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COUNTER-DIRECTED ENERGY WEAPONS: DEFENSE OF AIR ASSETS

by

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March 2020

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The global proliferation of directed energy weapon technology presents a new threat for the United States as competitors try to capitalize on the technology's relative high potential of mission success and low operational costs. The use of these weapons necessitates new engineering solutions for naval assets in order to keep pace. It is essential to proactively plan for counter-directed energy weapon methods, tactics, and capabilities. This capstone project characterized the adversarial-directed energy threat environment and developed and evaluated concepts for countering, evading, and neutralizing the potential threat effects against naval assets. In particular, the study focused on high-energy laser weapon systems and their effects on naval unmanned aerial vehicles. Capstone team members developed an evaluation tool that they applied to the concepts. The tool can be adapted to counter and defend a variety of assets. After the team applied systems thinking to this problem, it recommended methods for naval assets to counter these threats.

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ABSTRACT

The global proliferation of directed energy weapon technology presents a new threat for the United States as competitors try to capitalize on the technology's relative high potential of mission success and low operational costs. The use of these weapons necessitates new engineering solutions for naval assets in order to keep pace. It is essential to proactively plan for counter-directed energy weapon methods, tactics, and capabilities. This capstone project characterized the adversarial-directed energy threat environment and developed and evaluated concepts for countering, evading, and neutralizing the potential threat effects against naval assets. In particular, the study focused on high-energy laser weapon systems and their effects on naval unmanned aerial vehicles. Capstone team members developed an evaluation tool that they applied to the concepts. The tool can be adapted to counter and defend a variety of assets. After the team applied systems thinking to this problem, it recommended methods for naval assets to counter these threats.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAR	autonomous aerial refueling
ADS	active denial system
AGL	above ground level
AIS	automatic identification system
AO	operational availability
APKWS	advanced precision kill weapon system
ARB	arbitrary
BAMS	broad area maritime surveillance
BLOS	beyond line of sight
C3	command, control, and communication
CIED	counter-improvised explosive device
CMDS	countermeasures dispenser system
CONOP	concept of operations
CDEW	counter-directed energy weapon
CRS	Congressional Research Service
DE	directed energy
DEW	directed energy weapon
DoD	Department of Defense
DoDAF	Department of Defense Architecture Framework
DOT&E	Director, Operational Test and Evaluation
DT	dwell time
FL	flight level
FY	fiscal year
HARLID	high angular resolution laser irradiance detector
HEL	high-energy laser
HPM	high-powered microwave
ICBM	intercontinental ballistic missile
IED	improvised explosive device
ISR	intelligence, surveillance and reconnaissance
km	kilometers
kts	knots
kW	kilowatts
L&R	launch and recovery
laser	light amplified by stimulated emission of radiation

LCS	littoral combat ship
lbs	pounds
LEEDR	Laser Environmental Effects Definition and Reference
LOCUST	low-cost UAV swarming technology
LOS	line of sight
LWS	laser warning system
m	meters
MGTOW	maximum gross takeoff weight
mm	millimeters
MVP	minimum viable product
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
nm	nautical miles
nm	nanometer
ONR	Office of Naval Research
OV-1	operational view
PIN	P-type, intrinsic, and N-type
pwr	power
SBIR	small business innovation research
SCI-FI	science fiction
SDI	strategic defense initiative
SSL	solid-state laser
STTR	small business technology transfer
STUAS	small tactical unmanned aircraft system
SWaP	size, weight, and power
THEL	tactical high-energy laser
TOW	tube-launched, optically tracked, wire-guided
UAS	unmanned aerial system
UAV	unmanned aerial vehicle
UCAS-D	unmanned combat aircraft system demonstrator
UCAV	unmanned combat aerial vehicle
UI	user interface
USN	United States Navy
VBA	Visual Basic for Applications
WWI	World War I
WWII	World War II

EXECUTIVE SUMMARY

High-energy laser (HEL) weapons are receiving increasing interest from armed forces around the globe. Technology has reached a point where HEL weapons are being exploited by peer competitor nations due to the higher potential of mission success and lower operational cost when compared to traditional weapons. The use of these weapons will affect our naval tactics and necessitate new solutions to manage the threat. U.S. naval tactics use forward-deployed unmanned aerial vehicles (UAVs) putting them in close proximity to adversaries. This makes naval UAVs more susceptible to being targeted and damaged by HELs. Once HEL weapons are integrated into the littoral and maritime environments, U.S. naval assets must be capable of protecting themselves against such threats.

This capstone focused on characterizing future adversarial-directed energy weapon (DEW) threat environments and evaluating solution concepts for countering, evading, and neutralizing the threat. In particular, this study focused on HEL weapon systems as the directed energy threat and their effects on naval UAVs. The results of the capstone provide an understanding of projected UAV susceptibility to future HEL threats and identified countermeasure, or counter-directed energy weapon (CDEW), concepts that can be applied to protect naval UAV assets. HEL weapon systems focus a beam of electromagnetic radiation onto a small spot to burn through the target material and render a target incapable of accomplishing its mission (Kopp 2008). Directed energy weapons (DEWs) have been under development since the 1960s, but recent developments indicate that they will soon be fielded in combat operations (Cook 2013). A HEL's ability to precisely deliver energy at the speed-of-light targeting, low per-engagement cost, and "unlimited" magazine (limited only by the power available) make it a desirable weapon. Unclassified new reports have indicated that countries such as China and Russia have been demonstrating this weapon technology operationally; therefore, the U.S. must be prepared for such threats.

The team began the project by characterizing the DEW threat environment, which included studying the limitations and strengths of HEL systems. The HEL requires a finite amount of time, referred to as dwell time, to achieve a hard or soft kill on the target. A "hard kill" refers to structurally damaging the UAV whereas a "soft kill" may disrupt the

function but not permanently damage the target. The length of the required dwell time can be impacted by the output power of the HEL, the distance to the target, the line of sight requirements, the atmospheric conditions, and the material of the target. The atmosphere itself poses significant limitations for HEL weapons. Limitations include the effects of molecular and aerosol absorption and scattering of the laser beam. Turbulence, which is due to air cells of varying temperature and density along the beam that can act as tiny "lenses," limits the effect of HEL by causing the beam to break apart or wander (Nielsen 1994). Thermal blooming, which is due to heating of air in a column along the beam, can also limit HEL by defocusing the beam (Nielsen 1994). Atmospheric effects also include scattering due to smoke particles, which could be used in expendables to exploit in the countermeasure solution. Other factors affecting HEL lethality are the thickness, thermodynamic properties, and reflectivity of the target material. All of these target characteristics will affect the required HEL dwell time needed for a soft-kill or hard-kill. Joseph Blau and Keith Cohn gave a lecture on the topic, "Directed Energy Weapons Overview" in July 2019 at the Naval Postgraduate School in Monterey, CA. In this presentation, the time required to dwell on a finite point on a HEL target varies greatly but a general rule for a hard-kill is on the order of five to ten seconds per target.

The team evaluated naval UAVs in terms of their vulnerabilities in a HEL threat environment based on their type and assigned missions. The team considered possible destructive effects and performed component-based evaluation to determine which UAV components would have the highest probability of being targeted and the type of damage that would be inflicted. The team identified four specific UAVs as use-cases for countermeasure concepts based on the potential to operate in a DEW environment, the general operating altitude, the maneuverability, the missions employed, the general operational conditions, and the aircraft material. The four UAVs that were identified as use cases were the MQ-4C "Triton," the X47B "Pegasus," the MQ-8C "Fire Scout," and the STUAS "ScanEagle" aircraft.

The team used information gathered on HEL weapons and UAVs as targets to develop CDEW solution concepts. The CDEW solution concepts depended on the operational environment, atmospheric conditions, the size weight and power (SWaP) of the

UAVs, and the UAV missions that dictated operational altitudes, maneuvers, and proximity to HEL threats. The team identified five categories of CDEW solutions:

(1) operational tactics using atmospheric effects to passively protect UAVs,

(2) threat identification and early warning systems,

(3) onboard active countermeasure payloads such as decoys or smokescreens,

(4) onboard passive countermeasures such as the use of shielding, or ablative coating, and

(5) tactical maneuvering or swarm attacks.

The team studied the limitations of each approach and observed that each type of solution would not be appropriate for all types of naval UAVs. The team noted that the best method might in fact be a combination of these solutions based on the particulars of each type of UAV.

To evaluate the CDEW solution concepts, the team developed a modeling and analysis framework, including a simulation tool to calculate the dwell time required by an adversarial HEL to achieve a "hard kill" on the use-case UAVs. The team developed the simulation tool in "R" Studio. The tool models a HEL attack using the Beer-Lambert law for atmospheric extinction and UAV surface material characteristics for energy absorption. The tool requires the user to input the power of the DEW, the range from the weapon to the target, the UAV size, the UAV material, and the weather. The output provides a calculated dwell time given the specified parameter, such as the amount of time a UAV would have from HEL lock-on until it melted through the targeted surface. The team used the tool to model different survivability scenarios and determine how long it would take for a HEL threat to destroy a UAV in different HEL DEW threat environments. The parameters used in the case study remained unclassified but could easily be updated with real-world values to apply to any aircraft. The team used the tool to evaluate the effectiveness of several CDEW solution concepts applied to the four UAV use cases.

The HEL weapon has numerous obstacles to overcome before it will become a reliable and effective threat in tactical environments. However, DEW technology advancements are making progress and are likely to enter the threat environment of the future. This study provides a high-level look at the weapon threat and the countermeasure solutions that naval UAVs could utilize. Larger UAVs are capable of carrying additional payloads and can rely on active countermeasures to exploit atmospheric limitations. This provides many options for their countermeasure solutions including laser warning systems and active countermeasures requiring heavier payloads such as expendables, decoys, and smokescreens. For medium-size UAVs, passive countermeasures such as shielding, coating or ablative material may be the best option. For smaller UAVs, the best course of action may be employing evasive tactics such as swarm techniques or selecting reflective material during design.

This study aimed to increase awareness of the HEL threat to U.S. naval assets and propose solution concepts to counter this future threat. The team produced a foundational understanding and a modeling and analysis framework to evaluate CDEW solution concepts for naval UAVs. Future work can use the CDEW modeling and analysis framework along with more detailed and classified data on specific UAVs to determine the best combinational solution concept to protect that asset.

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I. INTRODUCTION

A. CAPSTONE PROJECT OVERVIEW

This capstone project addresses the potential adversarial use of directed energy weapon (DEW) technologies as a threat to naval unmanned aerial vehicles (UAVs). The team characterized the potential future threat environment to understand how it might affect naval operations. This is used in developing solution concepts for countering, evading, and neutralizing potential DEW threats against UAVs using various means and tactics. The team focused the study on high-energy laser (HEL) weapon systems as a type of DEW technology that may be fielded by adversaries in the near future. The intended benefit of this capstone study is to apply systems thinking to this potential threat environment to create a foundational understanding that will lead to systems solutions for the defense of naval assets operating in future DEW threat environments.

B. PROBLEM STATEMENT

The global proliferation of DEW technology presents a new threat that is being exploited by peer competitor nations due to the high accuracy and precision of HELs, their essentially unlimited magazines, and their low operational costs as compared to traditional weapons. The use of these weapons will affect naval tactics and necessitate new engineering solutions to keep pace with adversaries. 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. This pre-emptive measure is imperative to successfully defend against DEWs and protect naval assets. UAVs are particularly vulnerable, as they are generally made of lighter and thinner materials than manned aircraft, and their operational missions often place them in forward-deployed environments and therefore close proximity to adversaries. This makes naval UAVs more susceptible to being targeted and damaged by adversaries.

Figure 1 contains an operational view (OV-1) of a future DEW threat environment, illustrating the potential for adversarial surface-to-air and even air-to-air 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 a HEL attack. The figure also lists some strategies and tactics, including inherent limitations to HEL DEW systems, atmospheric effects, countermeasures, evasive maneuvers, and swarm tactics that may apply to the defense of UAVs operating in these future environments.

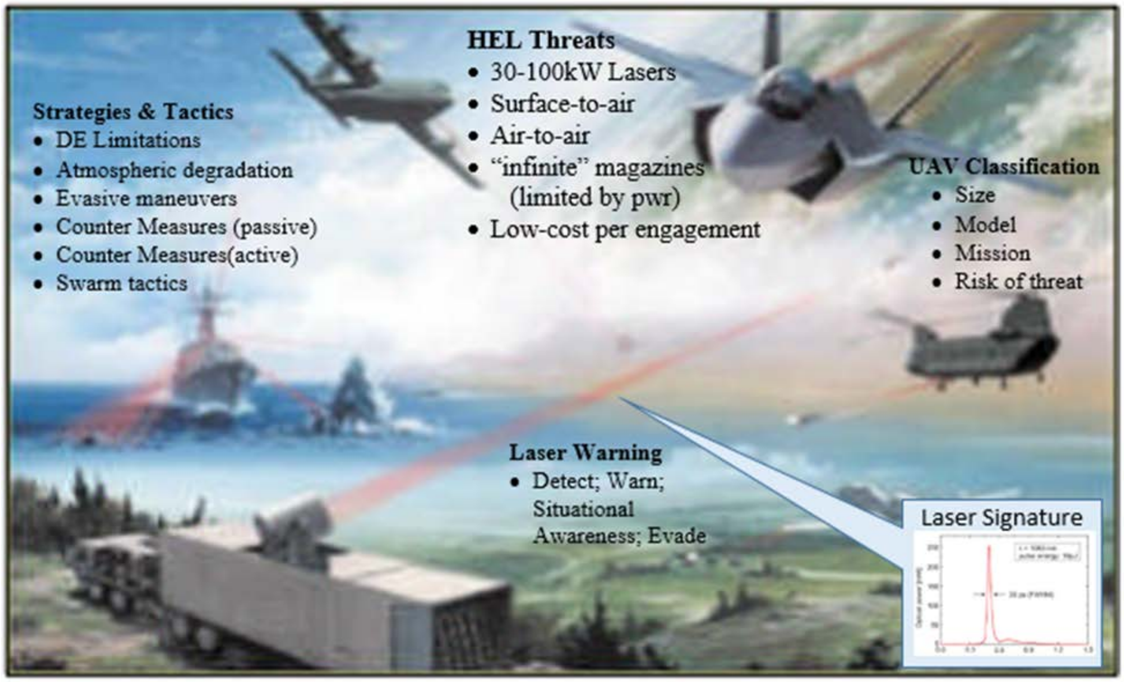

Figure 1. Counter-Directed Energy Weapons (CDEWs) OV-1. Adapted from Kiel (2007).

C. OBJECTIVES

This project examines the rapid development and potential use of DEW technology by adversaries and developed solution concepts to counter this threat. The project had three primary objectives:

1. To identify and characterize the potential adversarial DEW threat environment.

2. To identify possible CDEW methods, tactics, and capabilities that can provide active and passive protection of naval UAVs against adversarial DEWs.

3. To develop an analysis tool that determines the survivability of a UAV against a HEL weapon threat, given a set of parameters that include the UAV material, the atmospheric conditions, and capabilities of the HEL weapon threat.

D. STAKEHOLDERS

The key stakeholders for this project are the Office of Naval Research (ONR) Naval Air Warfare and Weapons Department and the Counter Directed Energy Weapons program offices. Additional stakeholders listed are:

The primary stakeholders:

- ONR Naval Air Warfare and Weapons Department.
- ONR CDEW research program.
- Technologists for Directed Energy, ONR.

Other key stakeholders:

- The Naval Postgraduate School's Department of Physics.
- Naval Air Warfare Center Weapons Division.
- Naval warfighter – UAV operators.

A high-level stakeholder analysis is displayed in Table 1.

Table 1. Stakeholder Analysis

Stakeholder	Category	Interests
Office of Naval Research (ONR) • Naval Air Warfare and Weapons Department. • CDEW Research Program. • Technologists for Directed Energy.	Sponsor – Meet Needs	Current research of CDEW and future naval capabilities. Possible solutions to DEW threat environment.
Naval Postgraduate School - Department of Physics	Modeling & Simulation Lead – Key Player	Development of multi-departmental laser modeling and simulation capability. Implementation capstone results to perform CDEW analyses.
Naval Air Warfare Center Weapons Division	Physical Configuration and Implementation – Key Player	Implementation of solutions to develop and produce UAVs and countermeasures to CDEW in threat environment.
Naval Warfighter - UAV Operators	User – Keep informed	Keep informed of new solutions and changes to UAV and effects on day-to-day operations to keep aware of threat.

E. TEAM OVERVIEW

The systems engineering capstone students conducting this project formed a group called "Team CDEW." The organizational structure of Team CDEW is illustrated in Figure 2. The roles for this project include capstone advisors, team leads and four sub-leads. These include engineering research leads, architecture leads, analysis and simulation lead, and lead editors. Designating leads allowed team members to manage, assign, and track the critical activities of the project, which included scheduling, research, architecture development, analysis of methods, simulation design, and delivery of the final capstone report.

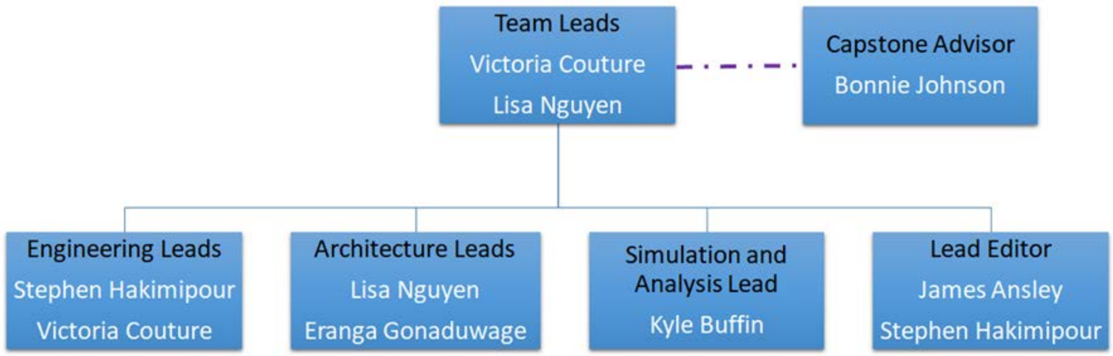

Figure 2. Team CDEW Organizational Structure

Each team role is further described in Table 2. The roles were allocated in a way to drive cooperation and utilize the expertise of the team members. Team members engaged with research personnel in the directed energy field to understand current use-cases, gather data and knowledge, and receive input for the project implementation.

Table 2. Team Members and Roles

Role	**Team Member**	**Responsibility**
Capstone Advisor	Bonnie Johnson	Provided guidance and supervised the progress of the capstone project. Reviewed and approved proposals and final deliverables.
Team Lead	Primary: Victoria Couture Secondary: Lisa Nguyen	Led the project team in completing the capstone project. Responsibilities included developing the overall project plan, team organization, schedule, team tasking, and weekly quad chart. Lead served as the primary liaison with the Capstone Advisor.
Architecture Lead	Lisa Nguyen Eranga Gonaduwage	Led requirements analysis and systems architecture through the development of the concept of operations (CONOP) and Department of Defense architecture framework (DoDAF) diagrams.
Simulation & Analyst Lead	Kyle Buffin	Led the data research to develop discrete event simulation tool efforts using VBA.
Engineering Research Lead	Stephen Hakimipour, Victoria Couture	Directed the research process, led the team through concept evaluation and validation concerning DEW technology capabilities and progress.
Lead Editor	James Ansley Stephen Hakimipour	Performed final proofing and ensured all project deliverables met all requirements.

F. ASSUMPTIONS AND CONSTRAINTS

The following assumptions and constraints were the limiting factors for this study:

- The study is conducted at the unclassified level.
- The study focused on HEL weapons as the type of DEW technology.
- The study focused only on defending naval UAVs.
- The study used available unclassified data on materials.
- The study used available unclassified data on lethality.
- The study used available unclassified data on atmospheric effects.
- The study found no data on active countermeasure effects on dwell times.

G. SYSTEM ENGINEERING PROCESS

The systems engineering process for this capstone research used the stated goals to designate phases that aligned with the desired output. Figure 3 shows how these phases were broken down into the three quarters using system engineering techniques to manage time and deliverable objectives. The key steps included research project planning, DEW threat analysis, system research, and CDEW concept development. Then, this information is used to develop a simulation model design, followed by testing and verification to deliver a complete threat/countermeasure analysis and potential solution.

