The detection of an active HEL weapon is critical to the protection of UAV assets. This type of CDEW solution supports other active methods such as evasion, countermeasures, and counterfire. The concept for HEL identification and warning is to integrate a payload onto a UAV that can detect laser threats and act as a laser warning system. Laser warning system technologies use semiconductor photodetectors or cascaded photodiode/phototransistor arrays that detect laser beams. Laser warning systems are used on some military helicopters for identifying laser rangefinders, designators, and beam-rider missiles.[17] The concept for this CDEW solution is shown in Fig. 7—a UAV would carry a laser warning system payload to detect enemy HEL weapons and alert other UAVs and offboard operators and systems via data links. The alert can then be used to implement active countermeasures or evasive maneuvers. Knowledge of the enemy HEL threat can also alert other naval assets in the area of operations such as manned aircraft and ships. The challenges related to this CDEW solution include the range and capabilities of the payload system, which may be limited to detecting particular types of HEL weapons and may also be constrained by atmospheric conditions. Also, this CDEW solution must be implemented during the UAV design and acquisition phase, because it requires that a UAV be designed to carry this payload.

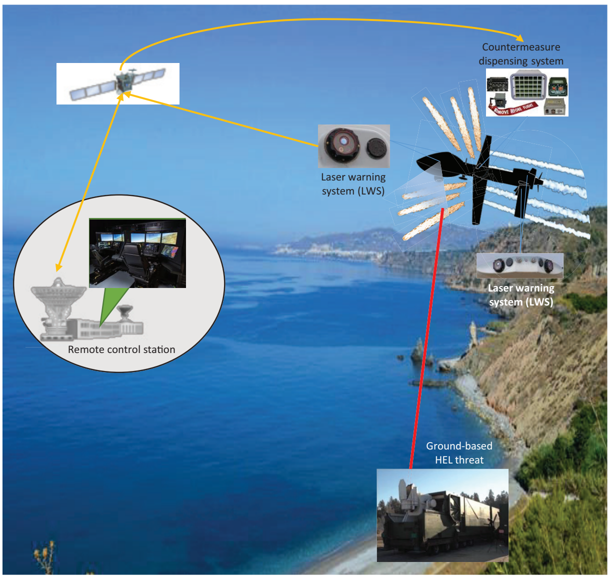

Fig. 7. Laser detection and warning payload operational concept.

5.3 UAV payloads for active countermeasures

Active approaches to defending UAVs against HEL threats involve implementing payloads on UAVs that are equipped with countermeasure or counterfire effects (expendables). CDEW expendables include smoke or aerosol screens, flares, laser dazzlers or jammers, and basic counterfire.[18] Table 8 describes four types of active countermeasures for UAV CDEW, and Fig. 8 illustrates them.

The four types of active countermeasure CDEW concepts are illustrated in Fig. 8. Active countermeasures that obscure UAVs are intended to distort the HEL's ability to track the UAV or maintain a line of sight (LOS). Flares can disguise the UAV by producing a bright light and intense heat. Fig. 8(a) illustrates the use of smokescreens (or fog screens) to create

Table 8. Types of Active Countermeasures for UAV CDEW

Active countermeasure methods	Description
1. Smoke or aerosol screen (see Fig. 8a)	Produces a smokescreen or fog to absorb and scatter the laser energy. Objective is to "hide" the UAV and increase the dwell time required or cause the HEL to lose track of the UAV altogether.
2. Laser jammer (see Fig. 8b)	This passive system analyzes an incoming HEL beam, determining the source location and intensity. The system uses this information to target and jam the laser source and disrupt its tracking ability. An example is the Helios system, which is a small UAV-mounted sensor package.
3. Basic counterfire (see Fig. 8c)	Uses a weaponized UAV payload to deploy weapons to destroy threat HEL if the HEL has been identified and its location is known.
4. Decoy countermeasure (see Fig. 8d)	Deploys a heated physical decoy to confuse the HEL and act as the HEL's target, allowing the UAV to leave the threat area.

a cloud of particles around the UAV to absorb and scatter laser energy.[19] The effect of the smoke or aerosol screen will depend on the size of the particles and the wavelength of the HEL; although it will not provide a total shield, it will reduce the intensity of the laser beam on the target, and it will increase the lethal dwell time. The Navy is developing active laser