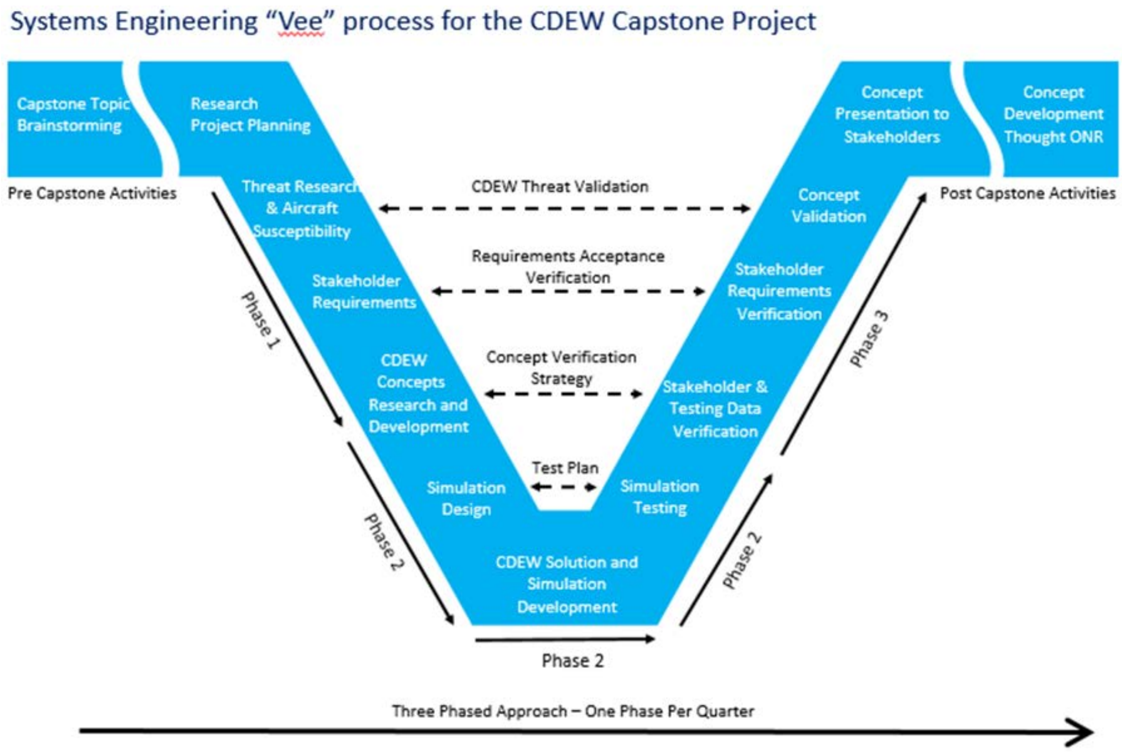

Figure 3. CDEW System Engineering "Vee" Model. Adapted from Blanchard and Fabrycky (2011).

The following is a breakdown of these processes and the ways each stage applied these concepts.

1. Capstone Project Planning

During the capstone planning phase, the team developed a research project plan that defined the details of the project including establishing the schedule, setting project goals and stakeholder requirements, identifying tools, needs, and support for outside collaboration, and performing configuration management of the project deliverables.

2. Threat Research and CDEW Concept Development

During the threat research and CDEW concept development phase, the team established the scope of the project, determining that the research would focus on the defense of naval UAVs from HEL threats—with the intent of identifying and evaluating CDEW solution concepts. During this phase, the team evaluated the HEL threat to UAVs, by characterizing the DEW threat environment and identifying different types of naval UAVs at risk. The team researched current foreign HEL systems in development. The team studied HEL weapon systems and their capabilities and limitations. The team identified naval UAV use cases.

3. CDEW Solution Development

The team conducted a systems engineering analysis to develop and evaluate concepts for countering DEW threats. The approach included the evaluation of limiting factors of HEL weapons, methods for early identification, assessment of passive and active countermeasures, and UAV swarm tactics that could yield higher survivability.

4. CDEW Model Design

The team used the information gathered during the previous phases to develop a modeling and simulation tool that they used to analyze the CDEW solution concepts applied to the different types of naval UAVs. The team evaluated the CDEW solution concepts using different HEL threat scenarios.

5. Testing and Verification

Following the model development, the team conducted testing to verify the validity of the simulation calculations. Testing using known sources validates the model to ensure its output is supported and represents accurate data. Therefore, the team used known examples of lasers propagating through space and used the same inputs as those examples to ensure we received the expected output. After testing with several known examples, the model's output is within the standard margin of error for all cases. This testing supports the model validity and was used to calculate dwell time survivability from HEL attacks.

II. THE DIRECTED ENERGY WEAPONS THREAT

The evolution of warfare has changed and progressed as technology has advanced. New technologies have brought innovative weapons with advanced accuracy and precision to the warfighter. As next-generation technology continues to develop stateside and around the world, the need for continuous progress and adaptability is apparent. One type of rising next-generation weapon is the DEW. According to the ONR, DEWs are "electromagnetic systems capable of converting chemical or electrical energy to radiated energy and focusing on a target, resulting in physical damage that degrades, neutralizes, defeats, or destroys an adversarial capability" (Morrison 2019, para. 1). Directed energy weapons are capable of engaging targets with a high probability of effectiveness. This efficiency creates a high-level of visibility and has become an attractive investment for U.S. and foreign militaries. There are different types of DEWs, including high-powered microwave (HPM) and high-energy laser (HEL) weapons. This study is focused on HEL weapons.

A. HIGH-ENERGY LASER WEAPONS

A HEL weapon system focuses a beam of electromagnetic radiation to a small spot to burn through the target material and render a target incapable of accomplishing its mission (Kopp 2008). Kopp explains that the production of the HEL beam is made possible by "pumping" energy into the laser gain medium. The chosen method to achieve this pumping can be another light source, electrical discharge, electrical current, or gas shockwaves (Kopp 2008). The laser gain medium can be gas, liquid, or solid material; most modern HELs use a solid gain medium and are thus referred to as solid-state lasers (SSLs). The pumping process creates a "population inversion" within the gain medium, whereby atoms are excited to higher energy levels. As the atoms decay back to lower energy levels, they can emit photons of light via spontaneous or stimulated emission; the latter is the process that can produce a powerful, coherent laser beam.

The HEL is not a kinetic or projectile type of offensive weapon, and it is not instantaneous. Kopp (2008) explains that HEL weapons deliver large amounts of stored energy to their target, causing incendiary or structural damage. The two fundamental differences between this type of weapon and kinetic weapons are (1) the HEL's ability to deliver effects at the speed of light, and (2) that HELs have essentially "unlimited munitions"—limited only by the power available.

Although the development of HELs has been progressing since the 1960s, recent developments and tests indicate that they will soon be fielded for combat operations (Cook 2013). With speed-of-light targeting, low per-engagement cost, and a high probability of hit, this lethal attack weapon presents military forces with a desirable solution.

B. BACKGROUND AND HISTORY OF DEW TECHNOLOGY

The idea of a "death ray" has captured imaginations since World War I (WWI) in the twentieth century. In 1978, the United States achieved the highest laser energy power, a 100kW laser, and destroyed a tube-launched, optically tracked, wire-guided (TOW) missile in-flight (Cook 2013). In the 1980s, President Ronald Reagan created the Strategic Defense Initiative (SDI) program, nicknamed Star Wars, which included the concept of using X-ray lasers to destroy intercontinental ballistic missiles (ICBMs) in flight. While the X-ray laser did not become a reality, the research and development efforts for lasers as missile defense systems and military weapon systems continues to this day. High-energy laser weapons now focus on systems over 100 kW (Cook 2013). Each of the U.S. military services has its own programs to develop HEL systems (Cook 2013). Cook (2013) points out that historical documentation suggests that the Soviet Union has been researching HEL weapon systems even longer than the United States. He states that while the United States focused on powerful rockets and ICBM research, other countries continued their DEW progress, although much has yet to be revealed.

As HEL systems are a relatively new development, they have seen only limited use in the Iraq and Afghanistan Wars fought in the early 2000s. In 2000 and 2001, the tactical high-energy laser (THEL), developed in 1996, shot down many rockets in testing but was never deployed due to cost and its inability to be used on vehicles (Feickert 2018). In 2002, Raytheon created the Active Denial System (ADS), which "projected a focused millimeter wave energy beam that induces a painful heating sensation on an adversary's skin with the intent of repelling individuals without injury" (Feickert 2018, 9). It was deployed in 2010 by the Air Force to Afghanistan but was withdrawn without having been used due to public opposition (Feickert 2018). In 2012, the Army deployed a counter-improvised explosive device (CIED) system called "Max Power" on troop transports designed to destroy improvised explosive devices (IEDs) on the battlefield. The CIED was deployed for nine months, when it was used in 19 combat missions (Feickert 2018).

When looking at WWI or World War II (WWII), there were limited aircraft, and those aircraft were slow moving and relatively easy to hit. However, transitioning into the twenty-first century, the adversaries of the United States have increased their offensive capabilities to include hypersonic missiles that can fly at speeds faster than Mach 5 and UAVs that can be used in swarm tactics. This poses the question of whether expending limited, expensive kinetic weapons on these swarms of UAVs and missiles is the best course of action? The DEW may address this challenge—as they are precise, able to hit drones while also being operationally cost-efficient. There is little historical data on the use of DEWs in the field—they are the weapon of tomorrow and will be present at the next major conflict.

C. HIGH-ENERGY LASER WEAPONS EFFECT ON UNMANNED AERIAL VEHICLES

The effect laser weapons have on a target is determined by the type of target, the material of the target, and the conditions during the engagement. The focus of interest here is UAVs targeted by HEL DEWs. The different components of UAVs can be affected differently by a laser, and lasers operating in different stages could change what effect the laser will have on a system (Kopp 2008). To assess the possible targeting of UAVs fully, the systems are broken out and their weaknesses discussed.

If the airframe is targeted, damage to the wings will affect stability, while other body distortions will impact the aerodynamics of the system. The material of the airframe will also determine how much damage or how long it takes for damage to occur: an example is that aluminum reflects significant portions of laser energy produced by a CO2 laser (Fahlstrom and Gleason 2012). Unmanned aerial vehicles with lighter material components are more susceptible to damage from laser countermeasures that may not only take down the craft but could deform airframe components, in turn, causing an array of possible issues with its flight. The effects of heat are assisted by travel speed, when it is easier for damaged material to scuff off and the full intensity to focus on the portion below (Cook 2013).

Targeting the power source with a HEL will cause heat damage that could render the UAV immobile. If targeted, pressurized fuel will burn off and explode, making the initial stages of operation more susceptible to this weakness because of the proportions of remaining fuel. Batteries can also fail destructively when exposed to the high temperatures, making them a potential target.

The material commonly used in electronics, navigation, communications, and control equipment will not handle the heat generated from a laser; they may not be a primary target but could quickly cease to work in this environment. Laser weapons produce electromagnetic radiation, which also interferes with electronic transmission. The light from the laser has bleaching effects on photosensitive components in visual surveillance equipment, which could affect operations of a payload before it is able to be used.

There are several different types of HEL DEW, categorized primarily by their gain medium. The gain medium determines the characteristics of the weapon such as wavelength, output power, efficiency, what materials they are effective against, and how they are affected by various atmospheric conditions. These variations will impact how the laser affects the UAV.

D. CURRENT FOREIGN DEW TECHNOLOGY

As DEWs become more prevalent, security threats to the United States continue to rise. Adversarial attacks that may not be easily detected with current means will need to be addressed, and current foreign technology understood. Though we cannot know everything, studying what has been released can provide knowledge about what we are soon to face. Several countries are actively trying to make advances in development for military strategies. Two prominent adversarial countries with known advanced technology in this area are China and Russia. Each country has made significant accomplishments alongside the U.S.A. in directed energy weaponry, mirroring similar form, fit, and function, causing a major security threat. The next sections delve into their imposing presence and currently known DEW technology.

1. China

China has devoted significant economic and political resources to its military forces over the years. According to Robert Wall of *Aviation Week & Space Technology* (1998, para. 1), "China is actively pursuing the development of directed-energy laser- and high-power microwave weapons to destroy satellites, aircraft, and missiles" backed up with significant funding to pursue military programs. Although dated, the actions are still consistent with the current state, and they have continued to make advances in the HEL realm, shown in current news of inflicting damage to the U.S. military. In May 2018, the Pentagon reported that military-grade laser weapons injured two U.S. pilots from a Chinese Navy base, and they continue to be a challenge in neighboring territories (Mehta 2018). Limited information is released on their current DEW technology, but show two developed weapon systems were found, known to be employed by China today.

China's Guorong Anti-Drone System, Figure 4, was developed by Guorong Technology, China Electronics Technology Group, and the public security bureau. It is a short-range, ground-to-air laser weapon system designed with a "detecting radar, electro-optical interference device, and high-power laser ejector," and it is reported that the system is capable of firing down a UAV in seconds from hundreds of meters away (Zhen 2018, para. 7).

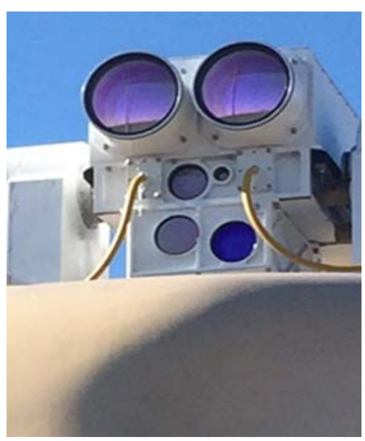

Figure 4. Guorong Anti-Drone System. Source: Zhen (2018).

The Silent Hunter, shown in Figure 5, was first unveiled at the South African Air Show in 2016 and used later that year in Hangzhou. This vehicle-based laser system is 30-100 kW and has a maximum range of 4 km. Its developers, China Poly Technologies, report that the weapon's beams can cut through a 5 mm thick steel sheet from 1 km away or five layers of 2 mm thick steel sheets from 800 m away (Zhen 2018).

Figure 5. The Silent Hunter System. Source: Lin and Singer (2017).

2. Russia

Among the competition of the world's most powerful countries, Russia claims the title of the first country in the world to attain significant achievements in the realm of laser weapons. As early as the 1950s, the Soviet Union began the development of laser weapons, and by 1972, carried out laser weapon tests. Similar to China, Russia seeks advantages to claim DEW capabilities against the U.S.'s defense in the warfighting domain (*BBC Monitoring International Reports* 2009). Although no specific information is found about to their investments in the study of HEL DEWs, Vladimir Putin has mentioned in numerous statements their laser weapons program with current testing in combat. He also states that these systems "will determine the combat potential of the Russian army and navy for decades ahead" (The Associated Press 2019, para. 1). Of particular notice is the Peresvet, seen in Figure 6, their military's first laser weapon system deployed in the fall of 2018.

The Peresvet HEL weapon system started delivering to The Russian Armed Forces, after being declared operational on December 1, 2018. Very little information has been released, including its power, locating capabilities, or intended targets. However, Russia's media outlet, Sputnik, published a short video of the system emerging in service. Putin stated, "I do not want to reveal more details. It is not the time yet. But experts will understand that with such weaponry, Russia's capacities for defending itself have multiplied" (Mizokami 2018, para. 7).

Figure 6. Peresvet Laser Weapon System. Source: Mizokami (2018).

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III. THE PROBLEM DOMAIN: AN ADVERSARIAL-DIRECTED ENERGY WEAPON THREAT ENVIRONMENT

In order to develop CDEW concepts for naval assets, it is first necessary to understand and characterize the potential future adversarial DEW threat environment. This project focuses on the HEL weapon as the future adversarial DEW threat. This chapter presents the types of soft- and hard-kills that are possible with future HEL threats and explores HEL limitations. High-energy laser limitations present CDEW solution opportunities, as they may be exploited to support naval asset survivability and countermeasure tactics. The findings of this chapter are used as a basis for CDEW solution concepts and evaluation methods presented in later chapters.

A. POTENTIAL THREAT CAPABILITIES OF ADVERSARIAL HIGH-ENERGY LASER WEAPONS

High-energy lasers require a finite amount of time focused on a small spot on a target to achieve a soft or hard-kill. This amount of time is referred to as the dwell time. The time needed to achieve this will depend on the thermodynamics of the type of material targeted and the power losses due to atmospheric conditions combined with the losses due to the targeted material absorption or reflectivity.

1. HEL Soft-Kills

The term soft-kill refers to the HEL delivering enough power to disrupt the function of the system but not necessarily penetrate the material skin or cause permanent damage to the target. This could be “dazzling” or blinding a sensor, disabling a motor, or causing a malfunction in an electronic component. Soft-kills may allow the enemy more stealth attacks during an engagement with unknown failures that could be ignored as a glitch rather than a hostile attack.

2. HEL Hard-Kills

The term hard-kill refers to the HEL structurally damaging the target, meaning the power delivered met the requirement to melt through the material. This could mean destroying critical or vulnerable components on the aircraft, rendering it incapable of completing its mission or incapable of continued flight. Unlike kinetic weapons, the lethality the HEL delivers can vary significantly depending on what is targeted and the power delivered to the target.

3. Naval Assets and Missions at Risk

Through the evaluation of this weapon, note that all naval assets could be at risk of future HEL attacks. Current assets do not have countermeasures in place to detect or protect the aircraft and will be at risk as these enter the maritime environment. Hard-kills are the most obvious and devastating attacks, but even soft-kills could do considerable damage to the mission. Lower power weapons or those experiencing significant losses may be able to achieve these soft-kills, creating anomalies in systems and debilitating operations. Depending on the power level achieved by the weapon and tracking capabilities, any aircraft in-range of a HEL could be at risk for these types of attacks. Unmanned aerial vehicles are generally made of thinner, lighter materials, and their missions place them in forward-deployed environments. This indicates UAVs will be specifically susceptible to these types of targeting threats as they begin operating. In Chapter IV, we will examine the specific vulnerabilities of the UAV components and the types of weaknesses the system has.

B. ATMOSPHERIC EFFECTS ON HIGH-ENERGY LASER WEAPON THREATS

When evaluating a HEL's effectiveness, the evaluation depends on two main factors: the target of the weapon and the scenario of engagement. The target of the weapon defines the power required to obtain an effective kill (i.e., missile, tank, UAV). The scenario of engagement (i.e., range, time to engagement, weather) defines how much extra power is needed so that the required kill power is achieved when the weapon reaches the target. This section focuses on the second point of weapon evaluation—the scenario.

1. Atmospheric Absorption and Scattering of Laser Beams

Loss of energy always occurs between the moments a weapon fires, and the moment the target is hit (Nielsen 1994). This is true for both kinetic and non-kinetic weapons. For example, wind drag, the curvature of the earth, and even gravity affect a bullet fired from a rifle. The bullet will have less power, or energy, at the time it reaches its target than the moment it was fired, due to atmospheric conditions. For HEL systems, as the laser or “beam of light” travels through space, the atmospheric environment similarly affects the laser. However, unlike kinetic weapons, wind drag does not affect the HEL’s beam of light, whereas the composition of the atmosphere does (Nielsen 1994).

The atmosphere’s gases and solid particulates (water droplets, dust, or aerosols) affect a HEL system’s beam of light. This light beam can be thought of as a stream of photons descending on a target. In a vacuum, the beam is unimpeded. However, when the atmosphere’s gas molecules and solid particulates are present, they can absorb or scatter photons and reduce the beam’s strength, or energy. As shown in Figure 7, some of the photons hit molecules and are absorbed or deflected, reducing the power of the beam.

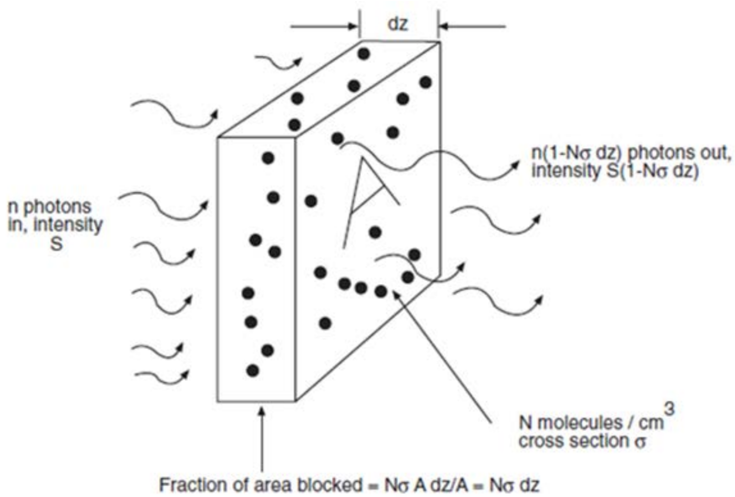


Figure 7. Scattering and Absorption Cross Section. Source: Nielsen (1994).

Detailed calculations can be performed to determine the exact loss of power due to this absorption or scattering of photons by molecules in the environment, but simply knowing that the power decays exponentially with the distance traveled (according to the Beer-Lambert Law) provides a useful calculation. The longer the distance, the more opportunities a photon has of hitting a molecule. A curve of this loss of power is shown in Figure 8.

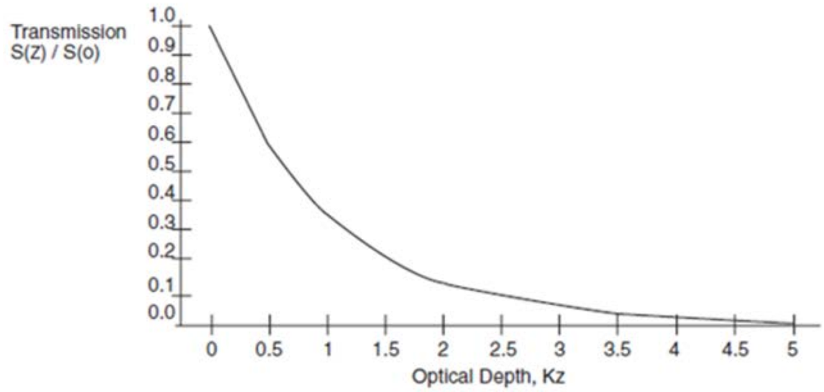


Figure 8. Transmission versus Optical Depth. Source: Nielsen (1994).

Another atmospheric effect on laser propagation is the change in types of molecules and the density of molecules as the laser beam travels a long distance or travels upward through different altitudes. For example, if a laser is fired toward the moon, the density of molecules lessens as it travels farther from Earth until it reaches space—which is a vacuum and there are no more molecules acting as obstructions, absorbers, or scatterers. Also, on the laser's way through the Earth's atmosphere, the laser beam would pass through many different types of molecules, like ozone, which are not typically found in lower altitudes. Additionally, aerosols such as water vapor and other particulates would contribute as much as gas molecules due to absorbing or scattering the laser beam's photons. In the case of aerosols, their density "fall off rapidly as altitude increases" (Nielsen 1994, 120).

A simple tactic for protecting naval assets from HEL threats based on atmospheric absorption and scattering is to operate assets at as great a distance from possible adversarial HEL systems as possible. Another tactic is to operate assets at altitudes that take advantage of higher densities of gas and solid particulates.

2. Atmospheric Effects Due to Laser Wavelength

Another factor affecting the amount of energy a HEL can transmit through the atmosphere is the wavelength of light produced by the HEL. Studies have shown how certain laser wavelengths may be more or less inclined to be absorbed or scattered due to the molecules in the atmosphere (Nielsen 1994). Therefore, the type of HEL being used as an adversarial threat and the type of atmospheric conditions present will both affect the threat's lethality. Nielsen (1994, 113) explains that "measurements of the output frequencies from a DF chemical laser measured a change in wavelength from 3.7886 to 3.7902 µm. This seemingly small change altered the amount of laser energy penetrating a 10 km path at sea level from about 90% to about 50%."

In order to exploit this atmospheric effect to protect naval assets, the type of adversarial HEL system must be known as well as the laser's wavelength. Given this knowledge along with the knowledge of the atmospheric conditions between the HEL location and the naval asset at risk, a predicted estimate of laser energy reduction may be calculated. Intelligence sources and HEL threat detection would have to predate this kind of calculation.

3. Atmospheric Turbulence Effects on Lasers

Another type of atmospheric effect on laser propagation is turbulence. Turbulence occurs when the sun heats the atmosphere, creating "hot spots," air cells with varying temperature and density, which can then be stirred up by wind. Turbulence has the effect of "introducing many tiny "lenses" into the beam" (Nielsen 1994, 120). Each air cell has a slightly different index of refraction than the surrounding air, thus causing light rays within the beam to refract (bend) in a myriad of random directions. The result is that the laser beam can break apart or be deflected.

In order to exploit the effect of turbulence to protect naval assets, a calculation predicting the amount of turbulence and its effect on the laser beam would have to be made. This calculation would require knowledge of the temperature at the location of the HEL system and along the beam path. However, there are weather forecasting models that can be used to estimate the temperatures and thus the level of turbulence to be expected.

4. Thermal Blooming

To address many of the effects that the atmosphere has upon the laser as it moves through the air, the adversary could simply increase the HEL's output power. However, as the laser's output power and intensity increases, a breaking point occurs at which the laser's propagation behavior becomes nonlinear. This breaking point occurs due to thermal blooming, which is an effect that occurs when the laser intensifies enough and modifies the environment that it travels through. Thermal blooming changes the physical characteristics of the molecules in the environment that the highly intense laser beam encounters. Thermal blooming occurs when a laser emits enough heat into the molecules in the atmosphere that the surrounding air temperature rises and results in reduced air density. Thermal blooming has a similar effect to turbulence but on a more impactful scale. The “lenses” created by thermal blooming act as diverging lenses, causing the laser beam to diverge from its center and become less focused (Nielsen 1994).

Another atmospheric effect related to thermal blooming occurs when a crosswind blows cooler air molecules across a laser beam experiencing thermal blooming. The crosswind cools down the first side of the laser beam that it reaches. This results in a “hot” side and a “cold” side to the laser beam, which bends the beam away from the now cooler side. Both the blooming and bending effects are shown in Figure 9. The figure illustrates that the focus of the beam is lost, meaning that the power is no longer concentrated in one spot any longer. If the atmospheric effects were causing linear distortions, an increase in laser power could reduce the distortion. However, once thermal blooming occurs, the state is nonlinear and increasing the laser’s power will exponentially reduce the intensity on the target (Nielsen 1994). One thing to note is that it takes time for the heated air to move away and for the density to fall causing a thermal bloom. The air moves away from the heating up laser at the speed of sound, providing a small delay before thermal blooming occurs once the intensity threshold is met.

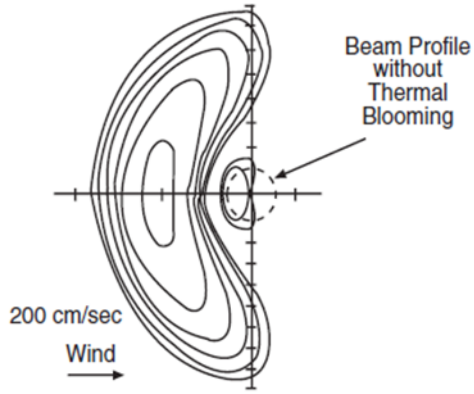


Figure 9. Beam Profile with Thermal Blooming and Bending. Source: Nielsen (1994).

Exploiting thermal blooming and other nonlinear laser effects could provide some protection to naval assets operating in an adversarial HEL threat environment. Knowledge of the type of HEL system, as well as its ability to produce high energy and intensity beams, would be required. The key metrics of distance and altitude of both the adversarial HEL system and the naval assets, as well as the amount and type of aerosols (i.e., sea or dust) and temperature of the general environment, would all have to be known. Using this information may make it possible to predict thermal blooming and other atmospheric limitations on the adversarial HEL's ability to damage the naval asset.

C. LINE OF SIGHT

All HEL threats require a direct line of sight (LOS) to their targets for soft or hard kill engagements. The HEL threat must sustain this LOS visibility for the time required to inflict soft or hard kill damage. This period is referred to as the dwell time. If an object obscures the target or if the target is able to maneuver and move away from the HEL LOS before the lethal dwell time is reached, the target is safe. Therefore, the HEL LOS can be viewed as a limitation that can be exploited to protect naval assets operating in DEW threat environments. Possible methods include UAV aggressive maneuvering and swarm tactics involving using some of the UAV assets as obstacles to obscure and protect other higher priority UAVs.

D. BATTLESPACE SMOKE PARTICLES

In a battlespace arena, explosions, and therefore smoke, are common occurrences. The smoke from explosions will have a significant effect on the capabilities of HEL threats. Wang (2013) discusses the properties of smoke particles and their impact on lasers—describing how they act as interfering aerosol particles creating multi-angle scattering characteristics and multipath signal distortion. Figure 10 shows the effects of smoke particle scattering angles on the penetrating light intensity. The left first figure shows the effect of the size parameter alpha, and the right figure shows the effect of the refractive index.

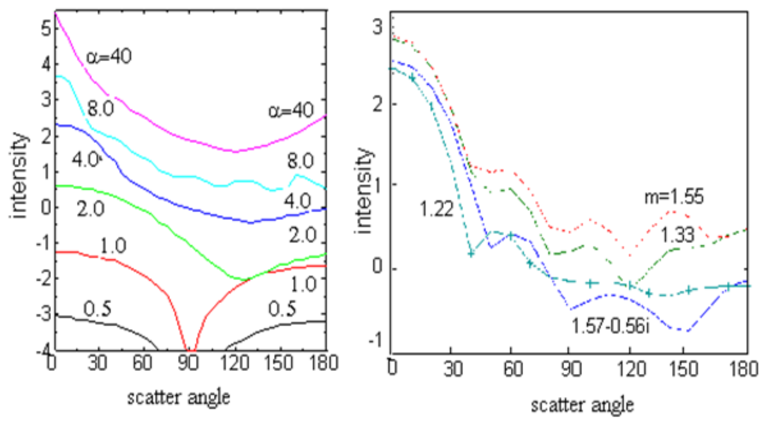


Figure 10. The Distribution of the Scattering Light Intensity Corresponding to Different Angles. Source: Wang (2013).

The size parameter and scattering angle of the smoke particles play important roles in laser scattering (Wang 2013). In the left plot in Figure 10, six different smoke particle sizes (according to alphas size) are plotted. The amount of penetrating light intensity is significantly affected by the different alpha size and scattering angle of the smoke particles. The refractive index of the smoke particles has less of an impact on laser scattering compared to the diameter of the smoke particles. The right plot in Figure 10 shows the laser penetration intensity due to smoke particle scattering at four different refractive indices. The level of the refractive index had less of an impact on the amount of laser light intensity that can penetrate the smoke particles than smoke particle size. However, smoke particles from explosions and fire that may occur in a battlespace environment will lessen the effects of adversarial HEL threats.

E. TARGETING AND DWELL TIME

Unlike projectile weapons that can affect a target instantly, HEL weapons are limited by their ability to maintain the laser on the target for a finite amount of time. Dwell time is the required time-on-target that results in a hard-kill to melt through the given material and damage the system. The energy focused on a target will be absorbed by the target material, which changes the internal temperature, eventually leading to melting (Chero and Javier 2017). This does not happen instantaneously—the absorbed energy initially heats the surface, and then heat is radiated away into the material (Chero and Javier 2017). The melting point of the surface is reached more rapidly than regions deeper where the material remains solid. Different materials and thicknesses require different dwell times based on their thermodynamic properties. How quickly this melting occurs depends on the target material, the material thickness, and any physical characteristics it exhibits.

The study titled "Feasibility of High Energy lasers for Interdiction Activities" focused on modeling various materials with different thicknesses and power levels to determine the dwell time required to reach the material's melting point (Chero and Javier 2017). This study found that depending on the target material, target thickness, and laser power, the required dwell time could range from less than one to over 100 seconds to melt through the target. Joseph Blau and Keith Cohn gave a lecture on this topic, "Directed Energy Weapons Overview" in July 2019 at the Naval Postgraduate School in Monterey, CA. In this presentation, they state as a general rule, to deliver sufficient energy for target destruction, using current HEL power levels, dwell time is approximately five to ten seconds.

To be effective, the HEL system must keep its laser beam on the target at a precise position for the required amount of dwell time. This can be problematic given maneuvering targets and requiring significant beam control of the system. It is challenging to maintain a laser beam on a precise spot on a target. This requires control to about the units of microradians, and environmental disturbances, atmospheric conditions, and platform vibrations can all cause interference with the beam director, making this even more difficult to achieve (Kiel 2007). A CDEW method that exploits the challenges of HEL precision targeting and dwell time is using the kinematics and maneuvering capabilities of our assets, including range, to our advantage.

High-energy laser systems have many technical and operational challenges to function as effective weapon systems. Physically, these include large system size, weight, and power (SWaP) along with appropriate cooling systems. High-energy laser SWaP requirements make it challenging for integrating HELs onto different platforms, such as vehicles, ships, and aircraft. Potential adversarial countries have been developing HEL systems for land-based vehicles and perhaps ships and aircrafts, but integrating these systems onto these platforms will likely limit the amount of laser power and intensity and type of laser possible. Additionally, the type of platform integration will place limits on the location, mobility, and line of sight of these future DEW threats. As our intelligence sources are able to identify HEL threats and gain knowledge of the particular HEL capabilities, this information will be vital to implementing particular CDEW tactics and design solutions.

IV. DIRECTED ENERGY THREAT VULNERABILITIES OF UNMANNED AERIAL VEHICLES

Naval UAVs may be highly vulnerable to future adversarial HEL threats based on their missions, which may take them into hostile environments and based on their physical size, components, and flight kinematics (altitude, speed, and proximity to threats). The UAV vulnerabilities to HEL threats were evaluated and ranked based on the likelihood of encountering a DEW, their operation in a DEW environment, and how well they are equipped to avoid or minimize DEW damage. For the operating environment, UAV systems were evaluated according to whether they support missions in hostile areas. For damage potential on the UAV, the materials composition, the fuel types they use, their flight patterns, and other potential areas that are listed as an interest of DEW operation were evaluated. Considered in the evaluation were UAV altitude, maneuverability, and single points of failure.

This chapter first describes the main components of UAVs and explains how they can be targeted and damaged by HEL threats. Next, the chapter discusses different types of UAVs and their different missions. Next, the chapter identifies four specific UAVs that represent the different categories of UAVs. Finally, the chapter evaluates these four UAVs in terms of their possible vulnerabilities to HEL threats.

A. DIRECTED ENERGY VULNERABILITIES OF UNMANNED AERIAL VEHICLES COMPONENTS

Chapter II introduced the possible types of destructive impacts that adversarial HEL systems can inflict on UAVs. Table 3 lists these possible effects.

Table 3. Possible Destructive Effects of HEL Weapons on UAVs

Possible Destructive Effects of HEL Weapons on UAVs
Loss of functional control (autonomous operations or remote control)
Loss of aerodynamical flight control
Loss of communication

Possible Destructive Effects of HEL Weapons on UAVs
Loss of stability
Structural distortions
Loss of power
Loss of sensors
Crash to the ground
Explosion

A typical UAV is composed of many components that have the following subsystems: the body and chassis, sensors, antennas, primary computer, power supplies, actuators and motors, and propulsion systems (Abhimanyu 2019). Each of these types of subsystems has varying levels of susceptibility to HEL threats. Table 4 summarizes the possible damage effects to a UAV based on the UAV component that is targeted. The following subsections describe how the different UAV subsystems can be targeted by HEL threats and provide more detail on how they can be negatively affected.

Table 4. HEL Damage Effects based on UAV Component Affected

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	Loss of mission-critical sensors, loss of calibrated sensors due to extreme heat of HEL, loss of flight control critical sensors.
Antennae	Loss of signal from operator, loss of critical data from external signals, loss of flight control from lack of operator input.
Primary Computer	Loss of system interoperability, loss of flight control.
Power Supply	Loss of power for critical systems, loss of flight control.

UAV Component Affected by HEL	Possible HEL Damage Effects
Actuators and/or Motors	Loss of flight control due to locked actuators, loss of sensor control due to locked controls.
Propulsion Systems	Loss of flight due to an uncontrollable or inoperable propulsion system.

1. UAV Body and Chassis

The body and chassis onboard a UAV are typically wrapped in a material coating that is designed to delay the effects of DEW, such as a dielectric or Bragg mirrors (Hambling 2019). This protective material coating is typical of all components of the UAV. Thus, the susceptibility of the body and chassis to DEW is dependent on the effectiveness of the material coating. Additionally, since this material coating covers the chassis, frame, and typically all onboard components, this will be the first component to feel the effects of DEW.

2. UAV Sensors

Sensors onboard a UAV provide data for functionality related to navigation, collision avoidance, and data acquisition, to name a few. The specific types of sensors found onboard the UAV depends on the mission that the UAV is running and the specific data that is required to be collected. The sensors onboard a UAV have a high susceptibility to the effects of DEW because typically sensors start to fail when large amounts of heat are directed at their collection points. The sensor will begin to report incorrect data, and ultimately fail, with the focused heat from a DEW.

3. UAV Antennae

The different types of antennas onboard a UAV do not have a large footprint but are extremely important for a successful UAV implementation. According to JEM Engineering (2018, para. 5), a highly experienced antenna engineering firm, “Antennas are among the most important electronic components of any UAV or UAS, for they allow the vehicle to transmit information to and receive information from other systems, as well as the people on the ground." The criticality of the antennas onboard a UAV makes this component a prime target for DEW on larger UAVs, which may have their antenna exposed. However, smaller UAVs may have less of an exposed antenna, due to space and weight constraints. Therefore, large UAVs with exposed antenna have a high susceptibility from DEW, while smaller UAVs have a lower susceptibility to DEW.

4. UAV Primary Computer

The UAV primary computer is integrated into every subsystem onboard, and therefore it is typically embedded deep inside the UAV body. This ultimately provides low susceptibility to the primary computer of being targeted by DEW. If a DEW successfully targets the primary computer, then there would be a wide range of adverse effects that would ultimately lead to a hard kill of the UAV. The primary computer drives all critical functions of the UAV, and with it disabled by DEW, the UAV would not be able to finish its mission.

5. UAV Power Supply

The power supply is typically a large component onboard the UAV, and therefore has a high susceptibility to being targeted by DEW. Depending on the type of propulsion system implemented, a battery, or liquid fuel source, the effect of a direct hit by DEW would be the same, a catastrophic failure due to a complete loss of power or an explosion. In either configuration, the damage to the power supply would result in a hard kill of the UAV.

6. UAV Actuators and Motors

The actuators and motors onboard a UAV typically support flight controls and sensor controls. These are more prominent in fixed-wing UAVs but can be seen in the rotary controlled UAVs as well. The actuators and motors controlling the flight controls, if disabled by a DEW, will bring an uncontrollable flight state into the UAV, which has a high likelihood of causing the UAV to be disabled. The actuators and motors have medium susceptibility to the effects of DEW because while they can operate the flight controls, they typically have a small footprint and therefore are more challenging to target than other more critical components of the UAV that have larger footprints.

7. UAV Propulsion Systems

Lastly, the propulsion system onboard a UAV has the highest susceptibility to DEW of any of the subsystems onboard a UAV. The high vulnerability is due to the nature of, disabling a propulsion system aboard a UAV, and the UAV is completely disabled. This is the primary goal of DEW, and the propulsion system typically has the largest footprint aboard a UAV, which makes it a prime target. Rotor-based UAVs with their propulsion system disabled will fall out of the sky, typically being destroyed. The UAVs that implement a jet engine as their propulsion system, upon becoming disabled from a DEW strike, may not be destroyed, as the UAV may be able to land from a forced glide. In both UAV propulsion system types, DEW has a high probability of delivering a hard kill on the UAV.

B. UAV SURFACE MATERIAL CHARACTERISTICS

When analyzing the characteristics of the varying types of surface materials on a UAV for defense against energy weapons, one of the most important to the success of the UAVs defense is the reflectivity of the material. According to RP Photonics, the reflectance is defined as the ratio of reflected radiant flux to the incident flux at a reflecting object. RP Photonics goes on to say that this is heavily dependent on the wavelength of the incoming beam (*RP Photonics Encyclopedia* 2019). Table 5 shows some of the reflectivity values for various materials when a tungsten light wavelength between 0.32 µm–1.1 µm is used. This wavelength is visible to the human eye and is not usable when determining reflectivity values for materials on a UAV seeking to defend against HEL assets, HELs are in the Infrared spectrum and are not visible to the human eye. The reflectivity values change drastically as wavelength changes as described earlier; Table 6 shows the reflectivity of pure uncoated aluminum at normal incidence as an example of this.

Table 5. Common Metal Reflectivity Values. Adapted from MatWeb (1996).

Reflectivity Values for Common Materials	
Aluminum	0.900
Chromium Annealed	0.700
silver	0.900
iron 1500 nm	0.650
gold 400 nm	0.270
gold 500 nm	0.500
gold 600 nm	0.850
platinum 589 nm	0.700
palladium	0.628
copper	0.630
lead	0.620
nickel 300 nm	0.413
tin 589 nm	0.800
gallium 589 nm	0.713
gallium 436 nm	0.756

Table 6. Reflectivity Values of Aluminum. Adapted from LBP Optics (2014).

Reflectivity of Pure Uncoated Aluminum	
Wavelength	**% Reflectivity**
248 nm	92.6
400 nm	92.0
532 nm	91.6
633 nm	90.7
800 nm	86.8
900 nm	89.0
1 µm	94.0

Reflectivity of Pure Uncoated Aluminum	
3 µm	98.0
10.6 µm	98.7
20 µm	99.0
100 µm	99.4

Currently, no material will reflect 100% of a HEL's beam. As stated earlier, some material compositions using Bragg mirrors can provide a reflectivity of up to 99.99%; however, this reflectivity would be very difficult to achieve on a military UAV since military UAVs are also designed to absorb microwaves from incoming radar. Therefore, for a UAV to have a surface material that protects against microwaves but is also reflective enough to delay the effects of an infrared HEL, all while maintaining a low weight for the inherent need of the UAV to be airborne, would be a feat in material science and is unlikely to be achieved. Figure 11 shows that some of the transmitted light will penetrate the surface material coating onboard the UAV while some of the beam intensity is reflected outward.

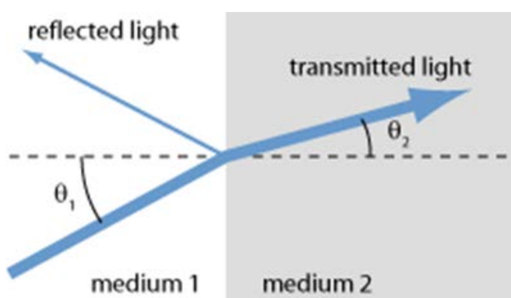


Figure 11. Refraction at an Interface between Two Media. Source: *RP Photonics Encyclopedia* (2013).

Reflectivity is also affected by the initial thickness of the surface material and any negative or abrasive changes that the material will cause a decrease in the reflectivity. Once a HEL hits the surface material of a UAV, it begins to melt. This melting will quickly affect the reflectivity of the material. Surfaces with high reflectivity are generally smooth;

therefore, when something alters the smooth surface to rough, for example, this will also affect the reflectivity by the development of hot spots that will rapidly lead to damage centers. The reflectivity characteristic of the surface material on a UAV is not the sole solution for defense against DEW. Instead, it is another method for increasing the dwell time before the DEW hard kills the UAV, with hopefully enough time for the UAV to complete the mission.

C. TYPES OF UNMANNED AERIAL VEHICLES

According to Fahlstrom and Gleason (2012), UAVs are organized by their size–as very small, small, and large. The Fire Scout is classified as small for reference. Further review found that the Department of Defense report “Unmanned Aircraft System Airspace Integration Plan” describes UAVs by groups (1–5), as shown in Figure 12. This indicates groups 1–3 is “very small,” group 4 is “small,” and group 5 is “large.”

UAS Groups	Maximum Weight (lbs) (MGTOW)	Normal Operating Altitude (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)	

Figure 12. DOD UAS Group Descriptions. Source: UAS Task Force Airspace Integration Integrated Product Team (2011).