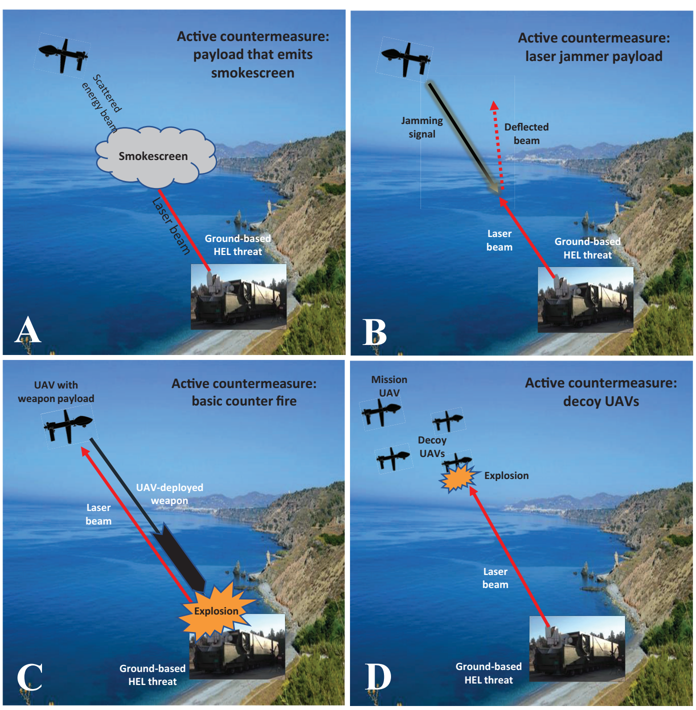

Fig. 8. Active countermeasure concepts for UAV CDEW: (a) smokescreen payload, (b) laser jammer payload, (c) basic counterfire payload, (d) UAV swarm with decoys.

jammers (illustrated in Fig. 8b) to analyze incoming HEL beams to determine HEL locality and beam intensity and use this information to target and jam the laser source, disrupting its ability to track the target.[20] The basic counterfire payload (shown in Fig. 8c) would fire munitions at an HEL laser source. Finally, the decoy concept (shown in Fig. 8d) deploys decoy UAVs to confuse adversaries. The decoys would act as targets for the enemy HEL to track and attack instead of the actual UAV.

5.4 UAV shielding

The first line of passive defense on a UAV is its material shielding. Three types of shielding for countering HELs are Bragg mirrors, reflective coatings, and ablative coatings. The Bragg mirror is a dielectric mirror composed of alternating layers of two different optical materials where each corresponds to a portion of the laser wavelength that it is designed to reflect.[21] The layers can be precisely constructed to reflect high percentages (up to 99.99%) of laser light for a particular wavelength. Bragg mirrors still allow some laser light penetration and are therefore useful as detractors for increasing the required dwell time, but do not offer a perfect defensive shield. Reflective coatings are designed to reflect laser light and are also highly dependent on the wavelength of the HEL laser. An operational concept is to spray UAVs with a temporary reflective coating just prior to a mission. The idea is to use intel knowledge of the HEL threat to select the appropriate reflective coating that is matched to the HEL's wavelength. Ablative coatings shield by acting as a surface material that can be sacrificed or ablated by the thermal energy of the HEL threat.[22] The concept is to coat a UAV with an ablative layer that will be destroyed first by the HEL laser beam, which will thus increase the dwell time enough for the UAV to leave the threat area.

5.5 UAV maneuvering and swarm tactics

Another type of active countermeasure to protect UAV assets against HEL threats is simply operating the UAVs strategically to take advantage of their inherent kinematic, maneuvering, and swarm capabilities. This CDEW solution benefits from knowledge of the enemy HEL threats—either ahead of time or in real time during operations. The UAVs are operated in such a way as to quickly maneuver away from active HELs or to operate in swarms with duplicates of UAVs, so that if some UAVs are lost, others will be able to continue the mission. These operational tactics can be employed before, during, and after an active HEL has engaged a UAV. The goal is to avoid, mitigate, or transfer the effects of the HEL weapon. UAV evasion maneuvers will experience latency between the controller and the flight components,[23] but active maneuvering to avoid an HEL may only have to "break" the laser LOS and avoid being targeted for the duration of the required dwell time. Research on UAV maneuvering capabilities has been primarily focused on the ability of UAVs to avoid missile threats. Developments are underway to improve UAV adaptive kinematics in the horizontal and vertical planes along with the use of onboard automation to detect threats and decide to maneuver.[23,24] The goal is to improve the response time by avoiding latencies inherent in remote control. UAV swarm operations is a growing area of interest and development. Employing swarm tactics as a CDEW solution can interrupt the HEL LOS or confuse the HEL's ability to target a particular UAV. The Navy is researching the launching of many UAVs that can be deployed simultaneously. An adversarial HEL would have to engage and defeat each UAV to avoid being overrun.[25]