The concept of UAVs started in WWI when early tests were conducted against one of the German zeppelins. However, due to concerns of control failures, the demonstration was scrapped. In WWII, the idea resurfaced, and about "15,000 UAVs were built in one Southern California plant alone for such purposes" based on the WWI Kettering Bug concept – the "first mass-produced unmanned aircraft" and used in service (Bunker 2015, 4; Barnhart et al. 2012, 4). Attempts were made, but they again encountered several issues and achieved very limited results. The U.S. military interest in UAVs was gradual over the years and only existed at low levels with minimal prototypes and fielding until 9/11. Combined with the 9/11 attacks and Section 220 of the National Defense Authorization Act, FY 2001, the idea of UAVs transitioned from a novelty to a mandate that UAVs will be incorporated with military forces. According to Robert Bunker in U.S. Army War College Press (2015), prior to these events, there were only an estimated 50 UAVs or less utilized by the intelligence community and armed services. Afterward, in a span of a decade, the U.S. Unmanned Aerial Systems (UAS) report conducted by Congressional Research Services (CRS), identified "7,494 Department of Defense (DoD) UAS platforms in the inventory," supporting diverse DoD missions and capabilities, including but not limited to, anti-submarine warfare, anti-surface warfare, electronic warfare, and reconnaissance, surveillance, and target acquisition (Bunker 2015, 6).

In its early developments and present-day, UAVs are recognized as a critical asset, serving as a surveillance role for military operations. However, they are not equipped for operation in combat air space due to "lack of survivability and insufficient capacity to respond to contingencies," as they are highly susceptible to adversarial attacks as well as weather changes (Jane's 2011, para. 6). In the Kosovo War, the use of UAVs was unprecedented. Although they kept the aircrew out of harm's way and were able to conduct crucial reconnaissance operations, taking images from the site

> which were then sent by datalink to the Royal Air Force station at Mildenhall in Suffolk, UK, from there to the Pentagon, and back out to NATO aircraft and the Air Operations Centre within 90 seconds [they were still] slow and vulnerable to ground fire, and they lack an all-weather capability because their wings can ice up. (International Institute for Strategic Studies 2000, 1)

Due to increasing threats and technology, the DoD is making great strides to overhaul their investments to achieve beyond collecting surveillance data. The United States Navy (USN) is following suit, looking to make significant investments in several major UAV programs to support specific combat mission requirements. *Jane's Defence Weekly* also reported that the Navy intends to pursue three different sizes of UAVs—"a long-dwell stand-off intelligence, surveillance, and reconnaissance (ISR) vehicle; penetrating surveillance and strike UAV; and a tactical system" (Jane's 2002, para. 3). Aside from mission capabilities, the Navy must also ensure that the selected UAVs will be able to operate safely from an aircraft carrier. In their pursuit of employing UAVs, the USN has evaluated and participated in various UAV program developments to accomplish their requirements. Four programs, Broad Area Maritime Surveillance (BAMS), the Unmanned Combat Aircraft System Demonstrator (UCAS-D), the Fire Scout, and Small Tactical/Tier II will be reviewed in efforts to follow the current endeavors of the USN.

D. FOUR USE-CASES OF NAVAL UAVs

There are multiple efforts of research and developments aimed at several UAV programs as they target various operational needs of the warfighter. The innovation of UAVs is still within its infancy, and the discovery of their capabilities is ongoing. The four cases of UAVs chosen in the following sections are a combination of current and future major programs being pursued by the DoD and competing for congressional attention. For the scope of the project and sponsorship, the focus will be on naval aircraft and these UAVs represent the various application to operational tasks within the United States Navy. The MQ-4C "Triton" is based on an existing Air Force UAV airframe, the RQ-4 Global Hawk, and supports BAMS, replacing the P-3 "Orion" to support the P-8A "Poseidon" Multi-mission Maritime Aircraft. With the expected purchase of the UAV at $55 million per unit and the goal of producing 68 aircraft, "the BAMS fleet will be the world's largest purchase of long-endurance navalized UAVs" (Putrich and Cavas 2008, 10). The X-47B "Pegasus" UAV is designed primarily for combat missions under the Unmanned Carrier Aerial Vehicle (UCAV) program. It is intended for strike and stealth capabilities, to operate in contested environments. The MQ-8B "Fire Scout" UAV is an active aircraft in deployment and it is a rotary-wing aircraft, displaying vertical take-off and landing capabilities, reconnaissance, situational awareness, and precise targeting. The ScanEagle is a part of the small UAVs and is distinguishable for being man-portable and of short range and loiter time. The four chosen UAVs represent the four programs being pursued by the U.S. Navy to defend against the advancing technology and capabilities of the adversarial threats.

1. MQ-4C "Triton" Broad Area Maritime Surveillance (BAMS) UAV

The BAMS was established for the USN to provide persistent capabilities for surveillance and actionable intelligence. Its mission is to support and mirror the platforms of the manned maritime intelligence, surveillance, and reconnaissance (ISR) such as the P-8A Poseidon. Northrop Grumman's MQ-4C, Figure 13, is the Navy's version of the Air Force's RQ-4B Global Hawk with modifications to meet the needs of naval warfighters. The FY 2015 DOT&E Annual Report (Gilmore 2016, 261) states that the modifications include "strengthened wing structures and an anti-ice and de-icing system" due to its missions across masses of water. The report also annotated that the radar system, which includes the electro optical, infrared sensors, and an Automatic Identification System (AIS), will provide users video footage and detailed imagery of the targets.

Photograph by Alex Evers

Figure 13. MQ-4C "Triton" UAV. Source: United States Navy (2013).

2. Unmanned Combat Aircraft System Demonstrator (UCAS-D) – X47B Pegasus

The UCAS-D program aims to produce UAVs capable of operating on an aircraft carrier for take-off and landing. The aircrafts developed under the program would be tailless and comparable to a fighter aircraft in size with the capability to launch and recover operations on the carrier.

A prototype for the program is the X-47B Pegasus shown in Figure 14. Built with the capabilities of ISR; it is designed and demonstrated to execute carrier-based launches and recoveries as a low-observable aircraft. It also successfully conducted the first ever-autonomous aerial refueling (AAR).

Photograph by Alan Radecki

Figure 14. X-47B "Pegasus" UAV. Source: DiMartino (2012).

3. MQ-8C Fire Scout

The MQ-8C "Fire Scout" Figure 15 aircraft developed under the vertical takeoff/landing tactical program. It is a rotary-wing UAV intended to assist on the littoral combat ships (LCSs) by providing target information as well as the capability to deploy weapons. The current modification employed by the Navy came about after the realization that they wanted to add more lethality and range to the LCS. With that focus, the Navy intends to have the Fire Scout carry out BAE System's advanced precision kill weapon system (APKWS) as well, and with that regard, the UAV was modified to a larger airframe to have the capacity to carry the payload.

Photograph by Mass Communication Specialist 2nd Class Alan Gragg

Figure 15. MQ-8C "Fire Scout" UAV. Source: United States Navy (2009).

4. Small Tactical UAS/Tier II UAS (STUAS)

The goal of the Small Tactical Unmanned Aerial System (STUAS) program for the Navy is to "provide persistent ISR support of tactical-level maneuver decisions and unit-level force defense," focusing primarily on endurance (Alkire et al. 2010, 3). The requirements help provide for smaller ships that are unable to support larger platforms or do not flight deck, as well as desolate areas. It allows those vehicles and fields to extend the LOS for greater coverage on a specified target of interest without the dependency on higher headquarters limited connections.

ScanEagle, Figure 16, is a STUAS the Navy signed and agreed upon for leasing with Boeing in 2005. The ScanEagle is a product designed and produced by Insitu Group in partnership with (and later acquired by) Boeing, "optimized for endurance rather than payload and employing a ship launch and recovery mechanism" (Alkire et al. 2010, 20). As the STUAS program intended, the ScanEagle does not require an airfield for deployment and is not designed with landing gear. Instead, it is launched using a pneumatic launcher, the SuperWedge, and recovered by a capture system, the SkyHook, both developed by Insitu Group.

Photograph by John F. Williams

Figure 16. ScanEagle. Source: United States Navy (2008).

E. EVALUATION OF DIRECTED ENERGY THREAT VULNERABILITY OF THE FOUR NAVAL UAV USE CASES

Using the four example UAVs discussed, the team constructed an evaluation of susceptibility to HEL systems based on their characteristics and operations as displayed in Table 7. On a scale of 1–5, each criterion is rated based on their vulnerability to HEL, with one being less susceptible and five as most, respectively, shown in the key color-coding following the table. The characteristics selected for evaluation were size, mission, normal operating altitude, range, speed, endurance, material, maneuverability, and fuel type.

The size of the UAV is an apparent vulnerability, with the larger the size, the greater the surface area, giving an adversarial HEL a greater opportunity to inflict damage. Three of the four UAVs evaluated are large, making them highly susceptible to this characteristic. The UAVs mission correlates with their operating environment. An aircraft conducting usual surveillance in peacetime environment will have less risk of encountering HEL threats than those in contested battlefields supporting other U.S. naval aircraft. Given this scale, the Triton UAV is the least susceptible for its patrol and surveillance mission whereas the Pegasus is most susceptible, performing in combat environments. A UAV's operating altitude is linked with the atmospheric conditions in the threat environment. As mentioned in Chapter II, with a greater altitude from the HEL, the higher the chances the UAV would be able to avoid the beam, as it would have to penetrate through more of the atmosphere. The same three, large UAVs operate at high altitudes as well, which provide them some protection. In this same area, the ScanEagle UAV is the most susceptible given that it operates below 3500 feet. The UAV's range may increase its ability to avoid a threat area using tactics to put more distance between it and the DEW. The ScanEagle would be the most susceptible with its short-range and the MQ-4C the least, designed with long-range capabilities. The speed determines the ability to flee from the HEL's beam coverage and harm's way. For this reason, the faster the platform, the less susceptible the UAV is to HEL threat, making the Triton and Pegasus the least susceptible of the four with an operational speed of roughly 300 kts. Endurance is the capacity of how long the UAV may operate and support its mission requirements. The length of time may also assist with the evading the threat while still operating within the air. The longer they are able to perform in flight, the higher the chance they are able to flee from the HEL and prevent the required dwell time, without compromising their ability to land before they run out of power. The Triton and ScanEagle UAV can both operate for over 24 hours, making them less susceptible. The aircraft material may arguably be one of the most significant properties to the UAV as the material contains different levels of reflectivity factors to deflect the rays of HELs. The reflectivity of composites is currently unknown due to possible ratio variation of mixtures for each aircraft, but aluminum shows the highest reflectivity, making it a huge asset for protection on the Triton. The maneuverability refers to the mobility of the aircraft. The less logistical footprint required for the aircraft, the more mobile the UAV is. This makes it more capable of dodging the laser or at least preventing the threat locking on an area for the required dwell time. The Pegasus, Fire Scout, and ScanEagle all display different variations of mobility, from stealth mode to small size to operation in remote areas, creating opportunities for them to escape from the threat and increasing survivability. On the other hand, Triton must have a supportable launch and recovery platform, limiting areas of landing before it is targeted by the HEL threat. The fuel characteristic defines the source of power an aircraft uses for operation such as combustible fuel or other energy source alternatives. All of the evaluated UAVs offer the same fuel type and for this reason, all four have a high risk of susceptibility, with possible cause of explosions or similar effects. The summation of the attributes with full details determining the susceptibility for the UAVs based on each is presented in Table 7 and allows for comparison between platforms.

Table 7. Evaluation of Each Naval UAV Use Case

Characteristics	MQ-4C Triton	X-47B Pegasus	MQ-8C Fire Scout	STUAS ScanEagle
Size	Largest	Largest	Larger	Medium
Mission	ISR/Maritime Domain Awareness (Navy)	Low observable capable of conducting aircraft carrier operations (i.e., Autonomous Aerial Refueling (AAR))	ISR/Reconnaissance, Surveillance, and Target Acquisition/Anti-Submarine Warfare	ISR/Reconnaissance, Surveillance, and Target Acquisition/Force Protection
Normal Operating Altitude	>FL 180	>FL 180	>FL 180	<3500 ft AGL
Operational Range (from launch)	8,200	1,600	150	60+
Speed (kts)	320	~ 300	135	43-68
Endurance (h)	24+	9	6—9.5	24+
Material	Aluminum and composite	Composite	Composite	Composite
Maneuverability	The logistics required for launch and recovery (L&R) can be very substantial	Stealth is incorporated into both the aircraft's design and its operating systems for maneuverability	Small L&R footprint - do not need runways or roads to takeoff or landing	Launches autonomously by a catapult launcher—no runway required

Characteristics	MQ-4C Triton	X-47B Pegasus	MQ-8C Fire Scout	STUAS ScanEagle
Fuel Type	JP-8	JP-8	JP-5/JP-8	Original: Gasoline New Development: Heavy Fuel

Rating	Remark
1	Least susceptible
2	
3	
4	
5	Most susceptible

Adapted from UAS Task Force Airspace Integration Integrated Product Team (2011), Cambone et al. (2005), Gertler (2012), Barnhart et al. (2012), Naval Technology (n.d.a, n.d.b, n.d.c), Air Force Technology (n.d.), Alex and Potts (2019), United States Navy (2019), Red (2009), Boeing (n.d.), Black (2010).

The Triton, although much larger in size, offers operators long duration, maximizing its mission capabilities. With its high altitude, the platform also offers the "ability to conduct flights at much higher altitudes where the vehicle is not visible with the naked eye" (Barnhart et al. 2012, 19). Due the increasing distance between the HEL and UAV, it would require greater power to reach the Triton. However, once it is within view of the HEL, landing safely may be a higher risk for the UAV due to the larger footprint for recovery. To compensate for the lack of mobility, the airframe is equipped with thicker material to increase the dwell time for protection.

Considering a UAV in group 4 such as Fire Scout, it could be estimated that it has a moderate potential to operate in a DEW environment given its mission capabilities. Similar to the Triton, its operating altitude may be appropriate to combat against HEL systems. The lower operational altitude of the Fire Scout may pose higher risk due to the visibility to HELs, but the atmospheric conditions of the lower levels may protect it from the HEL beam or reduce the HELs LOS. Fire Scout uses liquid combustible fuel, which is a sought-after target for DEWs. The rotor also creates a single point of operational failure versus fixed-wing UAVs, although the constant moving of the shaft may provide some protection from DEW damage.

The UCAV UAV, such as the Pegasus, has a high potential to operate in a DEW environment, given its tactical use in hostile areas (Naval Technology 2019). Unlike the Triton, the UCAV has a less predictable flight pattern, which is an advantage over DEWs. Another difference from the Triton is that the UCAV is one of the first UAVs to do a mid-air refueling. This adds an element of vulnerability to it, as the fuel is more open to targeting while undergoing this process. This refueling also puts the system into a more predictable flight pattern with the same issues as the Triton, except that there will be less opportunity to utilize evasive maneuvering.

The four cases chosen vary in combination of the characteristics and, as revealed, no one precise answer that will fit all cases. Whether it is a manned or unmanned aircraft, programs are chosen to support the different requirements and missions of the warfighter, therefore, each have different qualities. The evaluation of the UAVs does; however, show the vulnerabilities but also the opportunities, which may be improved to counter HELs. For example, in review of the Triton, although, its size poses a significant threat to HELs, it was selected to support the mission of constant broad area surveillance. To combat the risk, the designers built it with the highest material for reflectivity for defense. Similarly, the Pegasus has one of the highest risks based on their operating environment but was designed with stealth capabilities to go under radar as well as subsonic speed once it is encountered by a foe. In the case of the risk evaluation, the qualities will be quantified and factored in to calculate the dwell time required for the HELs to record a successful hard-kill, discussed in later chapters on the survivability tool constructed.

V. COUNTER-DIRECTED ENERGY WEAPON (CDEW) SOLUTIONS FOR UAVS

This chapter presents the various methods available for countering DEW threats against naval UAVs. It describes the countermeasure options and their drawbacks. The team studied the following five methods: tactical operations based on the environment, payloads for laser identification and warning, payloads for active countermeasures, passive countering techniques that can be implemented as UAV shielding, and operational tactics involving UAV maneuvers or the deployment of swarms of UAVs. Adopting any of these proposed solutions will increase the probability of the UAV to survive a DEW attack and implementing combinations of these solutions will increase those chances further. The impact of the increased weight onboard the UAV for the additional defense systems must also be considered as an approach is defined. As discussed in Chapter IV, UAVs range in size and carrying capacity. Each type of UAV may require a different countermeasure plan that is appropriate for it depending on its operating environment, capacity, and mission. Table 8 lists these countermeasure options.

Table 8. Types of CDEW Solutions for Protecting Naval 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 Active Countermeasures	Integrating payloads onboard UAVs to deploy active countermeasures for protection against HEL threats.
4	Passive Countering Techniques: 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.

CDEW Solutions for UAVs		
5	UAV Maneuvers and Swarm Tactics for CDEW	Using UAV tactics such as maneuvers to prevent laser LOS or dwell time; or the use of swarms that include UAV decoys.

Countering the DEW from an active or reactive perspective onboard the UAV needs to be considered. Solutions may include threat detection and the ability of the UAV to respond effectively to the threat. This chapter will outline technology that can be used to detect such attacks and some potential solutions such as obscurants and atmospheric degradation. Furthermore, passive countermeasures that increase the dwell time of HEL are considered. Lining the UAV surface with dielectric or Bragg mirrors or the use of ablative material coating could also make the UAV tougher to penetrate which could increase its lifetime and decrease the weapon’s effectiveness. Swarm techniques and unpredictable flight patterns make the UAV a difficult target to acquire and should be considered for an effective defense. Applying each of these concepts including environmental considerations, active and passive countermeasures, and other tactical operations will be discussed for inclusion into a final countermeasure solution concept.

A. ATMOSPHERIC CDEW OPERATIONS

Directed energy weapons are severely limited by weather and atmospheric conditions; therefore, one method of countering them utilizes this limitation with tactical considerations of the operational environment. Operational altitudes can also be used to limit DEW effectiveness and performance. Incorporating tactics for the UAV to travel into these environmental conditions will assist in countering the DEW. This section describes how atmospheric limitations can be used to increase the survivability of naval UAVs.

Atmospheric limitations may restrict the ability of the laser beam to reach the target and can indicate how the DEW limitations can be exploited to evade attacks. As discussed in Chapter III, the atmospheric effects include extinction, turbulence, and thermal blooming. Carn’s (2010) lecture describes extinction as an atmospheric condition that occurs through molecular and aerosol absorption combined with beam scattering. Such conditions deplete the transmitted radiation and require increased dwell time for HEL to remain effective against its target. Carn (2010) describes how optical turbulence causes laser beams to break apart which increases the spot size and reduces its concentrated power. Thermal blooming causes beam divergence, which results in decreased irradiance on the target. Joseph Blau and Keith Cohn gave a lecture on this topic, “Directed Energy Weapons Overview” in July 2019 at the Naval Postgraduate School in Monterey, CA. They stated the laser beam can also degrade if it encounters fog, haze, or rain. These atmospheric “countermeasures” could provide protection for UAVs. Understanding the details of how atmospheric conditions can affect laser beams can be used to develop UAV operational CDEW tactics.

Absorption and scattering due to molecules and aerosols in the atmosphere comprise the extinction coefficient. This coefficient characterizes the absorption and scattering at each point along the beam path and varies with location, altitude, season, and time of day (Carn 2010). Absorption in the atmosphere is due to inelastic collisions between photons and particles; the collisions cause beam energy to decrease through the generation of heat (Perram et al. 2010). Perram et al. points out that this generation of heat could also lead to thermal blooming. Scattering is the elastic collision between photons and particles; they maintain their energy but cause photons to change direction (Perram et al. 2010). Probability of extinction can be increased due to high amounts of aerosols in the environment; fires, volcanic activity, dust storms, and severe pollution can cause this (Carn 2010). Water vapor is also an aerosol that can be in the form of rain, fog, haze, or mist, and increases the probability of extinction. The extinction vulnerability has been shown to be more severe at lower altitudes and tends to be constant during horizontal propagation of the laser (Carn 2010). To use this condition to protect the UAV, operations conducted in cloud cover, dust storms, polluted areas, and during mist or rainfall will increase survivability and decrease the effectiveness of the DEW. Additionally, operating at the greatest distance from the threat or operating at the altitude with the highest density of gas and solid particulates will increase the probability of these effects. Although relying on these periodic events may not always be possible, understanding and using events to benefit the mission can increase success.

Atmospheric turbulence is defined as the fluctuation of pressure and temperature along the beam path (Perram et al. 2010). This can create random pockets of air with different indices of refraction, causing the beam to wander, jitter, or bend and increasing spot size. The terrain, temperature differences near the weapon, and temperature differences near the target location can affect atmospheric conditions, such as turbulence. Designing for all scenarios when building a DEW is challenging and therefore makes turbulence problematic to overcome. Maritime environments increase this effect due to the temperature differences of the sea and air as well as the friction of winds (Perram et al. 2010). For submarine-based weapons that operate near the ocean, findings show unstable and turbulent conditions increase during winter months, when the air temperature is less than surface sea temperatures (Blau 2015). Blau's paper indicated this could be overcome by weapon operation a few meters above the surface, although this is less favorable to submarines because of detection. Additionally, in warmer months, a more stable condition presents itself; but the laser performance is strongly reduced during stable conditions especially against aerial targets (Blau 2015). The random nature of the turbulence affects the ability of the beam to distribute power to the target; this increases the dwell time and decreases the ability to destroy the target efficiently. To take advantage of this effect, environmental conditions and weather must be considered. Over the water, the low flight will increase turbulence effects in colder months while not in warmer months. Theoretically, this may also be able to be induced with expendables to create a similar unstable density of molecules in the threat environment.

Another atmospheric effect that may be used to CDEW is thermal blooming. This is where the heating of the air creates divergent lenses to de-focus the laser beam; this will cause the beam to spread and decrease irradiance on the target (Carn 2010). Thermal blooming is most common for lasers of 100 kW or more, and can also be intensified with heat created by absorption. In higher altitudes and higher winds, thermal bloom is reduced (Carn 2010). Chapter III outlines that crosswinds of colder air molecules can create a "hot" and "cold" side of the beam and cause the beam to bend away from the colder side. Also, crossing shots may have less thermal blooming because the beam is continuously propagating through "new air." A practical approach to using this condition may be to employ “head-on” flight patterns; this will increase the likelihood of the beam propagating through “stagnant zones” of air along the beam path.

Table 9 outlines the different atmospheric conditions that could affect HEL performance. It aims to highlight the effects they have on a HEL and how they could fit into a countermeasure strategy. Some of these are new ways to manipulate the environment in order to generate these conditions. They may not exist in current expendables today, though based on research, they would be a potential countermeasure source from HEL attacks.

Table 9. Exploiting Atmospheric Conditions as a UAV Countermeasure Strategy.

Atmospheric Condition	Effect on Laser Beam	UAV Countermeasure Strategy
Extinction • Molecular and aerosol absorption. • Beam scattering.	• Depletes the transmitted radiation: increasing the dwell time • Absorption depletes light but also contributes to heat generation.	• Launch missions during high extinction conditions, such as rain, fog, haze, fires, dust storms, ash, smog, and high pollution. • Use expendables to create these conditions. • Operate at max distance from the threat. • Operate at altitudes that have the highest densities of gas and solid particulates.
Turbulence	Divergence: breaks laser beam apart, increasing spot size and reducing concentrated power.	• Exploit this by calculating temperatures at the operational environment. • Operate close to water in maritime environments. • Induce this with the use of expendables to create different indices of refraction in air.
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.

Adapted from (Blau 2015), Carn (2010), (Nielsen 1994) and (Perram et al. 2010).

To employ such tactics, three pieces of information will be required for the engineering solution: (1) knowledge of the HEL threat, (2) knowledge of the weather conditions at threat location, and (3) a decision aid tool to calculate the predictions of threat capabilities based on the known information. Within each of these pieces, the more information known will always be better. If the type of laser, wavelength, and/or power are known, additional countermeasures could be added to this solution prior to launch. Having a decision aid tool that can use this type of intelligence, may provide the decision-makers the ability to plan "safest paths," mission times, and predict effectiveness using these parameters.

The evaluation of the operational environment and atmospheric conditions can illustrate what obstacles the weapon must encounter. Use this knowledge and employ UAV missions when there is a high probability of atmospheric conditions to interfere with the weapon operation. Passive countermeasure defenses such as these can play a part in the overall countermeasure plan. Figure 17 describes an instance for utilizing atmospheric knowledge in a scenario.

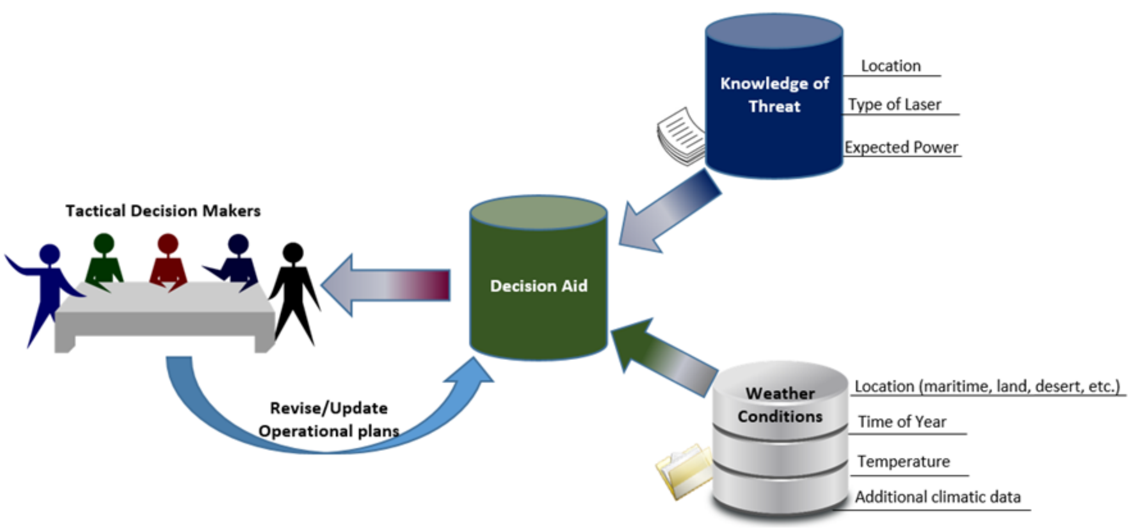


Figure 17. Tactical Planning Using Atmospheric Conditions

B. UAV PAYLOADS FOR IDENTIFICATION AND WARNING

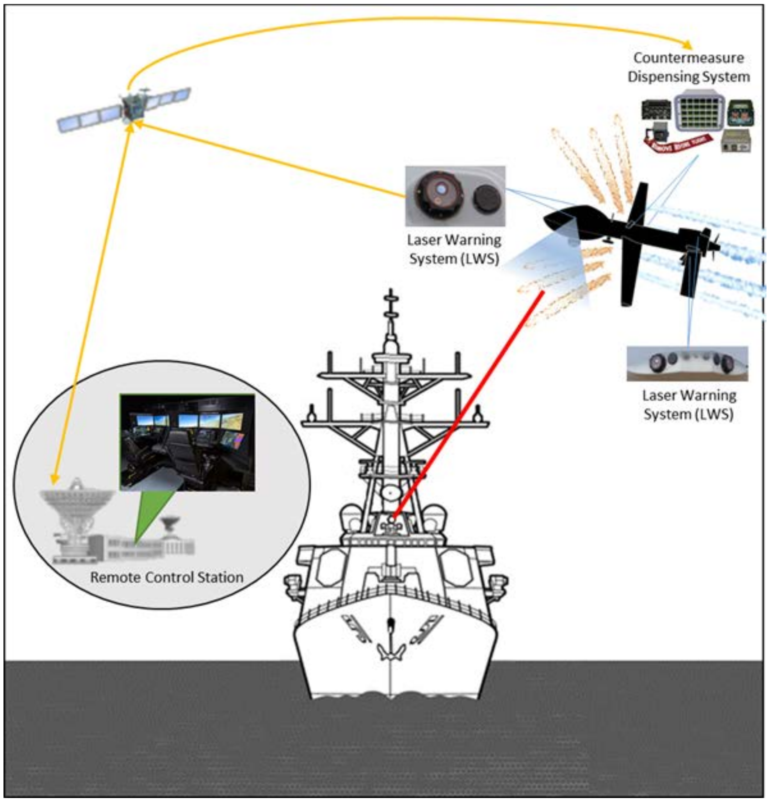
In contrast to passive countermeasures toward DEW, there are also active approaches that can be used to defend UAVs against HEL threats. This type of CDEW method involves the integration of payloads onto UAVs that can detect laser threats to act as a laser warning system (LWS), and/or produce a countermeasure effect such as smoke, dazzling, jamming, or even counter fire.

As laser weapons become an increasing threat, there is a greater demand for vigilance in combat operations. Installing a LWS will provide UAVs early detection and the capability to proactively engage active countermeasures. These payloads may be able to provide the atmospheric degradation mentioned in the previous section and allow the UAV to leave the threat area. Due to the power-to-weight ratio restrictions of UAVs, LWS have not been implemented operationally on the smaller vehicles, though they may be in the future with the effectiveness and prominence of HELs. The increase in availability of range finding technology can spill over to the field of UAVs as they are significant targets for DEWs (Haystead 2013). Understanding the technology behind the sensors lays a solid foundation to implement them onto platforms and begin a counterattack on HELs. The core technology behind the LWSs is semiconductor photodetectors, such as P-type, intrinsic, and N-type (PIN) diode arrays or cascaded/avalanche photodiode/phototransistor arrays that detect beams based on light sensitivity. Each type provides various sensitivity scales to meet specific requirements and capabilities. In comparison, phototransistor arrays provide more internal gain than PIN material, which aids the systems substantially higher light-sensitive to rays. Excelitas Technologies produces high angular resolution laser irradiance detector (HARLID) products, which are photo-detection sensors used in LWSs. They have been implemented in ground vehicles, naval vessels, aircraft systems, as well as hand carried by individual soldiers, to detect lasers and target designators. Effective LWSs required highly sensitive sensors, efficient speed in detection, and fast processing speeds to provide responsive aid to the warfighter. The combined efficiency with directing active countermeasures toward a threat will provide the most complete countermeasure solutions.

Several LWSs have been implemented on current aircraft systems for protection and situational awareness, such as rotary-wing aircraft, which are categorized as slow-moving vehicles that require more security. The AN/AVR-2B is a standard system used for the U.S. Army helicopters, whereas the U.S. Navy and Marine Corps implemented the latest variant of the AN/AAR-47, the AAR-47(V)2. The upgrade was intended to provide the functionality of the AVR-2/2A LWS, "detecting and declaring laser rangefinders, designators, and beam-rider missiles," thus increasing capabilities and reducing cost and weight of two systems vice one (Christie 2004, 141).

Aside from implementing LWSs, it must interface with a payload dispensing system to be effective as a countermeasure against HELs. As mentioned previously, they can release various expendables to distort the HEL's LOS and provide the UAV with the ability to avoid attack. In the next section, various types of expendables are discussed regarding the benefits they may provide to a countermeasure solution.

The threat identification OV-1 diagram, Figure 18, depicts the UAV enhanced with a laser warning system that is capable of detecting the HEL for early awareness as well as a countermeasure dispensing system. The identification alert would be sent from the UAV to the operator at the control station through telecommunication data links. The notification would allow the pilot to make countermeasure decisions during an attack or use an automatic dispensing tool. The data would be sent back to the UAV to perform the selected action through the data link. With the limited dwell time of a HEL, a control system that could make quick decisions and dispense automatically would be most efficient. This may include the maneuvering of aircraft to prevent the threat from locking on or deploying expendables for distraction to flee from harm's way.



Adapted from Concept Draw (n.d.), Florida Export Directory (n.d.), General Atomics (2018), and McQueary (2006).

Figure 18. OV-1 Threat Identification Operational Diagram.

C. UAV PAYLOADS FOR ACTIVE COUNTERMEASURES

Complementing the LWS alert, active approaches can be used to defend UAVs against HEL threats. In contrast to passive countermeasures, these produce an effect to deter the attack physically. This type of CDEW method involves the integration of payloads onto UAVs that can produce a countermeasure effect. These could be expendables such as “smoke or aerosol screen, laser countermeasure known as dazzlers, laser jammers, or a basic counter fire” (Haystead 2013). This concept does require the implementation of a LWS to identify the HEL threat and interfaces with the payload dispensing system to provide an effective countermeasure against HEL threats. The active countermeasure payload can release various expendables to distort the HEL’s LOS. Flares can disguise the vehicle by producing a bright light and the intense heat mimics the heat radiation of UAVs. Chaffs or smoke screens can assist by clouding the UAV to reduce the dwell time of the laser targeted on them. Jammers can also be triggered once the beam of the HEL weapon is detected to immobilize them before reaching the dwell time. As seen, UAVs can be customized with various combinations within their payload as long as their weight restrictions allow.

1. Smokescreen

One type of active decoy method is the use of a smokescreen for the UAV to "disappear" within. Directed energy weapons rely on light traveling through the atmosphere, so problems DEW have while tracking a UAV appear when smoke deploys out of the UAV as a smokescreen. As discussed earlier, smoke or fog absorb and scatter the laser energy (Ghoshroy 2015). The Chinese government is already exploring using a smokescreen as a type of armor for UAVs against DEW (Atherton 2019). Smokescreens have been used as concealment in war games for centuries, however now they are being used as an active defense for UAVs to delay or lose the DEW tracking altogether. Figure 19 shows the OV-1 diagram for the use of a smokescreen.

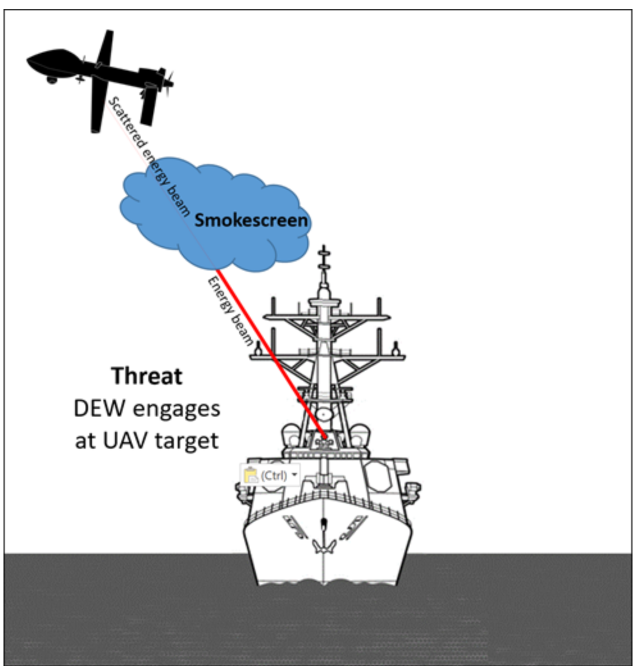


Figure 19. OV-1 Smokescreen Operational Diagram. Adapted from McKible (2018).

The size of the smoke particle impacts the scattering of the laser beam (Shu et al. 2006). The larger the diameter of the smoke particle, the more scattering of the laser beam. Therefore, deploying a smokescreen will result in more extinction of the laser beam. Even though scattering will not impact the atomic density of the laser beam, as the smokescreen scatters the beam, the beam will not be capable of delivering overall required energy density to the target. As a result, the DEW will not be able to deliver energy with the intended intensity for the intended period. This results in a longer dwell time to achieve the expected outcome.

An experiment was conducted which generated smoke particles to establish a multi-wavelength light scattering system using a smoke generator, a current equalizer, an inflow fan, and an outflow fan (Shu et al. 2006). The system in that experiment was capable of delivering uniformly distributed smoke particles into the scattering chamber. A similar mechanism could be used to generate smoke particles as a countermeasure device. The mechanism either needs to be able to produce smoke on demand or have stores to be released when needed. It will require a storage area on the UAV to store hardware dedicated to creating a smokescreen. Therefore, it will add weight as well as increase the cost of the system. In the experiment, the aerosol particles were released into a light scattering chamber. However, when countering a HEL attack, smoke particles will be released into the environment. Therefore, the smoke particles will not be guided uniformly as described in the experiment. However, if the smoke particle concentration is dense, it will cause more scattering of the DEW laser. Therefore, it is essential to use materials that could generate smoke particles with a larger diameter. At the same time, the more particles you can generate, the denser the smoke screen will be. If the smoke particle screen could extend for a longer distance, it will be able to scatter the incoming laser effectively (Shu et al. 2006).

2. Helios

The Navy is implementing a program called Helios, which consist "of a small UAV-mounted sensor package, Helios provides full analysis of the incoming DEW beam including localization and intensity" (Adsys Controls Inc. 2018, para. 1). This system uses this information to target the laser source jamming and disrupting the tracking, to counter the DEW (Adsys Controls Inc. 2018). This system is completely passive and it is said to have a low SWaP. Figure 20 shows an OV-1 for this technology. Depending on the UAV, this technology may be limited to group 3 and above, but this provides means to physically engage with the weapons and prevent its ability to complete its dwell time. The countermeasure plan could use of the Helios technology for aircraft that can support the SWaP needs.

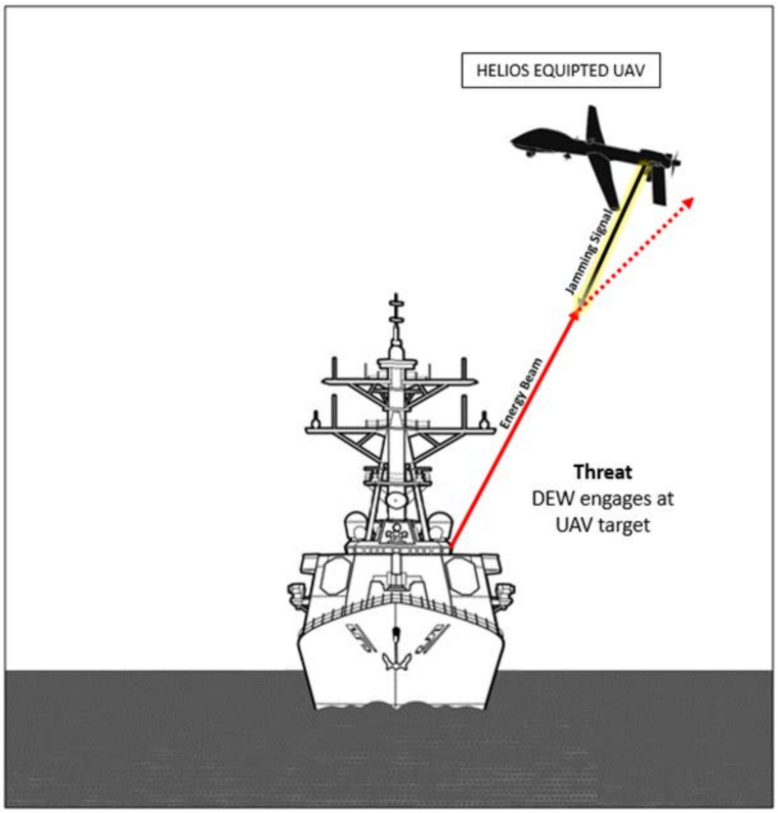


Figure 20. OV-1 for UAV Equipped with Helios. Adapted from McKible (2018).

Many countermeasure applications use decoys; they can obscure or confuse the tracking algorithms to allow the target to leave the threat area. A theoretical countermeasure the UAV could take advantage of is the deployment of heated physical decoys, to confuse the DEW as to which target is the tracked UAV. Research into this topic is unavailable, but from the need of the DEW to track the UAVs movement, there is an assumption that if a UAV deployed heated physical objects, the DEW may track the heat signature of the decoys and lose the tracking of the UAV itself.

D. THE USE OF UAV SHIELDING FOR PASSIVE COUNTERMEASURES AGAINST HELS

The first passive line of defense onboard a UAV against DEW is the material coating. The team decided the top three material coatings for defense against DEW to be Bragg mirrors, a reflective coating, and an ablative coating. The following section discusses each of these applications and the expected result of a DEW impact upon them.

1. Bragg Mirror

A primary strategy for countering DEW onboard a UAV is to implement a protective coating over the UAVs surface area that delays the effects of the DEW laser. One of these protective coatings is a dielectric mirror, also known as a Bragg mirror. Figure 21 shows an electron microscope image of an approximately 12-micrometer piece of a dielectric mirror being cut from a larger substrate.

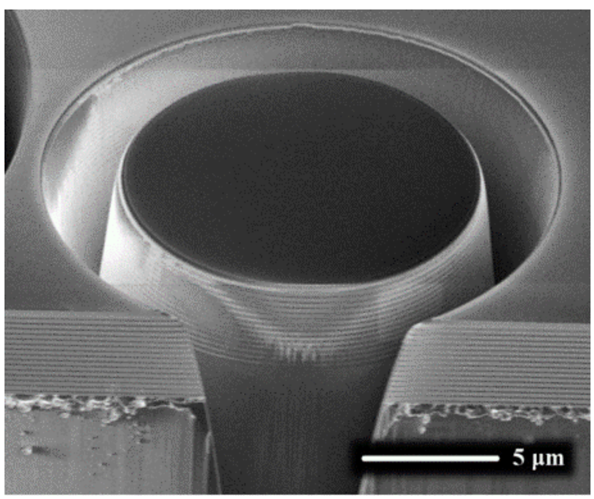


Figure 21. An Electron Microscope Image. Source: Wikipedia Commons (2007).

According to RP Photonics, Bragg mirrors are comprised "of an alternating sequence of layers of two different optical materials where each optical layer thickness corresponds to a portion of the wavelength for which the mirror is designed to reflect" (*RP Photonics Encyclopedia* 2019, para. 1). RP Photonics describes the operation of a Bragg mirror, where each interface between the two materials contributes a Fresnel reflection. A Fresnel reflection is "when a light beam reaches an interface between two different transparent media; it is partly transmitted to the other medium and partially reflected back to the original medium" (*RP Photonics Encyclopedia* 2019, para. 1). "All reflected components from the interfaces interfere constructively which results in a strong reflection" (*RP Photonics Encyclopedia* 2019, para. 2). The layers precise spacing can be adjusted to achieve reflectivity of up to 99.99% (Hambling 2019). Figure 22 shows a color scale of how the optical field penetrates into a Bragg mirror comprised of eight later pairs of TiO2 and SiO2 with a design wavelength of 1000 nm. It can be seen in Figure 22 that "there is little field penetration well within the reflection band" (*RP Photonics Encyclopedia* 2019, para. 5). It is important to note that if a UAV has a Bragg mirror coating that is designed at the same wavelength as the enemy DEW, then the DEW will not entirely be reflected off the UAV. Instead, the effects from the DEW would have an increased dwell time, delaying the "kill."