6. CDEW Analysis Tool: Evaluation of CDEW Solutions for UAVs

The research team developed a CDEW Analysis Tool using RStudio to represent an adversarial directed energy attack against UAVs based on UAV characteristics, threat characteristics atmospheric conditions, and proximity of UAVs to the threat. The tool, shown in Fig. 9, was used to evaluate four of the CDEW methods: using atmospheric effects, using Bragg mirror coatings on UAVs, using swarm configuration tactics, and using operational tactics (evasive maneuvers). The model received inputs from a system developed by the Air Force Institute of Technology called Laser Environmental Effects Definition and Reference (LEEDR),[26] which provided realistic environmental data to model atmospheric effects. LEEDR produces extinction coefficients at different altitudes based on weather data inputs.

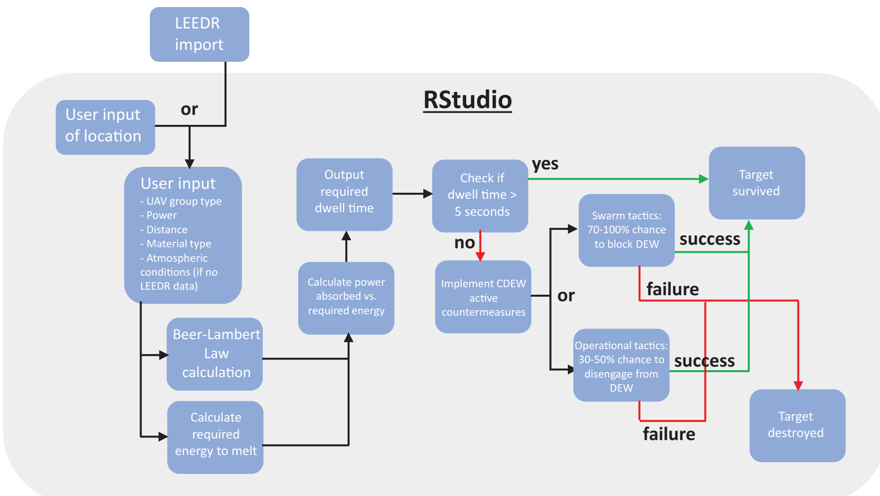

Fig. 9. CDEW analysis model schema.

The CDEW Analysis Tool was used to model the four different types of UAVs to study how each type might fare using each of the four different CDEW methods. Table 9 lists the analysis results—based on the assumption that if the dwell time required to "kill" (or destroy) the UAV was less than 5 seconds, the UAV would be considered destroyed. With no CDEW measure in place, only the Triton was deemed safe based on its far distance from potential directed energy threats. With adverse atmospheric conditions, the required dwell time increased for all four types of UAVs; however, only the BAMS UAV was safe, with a required dwell time of 72.69 seconds. The use of Bragg mirrors to coat the UAVs was determined to protect all of the UAVs, assuming that the threat laser's wavelength corresponded to the Bragg mirror coating.

Simulations were run to analyze the swarm tactics and operational tactics. The use of swarm tactics resulted in protection four out of five times for the BAMS UAV and rotary-wing fire support UAV, and protection three out of four times for the large combat UAV and small ISR UAV. The use of operational maneuvering tactics offered less protection—