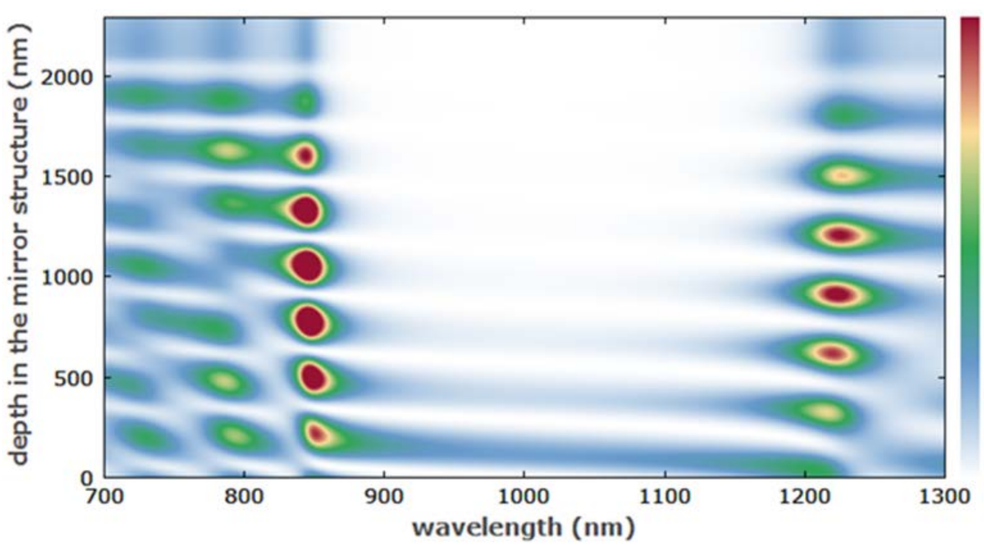


Figure 22. Color Scale of Optical Field Penetrating a Bragg Mirror. Source: Paschotta (2005).

Applying Bragg mirrors to a UAV surface would work as a defense to delay the effects of DEW; however, to work effectively, knowledge of the operational wavelength of the DEW in that environment would be required. This would allow the correct counter wavelength design in the Bragg mirrors on the UAV. Besides the need to know the enemy DEW exact design wavelength, there would also need to be many UAVs that are outfitted for all the variations of Bragg mirrors to the specific DEW wavelengths available for use. Ryan Hoffman, the previous program manager for the counter directed energy weapon program at the Office of Naval Research, said, “Protecting against all wavelengths would be ideal, but difficult” (Hambling 2019, para. 8). The OV-1 diagram shows this passive method of defense against DEW in Figure 23. This method has a medium to high reflectance of the beam from the DEW. This is because, while the Bragg Mirror is reflecting the beam, it is simultaneously losing material causing the reflectivity to lower over time.

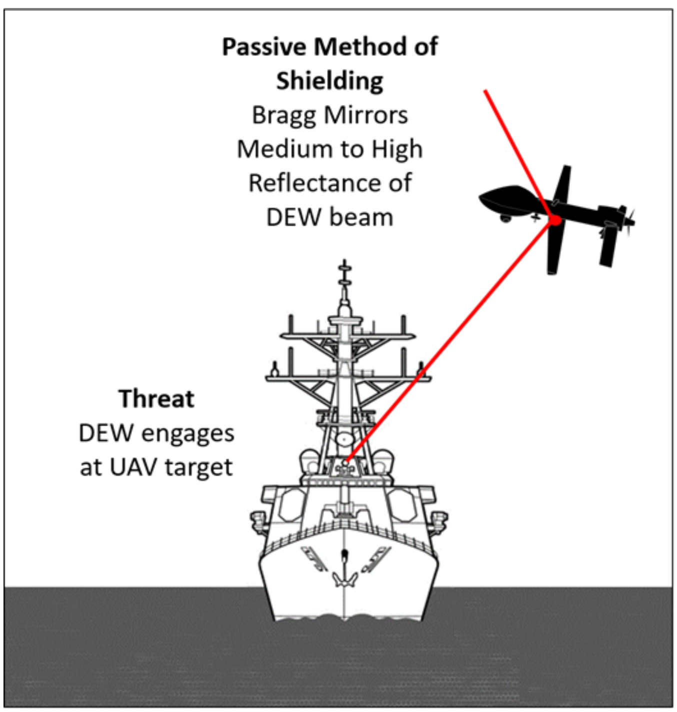


Figure 23. OV-1 of Passive Method of Shielding: Bragg Mirrors. Adapted from McKible (2018).

2. Reflectivity Coating

A more flexible way of shielding the UAV from DEW is a similar concept as the Bragg mirrors, but instead of a permanent mirror coating, a spray coating is used that can be reapplied. This is what the U.S. Air Force is working on with a current small business innovation research (SBIR) program with Luna Innovations Incorporated. The SBIR program's goal is to develop a spray coating that possesses reflectivity across the infrared band (1 micron to 20 micron) and minimizes heating due to absorption (Gunter 2009). This would allow an application of spray coating to a UAV prior to departing on a mission, to enable quick changes due to any new intelligence on the operating wavelength of the enemy DEW. Figure 24 shows an OV-1 diagram of this flexible application of a reflective coating. Since application of this reflective coating depends on the adversarial DEW wavelength in use in the operational environment, there will be a high reflectance of the beam off the UAV.

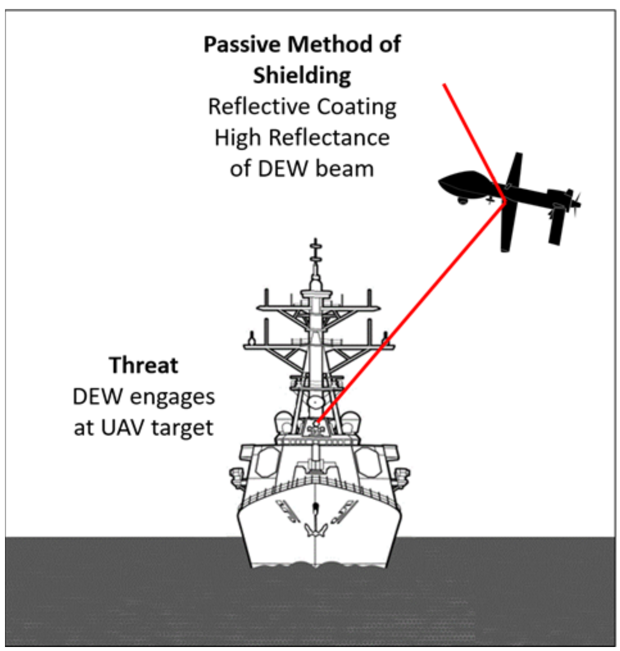


Figure 24. OV-1 of Passive Method of Shielding: Reflective Coating. Adapted from McKinley (2018).

3. Ablative Material Coating

Another method of shielding a UAV from the effects of DEW is by using an ablative material coating. While Bragg mirrors share some ablative properties, the primary function is reflectivity. An ablative coating's primary function would be to eliminate thermal energy by the sacrifice of surface material (Favaloro 2000). There are varying methods of applying an ablative material coating depending on the allowable weight for the coating. According to a study by the National Aeronautics and Space Administration (NASA), some application means for ablative material composite are via a spray coating or with sheets of a natural P50 sheet cork material that originates from the bark of a cork oak tree. This cork oak has excellent insulative properties (Davis 2017). Lining an UAV with this material in its natural state or via the composite spray will add time required for a DEW to penetrate the UAV. Ablative materials will not completely inhibit the effects of DEW, but it will increase the dwell time, which may give the UAV the opportunity to leave the threat area or complete its mission. Boeing recently conducted a test using a compact laser weapons system on a drone with ablative material; the DEW took 15 seconds to penetrate the UAV surface thanks to this application (Atherton 2019). Figure 25 shows an OV-1 diagram for an ablative material. The OV-1 shows the beam from the DEW causing a hot spot on the impact point. This is where the ablative material would rapidly deteriorate reducing its effectiveness, but continue to delay the dwell time.

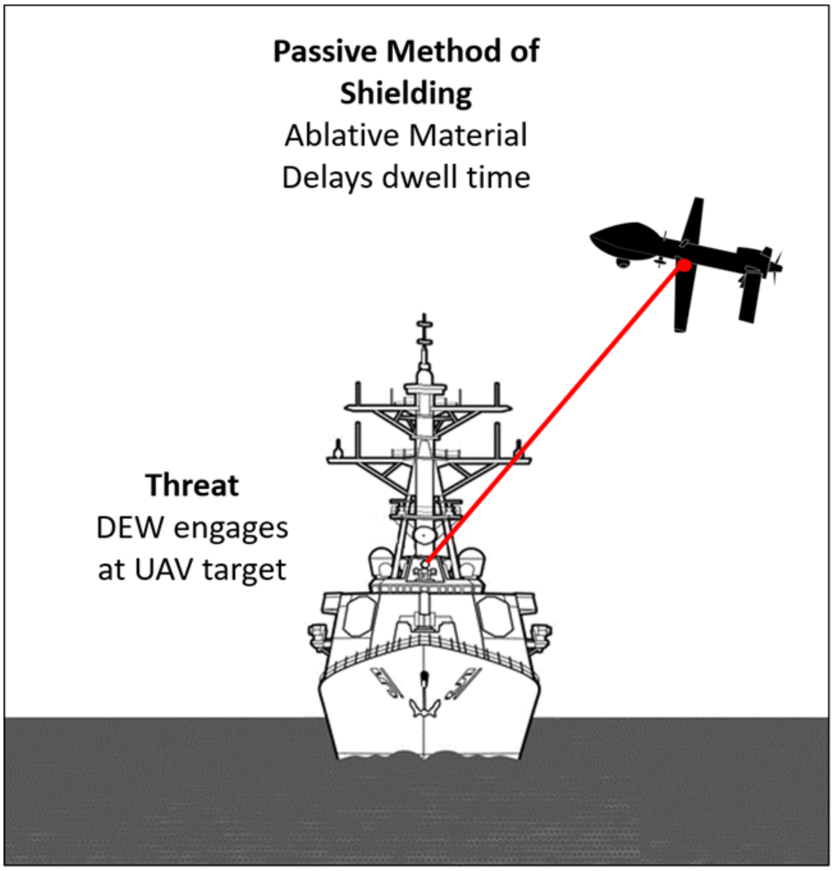


Figure 25. OV-1 of Passive Method of Shielding: Ablative Material Coating. Adapted from McKible (2018).

E. USING UAV MANEUVERING TACTICS AND SWARM TACTICS FOR CDEW

Operational tactics are the maneuvering of a craft. Specifically, the operational tactics UAV controllers can employ before, during, and after DEW targeting that can avoid, mitigate, or transfer the effect of that weapon. Looking at the weaknesses of HEL DEWs, are there any tactics that can accomplish these objectives, and what are the likelihoods of each to be effective? Do the tactics have more potential to damage the UAV than accepting the DEW attack? Levin, Nahon, and Paranjapes’ 2016 research describes some of the problems with evasive maneuvers and unmanned aircraft, including the latency between the controller and the components in the system. Although there currently is little research into UAVs avoiding danger, using operational tactics, the study opens some doors on where to start on unmanned systems carrying out these acrobatics. Figure 26 is a possible scenario where UAV maneuvering will assist in breaking the DEW LOS. The line between the UAVs represents the distance to the obstruction. If the time required to reach that position is less than the required “kill” dwell time, after the performance of an evasive maneuver minus the time it took to identify the threat, an automatic execution of that maneuver is performed.

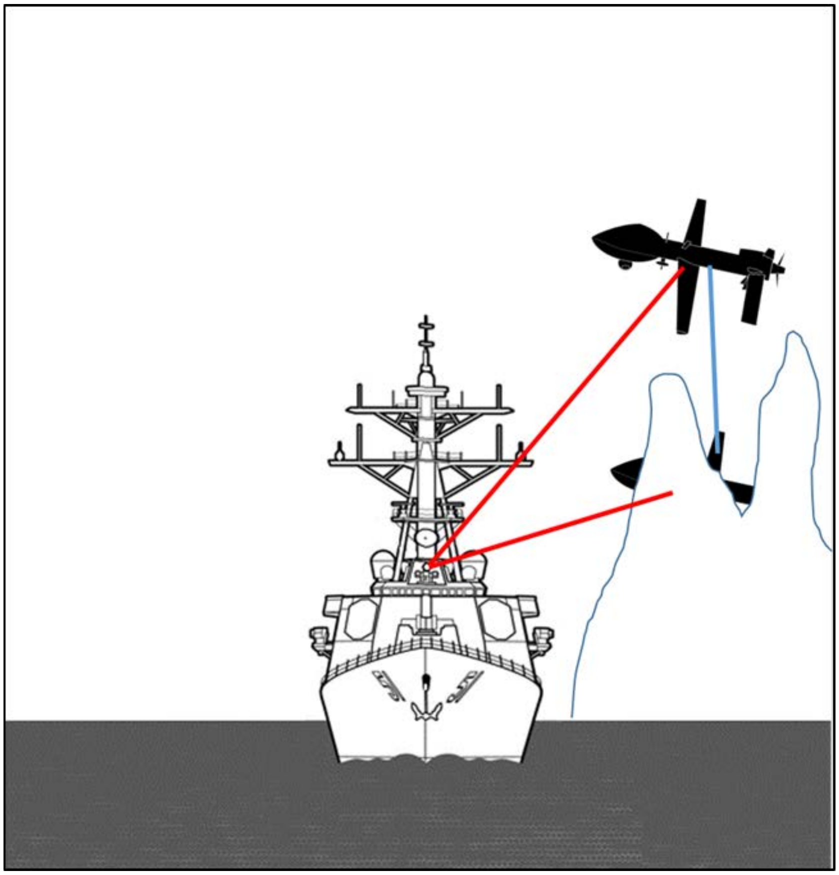


Figure 26. UAV Performing Maneuvers to Obstruct LOS. Adapted from McKible (2018).

The LOS element needed for the HEL DEW to make an attack is exploitable by operational tactics. Swarm operations are becoming an area of interest in the unmanned vehicle arena. Davis et al. (2018) discuss advancements in swarming practices, including behavior and size reduction. Many of the behaviors in the video focus on accomplishing the mission through numbers, but with a different focus, a swarm could become a defense tactic allowing more time for the target UAV to execute other methods by becoming screens, transporting screens, or effectively becoming their own environmental factor. Figure 27 displays a theoretical swarm tactic in defense of a target UAV. These tactics can interrupt the LOS, affect the flight pattern, or distract the targeting system of the DEW. The ONRs Low-Cost UAV Swarming Technology (LOCUST) research is evaluating the swarm technique using thirty UAVs launched from tubes that can be deployed simultaneously. With the LOCUST program, a DEW would have to engage and defeat each UAV much faster to avoid being overrun (Atherton 2019). Some of the drawbacks to this tactic are the size and launch requirements, which are both currently being addressed by migrating to quadcopters because of the smaller launch requirements and reducing the internal component size to ultimately reduce the airframe size (Davis et al. 2018). The implication of the video is with the reduction in size and launch footprint; there will be a reduction in cost, which may make the idea of losing a low-cost defense drone more desirable than that of a higher cost UAV carrying ISR specialized payloads or other costlier stores.

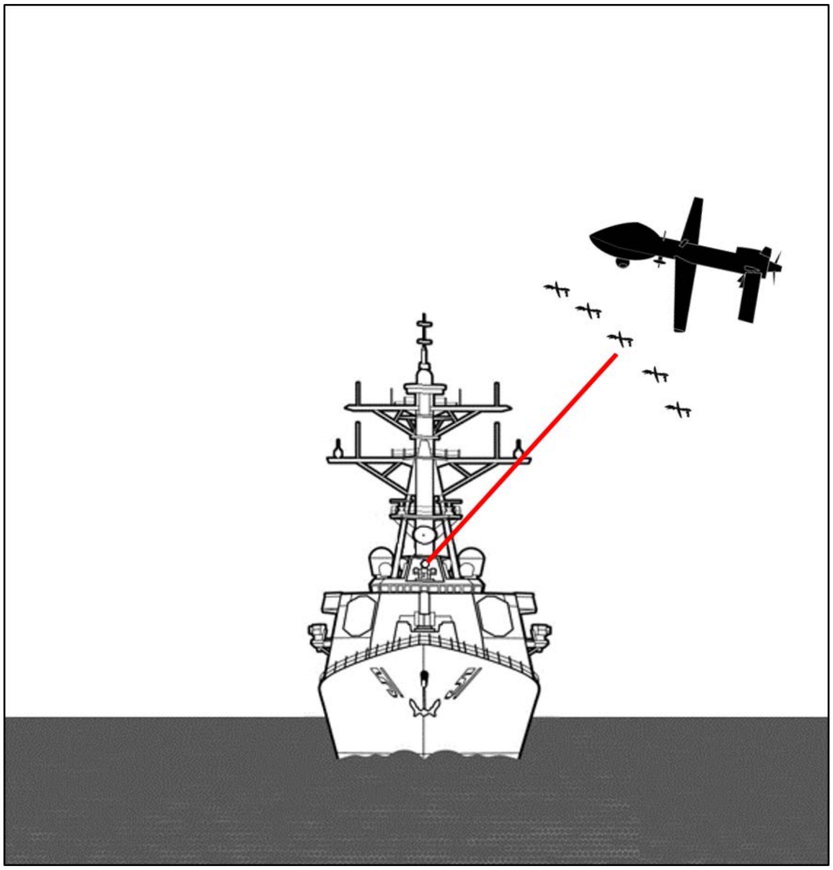


Figure 27. UAV Defended by Swarm Tactics. Adapted from McKible (2018).

The need to predict the flight path of the target UAV to maintain dwell can be exploited; some research is being conducted on fixed-wing UAVs and their ability to pull off different techniques used by manned air vehicles to disengage from a hostile entity. Although much of the current research focuses on avoidance of missiles, Yomchinda (2015) and Levin, Nahon, and Paranjapes' (2016) delve into using automated techniques based on constant motion and applied forces to produce avoidance maneuvers in both the horizontal and vertical planes. If the tactics can be done in an autopilot type fashion either triggered by the remote operator or detection systems, then the latency issues will not affect locally run programs to the component. These evasive displays will either change the target area on the craft or confuse the course prediction component of the DEW effectively restarting the dwell time.

It has been discussed, that the atmospheric parameters such as temperature, humidity, and particle density can have adverse effects on HEL DEWs. Although little study has been done, if the UAV can detect changes in close range conditions, this can be used to its advantage. Positioning trees or a ridgeline between the UAV and the DEW will be 100% effective in eliminating damage from that source due to LOS. Moving into thick clouds or other climate conditions will have an impact on the success of the weapon as well. Combing maneuvering capabilities with other countermeasure techniques can provide a multilayered defensive strategy to the UAV countermeasure solution.

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VI. EVALUATION OF CDEW SOLUTIONS

To evaluate the effectiveness of the CDEW methods described in Chapter V, a model was developed that could be used to test those methods. The team first had to understand the entirety of the problem and how a DEW interacts with its surroundings and its target. This model utilizes Beer-Lambert Law, as discussed in Chapter IV, which derives the loss of power due to the propagation of the laser through a medium. The team is then able to calculate the power arriving at the target from a DEW. Chapter IV discusses how the type of material effects the efficiency of reflectivity. Using the reflectivity values and specific material properties, the model calculates the required dwell time a HEL must take to melt through a target. Lastly, some of the active countermeasure techniques discussed in Chapter V, swarming and operational tactics, can be evaluated to change the result of the calculated dwell time. To be able to evaluate these CDEW methods a high-level approach was taken. The team decided this is the best path forward as even though the fidelity of the data might be low, having a good process will allow for future work to expand upon the model developed here using validated values of effectiveness.

A. MODELING CDEW METHODS

To develop this model, a toolset that allowed the user to perform calculations on an iterative basis and the ability to create a user interface (UI) was top priority. Visual Basic for Applications (VBA) through Microsoft Excel was used to create a minimum viable product (MVP). However, due to limitations of the VBA architecture and lack of UI development tools natively involved, another route was taken for the final prototype. The team decided to use “R” Studio, which is a statistical computing language and application. Not only is “R” Studio powerful enough to calculate the model effectively and produce charts, but it can also be used to develop a standalone application with a UI. The team found realistic environmental data through an application already developed by the Air Force Institute of Technology called Laser Environmental Effects Definition and Reference (LEEDR). The LEEDR application takes a location and the user can either enter weather inputs or use actual weather data, outputs the total extinction coefficient at different altitudes. This can then be used in the Beer-Lambert Law calculation and is the summation of the scattering and absorption effects the atmosphere has on the laser as it propagates through space.

The tool fundamentally calculates and defines the probability of survivability for the UAV based on the parameter of conditions given by the identified threat. Although most information on HEL lethality is currently classified, the tool is developed using general laws and theories of thermodynamics to determine the HEL lethality at an overarching view, as discussed in previous chapters. Using the concepts of physics and metrics for laser damage, the calculations set the foundation for the tool to determine the dwell time required against the UAV to categorize it as a hard kill. Joseph Blau, from the Physics Department of the Naval Postgraduate School, discussed laser effects in his lecture "Directed Energy Weapons: Laser Damage Physics," for his Fall course PH4858 Electric Ship Weapon Systems through Blackboard Collaborate. In his lecture, the goal of laser damage is to target the smallest possible constant area with the highest energy as quickly as can be achieved with a hard kill measured at roughly five seconds for a UAV. Although a hard kill is measureable, measuring extended dwell times and what disrupts them is less accurate. Therefore, without proper data to gauge between a hard kill, soft kill, and safe the team decided to test if the dwell time is less than 5 seconds any other length of time is safe. On the other hand, if the dwell time is less than 5 seconds the user may choose to employ an active countermeasure. While theoretically discussed in previous chapters, data on the effectiveness of these countermeasures are either classified or unavailable. Without concrete data, nominal data was used to evaluate the active countermeasures. Figure 28 depicts how the model works and where the calculations are made.

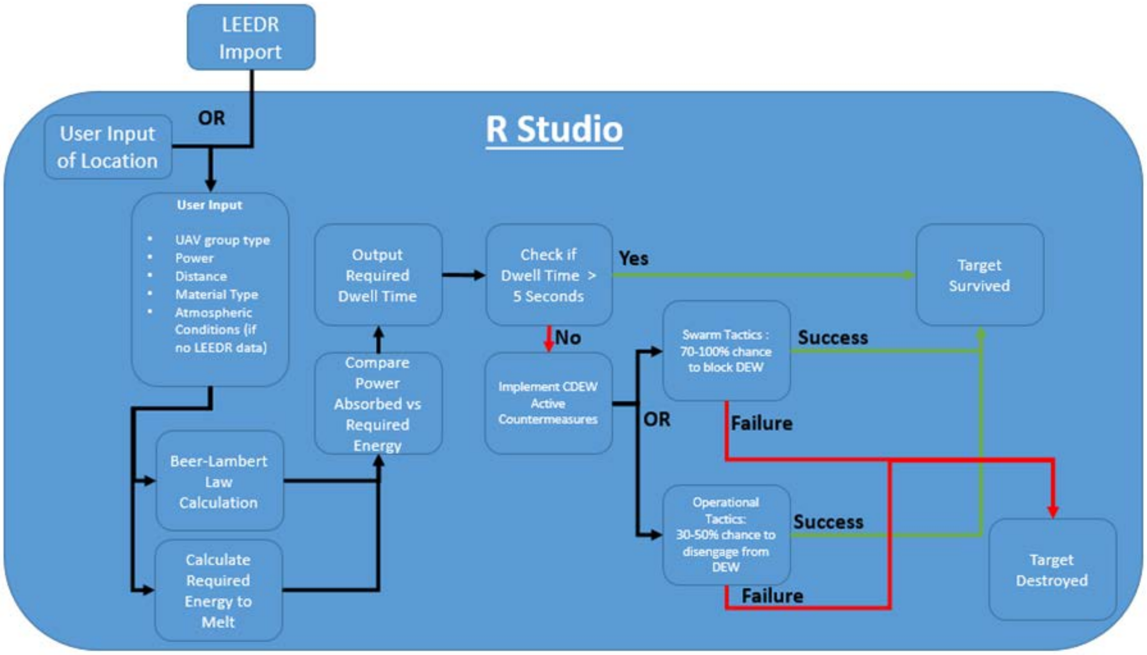


Figure 28. CDEW Model Flow Diagram

"R" studio gets input from either a LEEDR import or user input of the location. The inputs are UAV group type, power, distance, material type, and atmospheric conditions. Using those inputs, the Beer-Lambert Law power losses, and energy required to melt the target material is calculated. The resulting is the total absorbed power by the target and the required energy to melt through it. Based on this comparison, the algorithm calculates the required dwell time. If the dwell time is greater than five seconds, the target survives. If the dwell time is less than five seconds, a CDEW active countermeasure method is implemented. The countermeasure method would be either a swarm tactic or an operational tactic. Using nominal data, the swarm tactic has a 70–100% chance to block a DEW. An operational tactic has a 30–50% chance to disengage from the DEW. Failure from either of those active countermeasures would result in the target being destroyed while success would lead the target to survival. This allows the user to graph the intensity of the HEL as the range changes in that environment. The goal of this tool is to assist the evaluator in making educated decisions along the acquisition life cycle for a particular UAV and help determine the survivability of an aircraft given its current capabilities for survival against a HEL attack.

1. Model Inputs

To explain the model further, each input is discussed. Figure 29 shows the overall layout of the input tool. Next, each section is enlarged to show more detail.

Figure 29. Input Screen for CDEW Model

There are five sections to fill out by the user: power, range, UAV group type, HEL target material type, and weather conditions (if LEEDR not used). The first, power is a simple numerical input that the user provides in kW as shown in Figure 30.

Figure 30. CDEW Model Power Input

Next, is the range input, which again is a simple numerical input. The caveat to this is that it is the ground range distance to target, as shown in red in Figure 31.

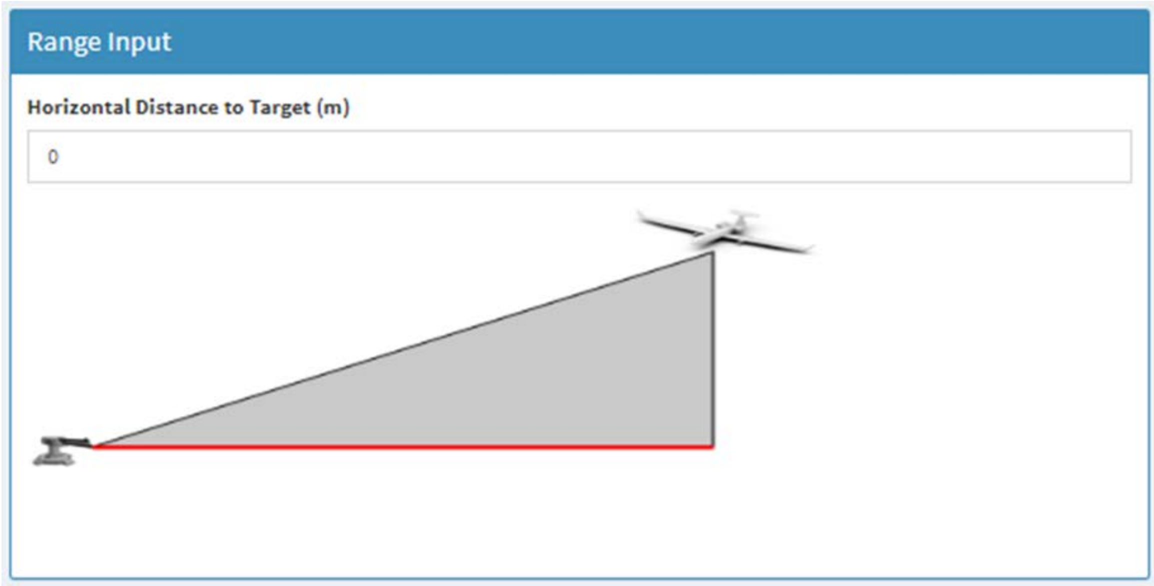
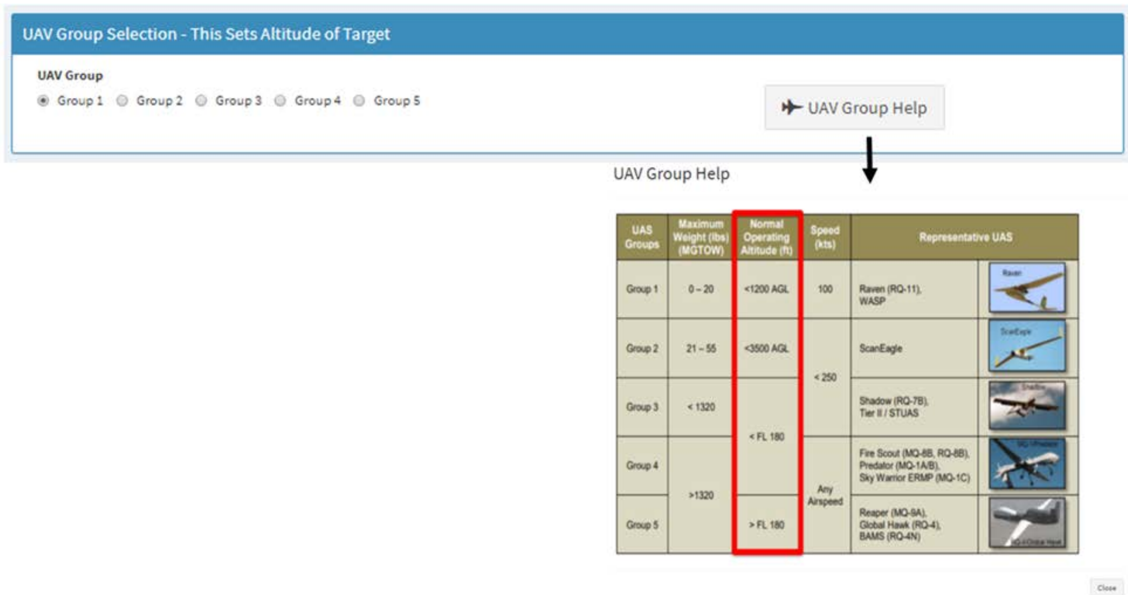


Figure 31. CDEW Model Range Input

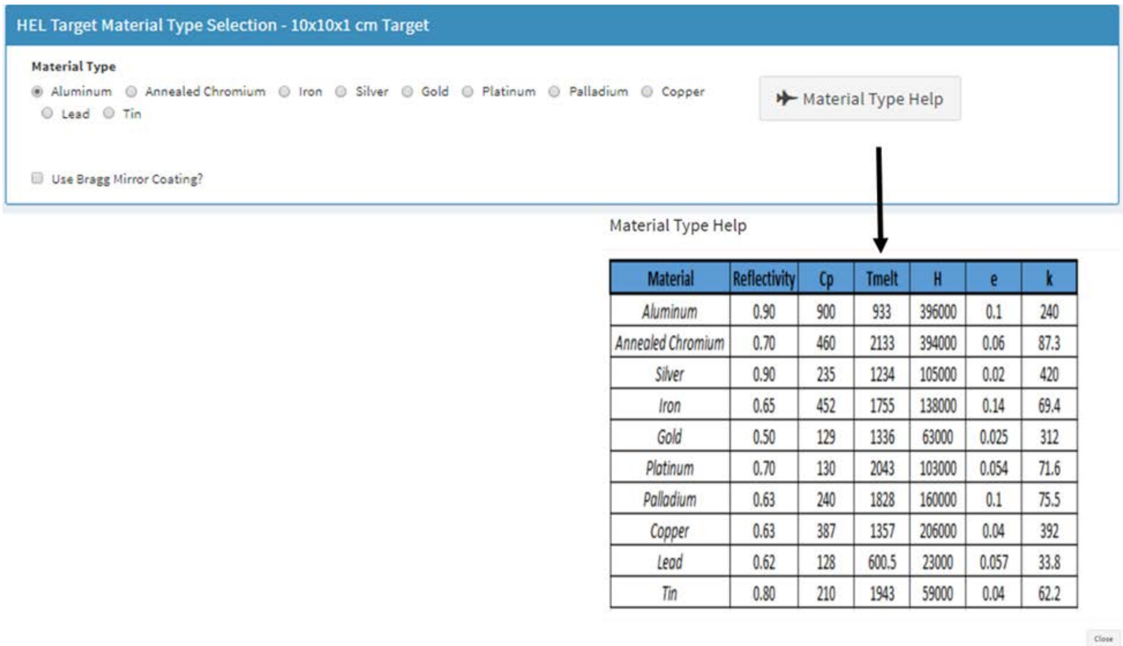
The next input is the UAV group selection. This sets the altitude of the targeted UAV. The normal operating altitude of each group was used. As shown in Figure 32, the user may also click the “Help” button to see more information as to what each UAV group type is.



UAS Groups	Maximum Weight (lbs) (MGTOW)	Normal Operating Altitude (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)

Figure 32. CDEW Model UAV Group Selection and Help

The next input is the HEL target material type selection. It needs to be noted, for the melting calculation, an area is required, for this model a 10x10x1 cm target is chosen. As 10 cm is a standard value when computing energy to melt and 1 cm thick is thicker than any UAV skin, so all UAVs would be covered in this model. Just as in the group type, the user may click on the “Help” button to see the values involved when choosing each material. Below the Material Type buttons, is a checkbox asking the user if they would like to use “Bragg Mirror Coating.” By checking that box, it sets the reflectivity of the chosen material to 99% and is considered as using a passive CDEW method. This is shown in Figure 33.



Material	Reflectivity	Cp	Tmelt	H	e	k
Aluminum	0.90	900	933	396000	0.1	240
Annealed Chromium	0.70	460	2133	394000	0.06	87.3
Silver	0.90	235	1234	105000	0.02	420
Iron	0.65	452	1755	138000	0.14	69.4
Gold	0.50	129	1336	63000	0.025	312
Platinum	0.70	130	2043	103000	0.054	71.6
Palladium	0.63	240	1828	160000	0.1	75.5
Copper	0.63	387	1357	206000	0.04	392
Lead	0.62	128	600.5	23000	0.057	33.8
Tin	0.80	210	1943	59000	0.04	62.2

Figure 33. CDEW Model Material Input and Help

The last input is the weather condition. The user has three options, clear, cloudy or foggy. Each one has differing optical depth values, depending on the location chosen by the user. For example, the data for cloudy weather in Jacksonville is different from the cloudy weather in San Diego. The user may also click on the “Help” button to see how the different weather effects will affect transmittance. This is shown in Figure 34.

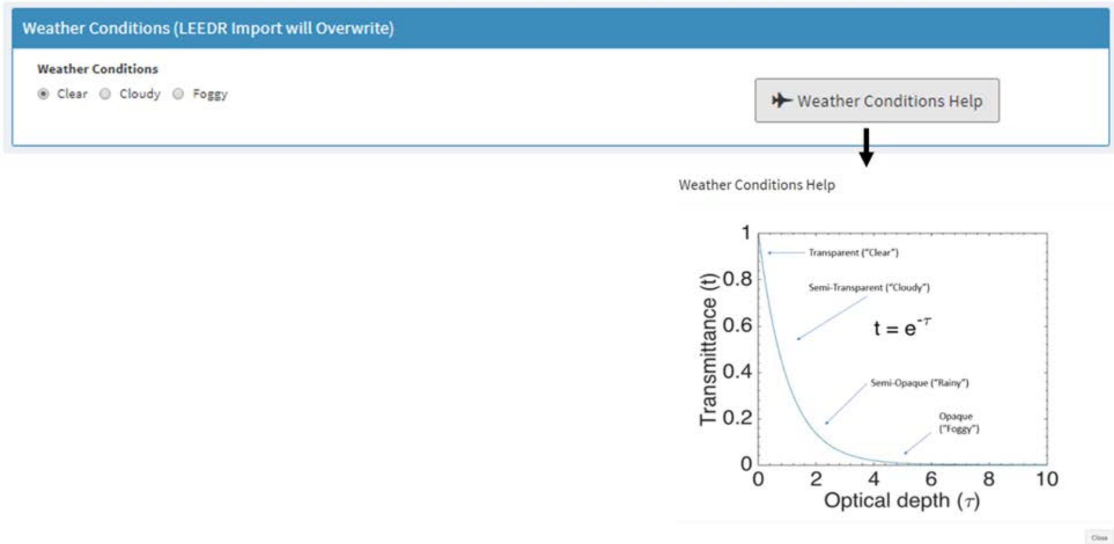
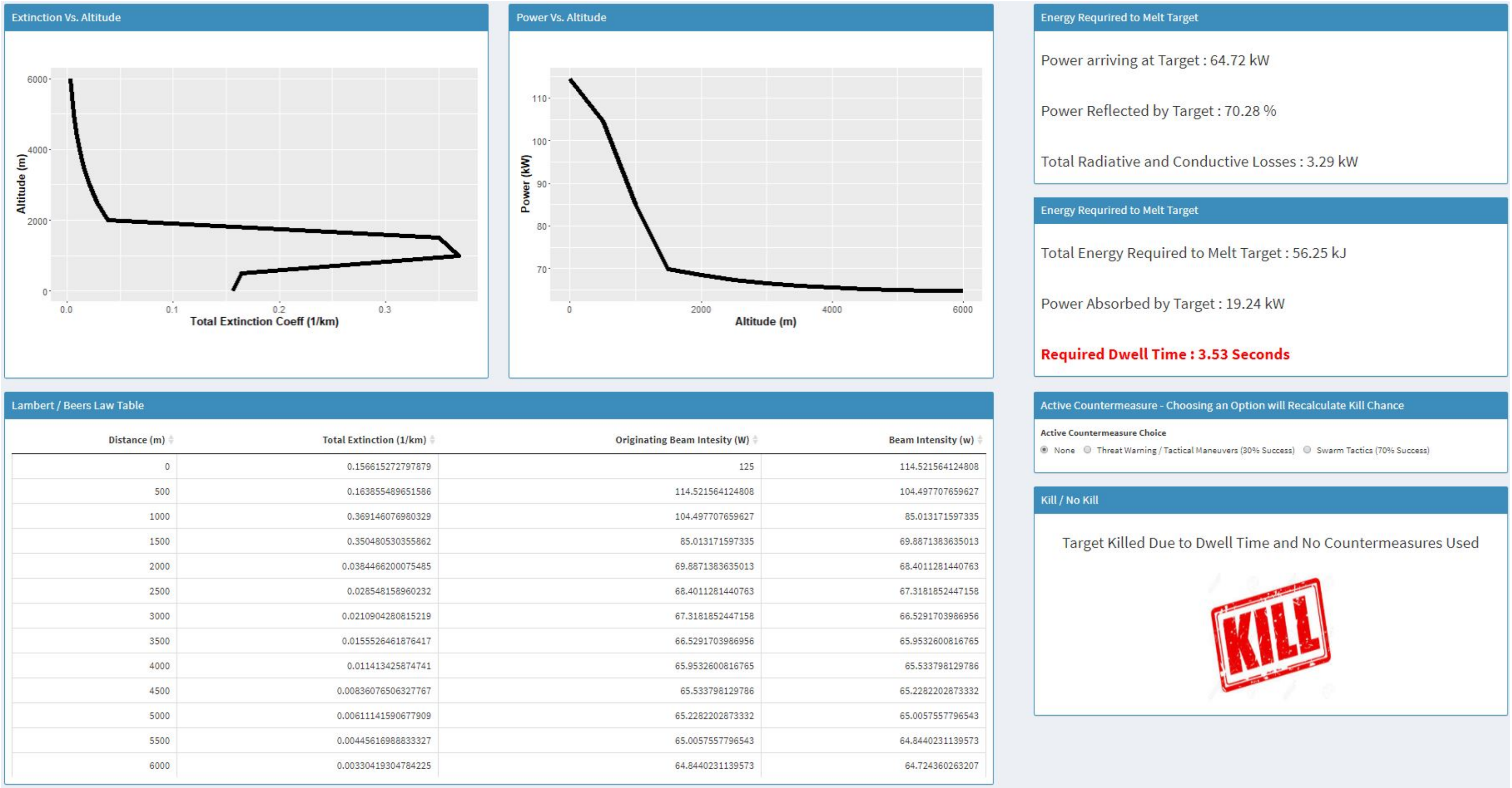


Figure 34. CDEW Model Weather Input and Help

2. Model Outputs

After putting in the last input, the user may hit the run button and the model will then calculate using the given values. Figure 35 shows the results page that displays after the model has completed its calculations.



Distance (m)	Total Extinction (1/km)	Originating Beam Intesity (W)	Beam Intensity (w)
0	0.156615272797879	125	114.521564124808
500	0.163855489651586	114.521564124808	104.497707659627
1000	0.369146076980329	104.497707659627	85.013171597335
1500	0.350480530355862	85.013171597335	69.8871383635013
2000	0.0384466200075485	69.8871383635013	68.4011281440763
2500	0.028548158960232	68.4011281440763	67.3181852447158
3000	0.0210904280815219	67.3181852447158	66.5291703986956
3500	0.0155526461876417	66.5291703986956	65.9532600816765
4000	0.011413425874741	65.9532600816765	65.533798129786
4500	0.00836076506327767	65.533798129786	65.2282202873332
5000	0.00611141590677909	65.2282202873332	65.0057557796543
5500	0.00445616988833327	65.0057557796543	64.8440231139573
6000	0.00330419304784225	64.8440231139573	64.724360263207

Figure 35. CDEW Model Results Page

The graph in the top left of Figure 35 depicts how the Total Extinction coefficient varies with altitude. This relates to how much power is lost as the laser propagates through the atmosphere. In the middle, is a graph relating power to altitude. As the laser is fired from ground level, the power decreases as altitude increases. The table below the two charts in Figure 35 provides the exact values for the two charts above. On the right-hand side is the values needed in calculating the dwell time required to melt through the target. Figure 36, shows how these values are broken up into two sections to arrive at the required dwell time.