Table 9. CDEW Model Test Case Results

Model inputs	BAMS UAV	Combat UAV	Fire support UAV	Small ISR UAV
Size	Largest	Largest	Larger	Medium
Normal operating altitude	> FL 180	> FL 180	> FL 180	< 3,500 AGL
Average proximity	8,200 nm	1,600 nm	150 nm	60 nm
Material	Aluminum	Composite	Composite	Composite
DEW Power	100 kW	100 kW	100 kW	100 kW
CDEW method (note: DT = dwell time) If DT < 5 seconds, the UAV is considered “killed.” If DT > 5 seconds, the UAV is “safe.”				
None	SAFE DT = 31.16 s	KILL DT = 3.38 s	KILL DT = 3.22 s	KILL DT = 3.02 s
Atmospheric (cloudy)	SAFE DT = 72.69 s	KILL DT = 4.64 s	KILL DT = 4.26 s	KILL DT = 3.92 s
Material (Bragg mirrors)	SAFE DT = inf	SAFE DT = inf	SAFE DT = inf	SAFE DT = inf
Swarm (#pass / #fail)	SAFE (4 / 1)	SAFE (3 / 2)	SAFE (4 / 1)	SAFE (3 / 2)
Tactics (#pass / #fail)	SAFE (3 / 2)	KILL (1 / 4)	KILL (2 / 3)	KILL (2 / 3)

protecting the BAMS UAV three out of five times, protecting the rotary-wing fire support UAV and small ISR UAV two out of five times, and protecting the large combat UAV only one out of five times.

7. Conclusion

Adversarial advances in directed energy technology present a novel type of threat environment that is hard to detect and potentially lethal to U.S. forces and assets. The deployment of these weapons will impact U.S. naval tactics and will necessitate new engineering solutions for naval assets to keep pace. The U.S. Navy needs to prepare for the presence of a DEW threat environment in littoral and maritime environments.

DEW threats are highly complex and hard to detect. HEL laser beams interact in a complex manner with their environment and many contributing factors affect whether an HEL weapon shot will be effective: HEL technology (power, wavelength, adaptive optics, and targeting ability), atmospheric effects, engagement geometry, and target characteristics (size, materials, reflectivity, and material thickness). The Navy can exploit these complex factors and use them for CDEW methods. Naval assets can “hide” using existing atmospheric conditions or create their own environmental CDEW effects, such as smokescreens. Assets can avoid an HEL weapon’s LOS or required dwell time by maneuvering away in time or using swarm tactics or decoys to confuse the adversary.

Some CDEW solutions need to be engineered: active payloads, decoys, and passive shielding. Some CDEW solutions can be implemented during operations: atmospheric operations, maneuvering, and swarm tactics. Many CDEW solutions will require HEL detection and characterization. Implementing multiple CDEW solutions is the best strategy when possible and feasible.

NPS has used its CDEW analysis tool to conduct an initial evaluation of several CDEW methods for protecting naval UAVs against a directed energy threat. NPS is developing a higher fidelity model to continue to study CDEW concepts against future directed energy threats. The scope of the analysis can be expanded to evaluate CDEW methods for other types of military assets including manned aircraft, ships, missiles, satellites, and land-based systems.

Continued development of shielding materials and CDEW payloads is critical to protect military assets in future DEW environments. Modeling and simulation can support planning and preparation for implementing operational CDEW measures such as atmospheric operations, maneuvering tactics, and UAV swarm tactics. Eventually, these CDEW solutions can be tested in more realistic environments. Finally, this study recommends the development of decision aids to support making sense of the complex directed energy factors involved in the real-time implementation of operational CDEW solutions.

References

1. Kiel, D., *A Vision for Directed Energy and Electric Weapons in the Current and Future Navy*. Paper presented at Amer. Soc. Nav. Eng. Days, Arlington, VA (2007).
2. Zhen, L., *How China's Military has Zeroed in on Laser Technology*, South China Morning (2018). Retrieved November 17, 2021, from https://www.scmp.com/news/china/diplomacy-defence/article/2144756/how-chinas-military-has-zeroed-laser-technology
3. Xuanzun, L., *Military Developing Airborne Laser Attack Pod*, Says Report, Global Times (2020). Retrieved November 17, 2021, from https://www.globaltimes.cn/content/1175931.shtml
4. O'Connor, T., *Russia's Military has Laser Weapons That Can Take Out Enemies in Less Than a Second*, Newsweek (March 12, 2018). Retrieved November 17, 2021, from https://www.newsweek.com/russia-military-laser-weapons-take-out-enemies-less-second-841091
5. Pickrell, R., *Russian Laser Weapon Designed to Obliterate Targets "Within Fractions of a Second" Just Entered Combat Service*, Business Insider (2018). Retrieved November 17, 2021, from https://www.businessinsider.in/defense/russian-laser-weapon-designed-to-obliterate-targets-within-fractions-of-a-second-just-entered-combat-service/articleshow/66962172.cms
6. Killalea, D., *Russia's New Laser Can Reportedly Shoot Down Satellites*, Innovation News (2018). Retrieved November 17, 2021, from https://www.news.com.au/technology/innovation/russias-new-laser-can-reportedly-shoot-down-satellites/news-story/ef6b93c8eef6713c857b0837fca75127
7. Lin, J. Singer, P., Pop. Sci. (2017). Retrieved November 17, 2021, from https://www.popsci.com/china-new-weapons-lasers-drones-tanks/
8. *Airshow China 2018: CPMIEC Undiscloses LW-30 Laser Weapon System*. Army Recognition (2018). Retrieved February 19, 2022, from https://www.armyrecognition.

com/airshow_china_2018_zhuhai_news_show_daily_coverage/airshow_china_2018_cpmiec_undiscloses_lw-30_laser_weapon_system.html

9. *UAS Task Force Airspace Integration Integrated Product Team, Unmanned Aircraft System Airspace Integration Plan*. Version 2.0. Washington, DC: Department of Defense (2011).
10. Pearson, F., *The Way Ahead for Maritime UAVS*, Naval War College, Joint Military Operations Dept., Newport RI (2006). Retrieved December 14, 2022, from https://apps.dtic.mil/sti/pdfs/ADA463705.pdf
11. Gilmore, J., *Operational Test and Evaluation FY 2015 Annual Report*. Washington, DC: Department of Defense (2016).
12. Alkire, B., Kallimani, J., Wilson, P., Moore, L., *Applications for Navy Unmanned Aircraft Systems*, Santa Monica, CA: RAND (2010).
13. Barnhart, R., Hottman, S., Marshall, D., Shappee, E., *Introduction to Unmanned Aircraft Systems*, Boca Raton, FL: CRC Press (2012).
14. Hewitt, C., *Analysis of Broadband Metamaterial Shielding for Counter-Directed Energy Weapons*, master's thesis, Naval Postgraduate School, Monterey, CA (2017).
15. Carn, S., *Transmission Lecture*, Michigan Technological University (2010).
16. Blau, J., Cohn, K., *Directed Energy Weapons Overview*, Naval Postgraduate School, Monterey, CA, Lecture (2019).
17. Christie, T., *Operational Test and Evaluation FY 2004 Annual Report*. Washington, DC: Department of Defense (2004).
18. Haystead, J., J. Electron. Def. **36**(12), 26 (2004).
19. Ghoshroy, S., *Navy's New Laser Weapon: Hype or Reality?* Bulletin of the Atomic Scientists (2015).
20. Hambling, D., *Drones Get First Anti-Laser Lasers to Stop Being Shot Down*. NewScientist (2016). Retrieved February 19, 2022, from https://www.newscientist.com/article/2105362-drones-get-first-anti-laser-lasers-to-stop-being-shot-down/
21. Makri, E., Ramezani, H., Txampilos, K., Vitebskiy, I., Phys. Rev. A **89**(3), 031802 (2014).
22. Favaloro, M., *Ablative Materials*. Kirk-Othmer Encyclopedia of Chemical Technology (2000). https://doi.org/10.1002/0471238961.0102120106012201.a01
23. Levin, J., Nahon, M., Paranjapes, A. *Aggressive Turn-Around Manoeuvres with an Agile Fixed-wing UAV*. IFAC-PapersOnLine **49**(17), 242 (2016).
24. Yomchinda, T., *A Study of Autonomous Evasive Planar-Maneuver Against Proportional-Navigation Guidance Missiles for Unmanned Aircraft*. 2015 Asian Conf. Def. Tech., Hua Hin, Thailand, 210 (2015).
25. Atherton, K., Pop. Sci. (2015). Retrieved February 19, 2022, from https://www.popsci.com/boeing-unveils-compact-anti-drone-laser/.
26. Fiorino, S., Randall, R., Via, M., Burley, J., J. Appl. Meteor. Climatol. **53**(1), 136 (2014).