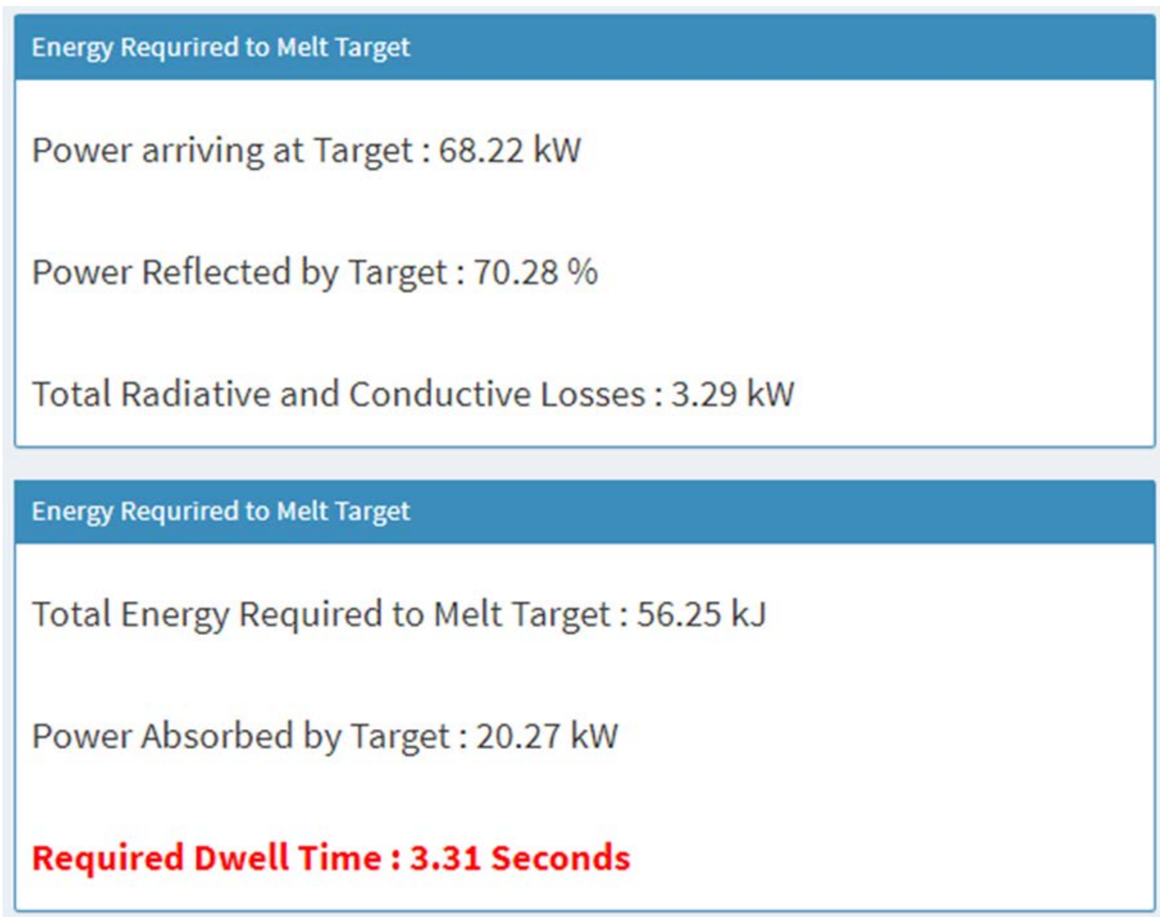


Figure 36. CDEW Model Dwell Time Calculation Outputs

Lastly, the model outputs the “Kill or Safe” stamp. This checks if the dwell time is within the kill window of less than 5 seconds and determines a hard kill or safe. However, the user may "roll the dice" and employ an active CDEW method. These options are shown in Figure 37.

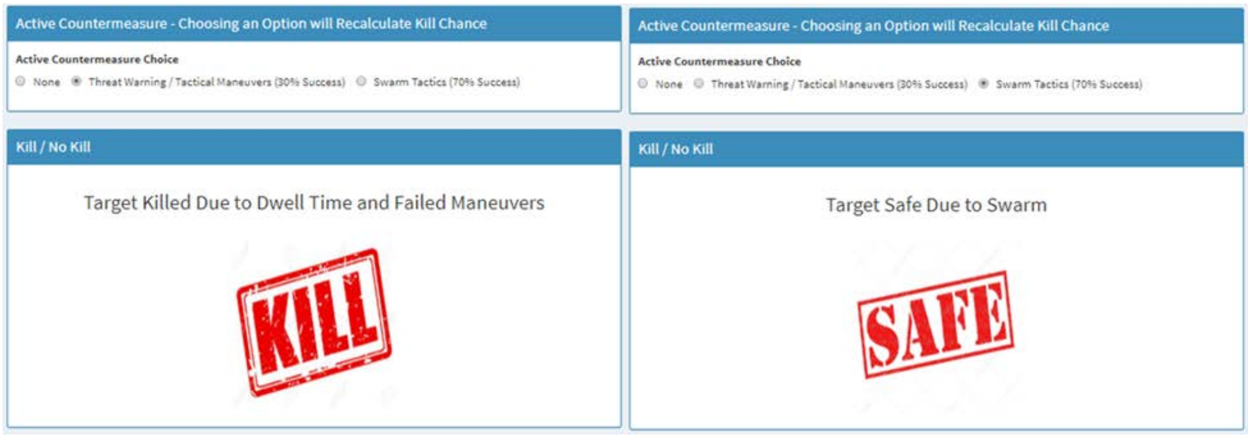


Figure 37. CDEW Model Active Countermeasure Output

B. PHYSICS DISCUSSION

To determine a "Kill or Safe" value, the model had to calculate many values. The theories, laws, and equations were explained in previous chapters and can be referred to as needed but the application of those equations are discussed within this section. Of note, an assumption had to be made for the wavelengths of the HEL as the data and computations differ for each wavelength. Due to the lack of availability of data for all wavelengths a select few were used. By restricting the wavelengths to a select few, the model was able to be more precise and accurate.

1. Power Lost due to Atmospheric Effects

The first calculation the model does is for the loss of power from the laser propagating through the atmosphere. The model uses Beer-Lambert Law to calculate this. The Beer-Lambert Law shows the exponential loss of power as a beam of radiation passes through a gaseous substance over a distance (Cleveland and Morris 2014). The formula (1),

$$
\begin{aligned}
&I = I_0 e^{-\varepsilon z} \\
&I = \text{current power} \\
&I_0 = \text{originating power} \\
&\varepsilon = \text{extinction coefficient} \\
&z = \text{distance}
\end{aligned} \tag{1}
$$

is used for the Beer-Lambert Law calculations. By utilizing the wavelength of the beam and properties of air at given altitudes, this power loss can be used to find the available power once the target is reached. Within the model, the extinction coefficient varies as altitude increases. Accounting for this we integrated the equation over the distance from the HEL to its target. The table created on the results page of the model displays each step of this integration. The results page shows the final value in the top right-hand section under "Power arriving at Target." There are some shortfalls to the Beer-Lambert Law that may warrant additional testing if conditions such as highly scattered materials or rough surfaces are a factor (McGunnigle, Dong, and Wang 2012 and Gobrecht et al. 2015). McGunnigle, Dong, and Wang discuss how the material that disperses the energy of the beam tend not to follow the exponential decrease in energy given by Beer-Lambert Law. Gobrecht et al. research into using a dye in highly scattered materials to increase the probability of Beer-Lambert Law applying.

Although not natively used in the calculation are the effects of diffraction, turbulence, and thermal blooming. These effects, as discussed in Chapter III, may have a noticeable impact on the effective power output by a DEW. However, if the LEEDR atmospheric data contains turbulence data, the model will appropriately include those in its calculations. While these are not currently included in this model, the flexibility of the model will allow future efforts to include them.

2. Power Absorbed by Target

Next, the model determines the power absorbed by the target. This is a simple calculation, formula (2), involving the power arriving at the target and the target's material reflectivity. In the top right-hand section of the results page displays reflectivity under "Power Reflected by Target."

$$
\begin{aligned}
&P_{abs} = P_{arr} R \\
&P_{abs} = \text{power absorbed by the target} \\
&P_{arr} = \text{power arriving at the target} \\
&R = \text{reflectivity value of the material}
\end{aligned}
\tag{2}
$$

3. Energy Required to Melt

Next, the model must calculate the energy required to melt its target (Q_{melt}). This is found by adding the energy required to reach melting temperature (Q_1) and the energy required to melt material at its melting point (Q_2). The formulas (3)–(5) show this process.

$$
\begin{aligned}
&Q_1 = C_p m \triangle T \\
&C_p = \text{specific heat capacity of target material} \\
&m = \text{mass of target material to melt} \\
&\triangle T = \text{change in temperature}
\end{aligned}
\tag{3}
$$

$$
\begin{aligned}
&Q_2 = m \triangle H \\
&H = \text{target material heat fusion}
\end{aligned}
\tag{4}
$$

$$
Q_{melt} = Q_1 + Q_2 \tag{5}
$$

The values used by each material type can be found within the “Help” section of the target material type within the model itself. The final Q_{melt} value is shown in the second section on the right-hand side of the results page as “Total Energy Required to Melt Target.”

4. Power Lost due to Thermal Losses

Lastly, the model must determine the thermal losses. The thermal losses remove power from the target area. Therefore, to melt a target, absorbed power must exceed power losses. Calculation of formula (6) provides the power radiated away.

$$
\begin{aligned}
&P_{rad} = \varepsilon\sigma A_{rad}\left(T_{melt}^4 - T_0^4\right)\\
&\varepsilon = \text{emissivity}\\
&\sigma = \text{Stefan-Boltzmann constant}\\
&A_{rad} = \text{cross-section area of the target}\\
&T_{melt} = \text{melting temperature}\\
&T_0 = \text{ambient temperature}
\end{aligned}
\tag{6}
$$

The power conducted away is given by the formula (7).

$$
\begin{aligned}
&\frac{P_{cond} = kA_{cond}\left(T_{melt} - T_0\right)}{\vartriangle r}\\
&k = \text{thermal conductivity of target}\\
&A_{cond} = \text{surface area over which conduction occurs}\\
&\vartriangle r = \text{distance of temperature gradient}\\
&T_{melt} = \text{melting temperature}\\
&T_0 = \text{ambient temperature}
\end{aligned}
\tag{7}
$$

The total power loss is found by adding the total power radiated away, and the total power conducted away. It is given by the formula (8).

$$
P_{loss} = P_{rad} + P_{cond} \tag{8}
$$

P_{loss} is shown in the model in the top right section of the results page as the "Total Radiative and Conductive losses."

C. SURVIVABILITY MODELING

With a fully developed model, the team evaluated some of the proposed CDEW methods against nominal data or the four use-case UAVs proposed in Chapter IV. As previously discussed, CDEW methods can be either passive or active. The team selected two passive CDEW methods and two active CDEW methods for analysis. The two passive methods selected were: (1) shielding with Bragg mirrors or some other coating and (2) using weather events as a passive-countermeasures. The two active methods selected were (1) using swarm UAV tactics and (2) using operational tactics as active-countermeasures.

The tool was able to model the passive-countermeasures fairly accurately; but the active countermeasures were modeled at a high-level and could only provide estimated results. The tool modeled weather events as a passive countermeasure by allowing a user to select weather conditions from a set of nominal values for clear, cloudy, or foggy. These weather conditions were chosen as "low – medium – high," indicating their impact on the HEL beam as it propagates through space. A LEEDR import can have more realistic and fine-tuned data for weather conditions, which would provide a more robust analysis of the effect the atmosphere had on the DEW.

The tool modeled UAV coatings by providing a "Bragg Mirror Coating" target material type option. This option set the reflectivity of the UAV coating to 99% meaning that no matter how much power reached the target (power after Beer-Lambert calculation), 99% of that power would be reflected and not absorbed by the target. This passive CDEW solution would make it nearly impossible for a HEL to destroy a UAV. An assumption was made that the Bragg Mirror coating was designed to the specifications of the given threat laser.

For the active countermeasures, the tool allowed the user to select swarm tactics or operational tactics. The model would first calculate the dwell time required based on the threat scenario, UAV proximity from the HEL, the weather, and the passive coating. The dwell time would be provided to the user. The tool was set to calculate with an 70% success rate for swarm tactics because there is a high likelihood for the deployed swam to intercept the beam, but it is not guaranteed. The tool was set to calculate a 30% success rate for operational tactics since it is less likely that a UAV maneuver will make the HEL tracker lose its target. While the values used in the tool's calculations are high-level and low fidelity, the process would be the same for calculations with validated effectiveness values. Once more accurate data becomes available, it would simply be a plug and play into the model since the logic is already included.

D. CDEW CASE STUDY RESULTS

To test the model, the team used as close as possible to the four UAV test cases. Some of the data for the test cases were classified or unavailable to the team, and nominal values were used in their stead. Table 10 shows each UAV test case, where a different

CDEW method was implemented while keeping everything else the same. This showcased the effect each method had on the test case.

Table 10. CDEW Model Test Case Results

Model Inputs	MQ-4C Triton	X-47B Pegasus	MQ-8C Fire Scout	STUAS ScanEagle
Size	Largest	Largest	Larger	Medium
Normal Operating Alt	> FL 180	> FL 180	> FL 180	< 3500 AGL
Average Proximity	8200 nm	1600 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)				
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)

To evaluate each of these test cases, assumptions had to be made. They are as follows:

- Material properties data, if it is composite or the data is unavailable, a nominal value was used. This nominal value is the average of all material property data available to the application.
- Atmospheric effects are limited to the loss due to scattering or absorption only.
- % Pass for Swarm and Operational Tactics were assumed to be 70% and 30% respectively due to their ability to make the DEW lose its target.

- All test cases were flying in the same location in Jacksonville, Fl., for base weather condition purposes.
- Weather conditions such as "cloudy" affected the aerosols in the air from 0 ft to 7000 ft elevation.
- All test cases used the same HEL using the same power output.
- Five attempts at using active countermeasures were used as a sample size.
- This model is only valid for DEW wavelengths of 1 µm, 1.6 µm, 2.1 µm, or 4 µm.
- The target is "safe" if the dwell time is 5 seconds or greater.

Analyzing this data, the team drew some general conclusions. The MQ-4C Triton was the only test case where data for all inputs were found. Although the X-47B Pegasus's material type was found, being a composite, it was unclear of its internal material properties and an average value was used in its place. This meant that one of the major factors that can affect a HEL's lethality, the target material, is the same in three of our four test cases, a nominal value. This resulted in very similar results for those three test cases. However, that meant with all else being the same, that the difference in operating altitude from the X-47B Pegasus and MQ-8C Fire Scout to the STUAS ScanEagle is what contributed to the ~0.3 second increase in dwell time. We can see this take further effect when looking at the weather. The cloudy data caused the HEL beam to hit more aerosols resulting in ~0.5 second increase in dwell time.

The biggest take away from the results was that the reflectivity of the target made the biggest difference. Aluminum has a 90% reflectivity value, whereas the nominal value for composite materials is ~70%. This is a direct 1:1 ratio loss of power, if reflectivity is 90% then 90% of power is reflected away from the surface. In looking at the results for the MQ-4C Triton, it survived every engagement mainly because aluminum is 90% reflective. It also helped that it is the largest and operates at the farthest distance from the HEL threat. By incorporating mirror coating or Bragg Mirrors as a CDEW method, the reflectivity of the target is increased to 99%. Every test case with Bragg Mirrors in the model succeeded and was not even close to being in danger.

Analyzing active countermeasures through the use of swarm, and operational tactics, a UAV might have a chance to survive, especially using swarm techniques. However, of the five attempts modeled none of the test cases had a perfect survival rate. Whereas compared with the Bragg Mirrors, they survived 100% of the time. This was a strong indicator in favor of using passive material coatings for UAVs operating in future DEW environments. The use of active countermeasures could be an additional method, but should not be relied upon solely. Swarm and operational techniques amount to a "roll of the dice" chance for surviving a HEL attack. Having a stronger passive countermeasure is less reliant on probability and is consistently able to protect the UAV.

This tool was able to calculate the survivability in terms of dwell time and the probability of survival of each UAV at a given location with specific operating conditions. Though the data used was mostly theoretical due to classification levels, this tool could be utilized with more accurate data to produce a more high-fidelity evaluation of UAV CDEW solution concepts. Future work could evolve to determine each UAV- specific solution concept that works best in a variety of operating conditions by ensuring each element of the model can account for all the variables in each situation.

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VII. CONCLUSION

A. SUMMARY OF WORK

The goal of this capstone was to identify and characterize future adversarial-DEW threat environments and identify solution concepts for countering, evading, and neutralizing the threat effects against naval assets. The study focused on HEL weapon systems as the directed energy threat and its effects on naval UAVs. The study outlined weapon limitations, tactical methods, and countering capabilities to develop this analysis. A modeling tool was developed to provide analysis capabilities in evaluating the survivability of different types of UAVs within different environmental conditions. The team observed a primary take-away from this study—that HEL threats have numerous obstacles to overcome to be effective weapons. Technology, however, is progressing swiftly, and HELs are likely to be found on the future battlefield.

B. SUMMARY OF RESULTS

This study outlined how countermeasure strategies can optimize their effectiveness by using atmospheric limitations during UAV design and mission planning. Larger UAVs (such as groups three or higher) that could be capable of sustaining payloads may utilize countermeasure techniques from LWSs and active countermeasures to exacerbate these atmospherics effects. Decoys, smokescreens, and expendables could be used effectively to simulate environmental disturbances around the UAV. Newer technologies, such as the Helios program, use counter-laser jamming to disrupt the tracking ability of the laser beam. This countering device may prove to be the most direct active countermeasure available but on smaller UAVs due to weight restrictions, it is not a viable option (Adsys Controls Inc. 2018). Passive countermeasures such as shielding, through the use of Bragg mirrors or reflective and ablative coatings, may be the only options for these smaller UAVs. Unfortunately, the effectiveness of these coatings is limited to a particular wavelength and adds weight to the aircraft. Depending on the threat environment and how many variations of threat HEL weapons exist, this may not be a feasible approach. Smaller UAVs may need to employ evasive tactics or swarm techniques as their best countermeasure for the mission.

The dwell time will limit the swiftness of the HEL attack long enough to complete the objective. Overall, understanding the environmental limitations of the HEL (and many other laser tracking systems) and using this time to launch missions may be the least costly approach, if it is an option.

Based on current (unclassified) information on UAVs, DEWs, atmospheric effects and potential countermeasure methods, this study has outlined all (currently documented) options. The team's modeling tool used this information to allow further analysis of survivability given weapons parameters, range, UAV material, and atmospheric effects to determine the required HEL dwell time. This length of time—which amounts to the required time for a hard kill of the UAV—provides knowledge of how much time there is for the UAV to actively counter the threat. In the future, this kind of analysis could be performed operationally with live data, intelligence of the threat HEL, and knowledge of the UAV, to inform a future UAV operator (perhaps with the aid of an automated CDEW decision aid) to evaluate survivability and employ countermeasure plan.

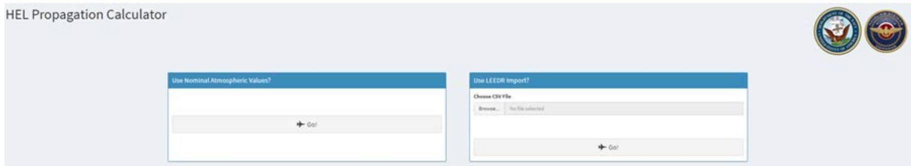
C. BENEFIT OF THE STUDY

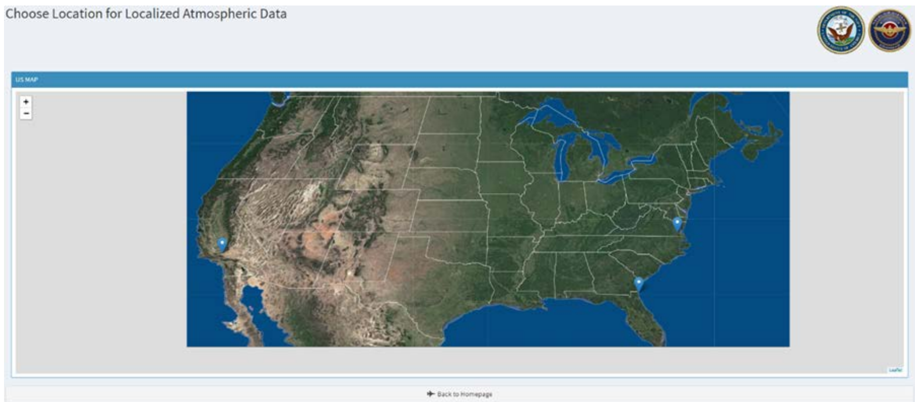
This study applied systems engineering thinking to the CDEW problem space. The benefits provided are the foundational understanding of future adversarial-directed energy threat environments and methods for naval assets to counter these threats to UAVs. Unmanned aerial vehicles are particularly susceptible to DEW threats due to typically having a small mass and potentially operating in close proximity to adversaries, making them an easier target with a lower power adversarial HEL. This insight of how to implement protection for UAVs from HEL threats provides support for future naval missions and UAV developmental designs. Moreover, this study produced a framework for modeling and analyzing of CDEW solution strategies. The statistical model provides the means to analyze and adjust scenarios for possible outcomes of HEL attacks on UAVs. Analysis of dwell times supports the evaluation of CDEW solution concepts and provided the means to assess different types of UAVs independently for the optimal solution. This research was restricted to unclassified data which limited the direct application of the model results. However, future studies can use this team's modeling and analysis framework as a foundation for analysis and implementation of CDEW solutions with true data. The methods researched and outlined here strive to provide the means for the future development DEW of countermeasures on each of the five groups of UAVs, while emphasizing the limitations of this type of weapon and how to exploit it.

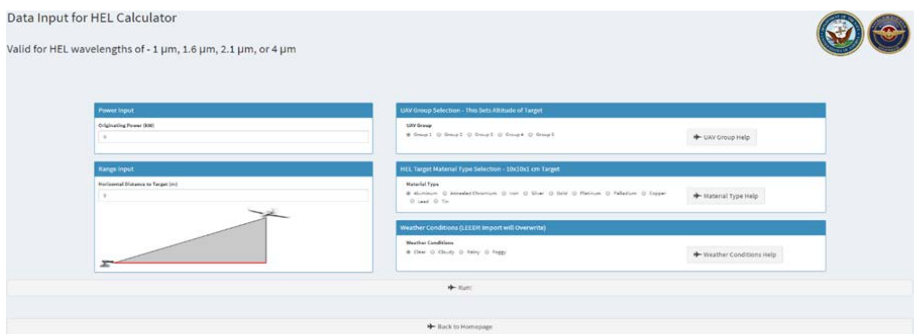
D. FUTURE STUDIES

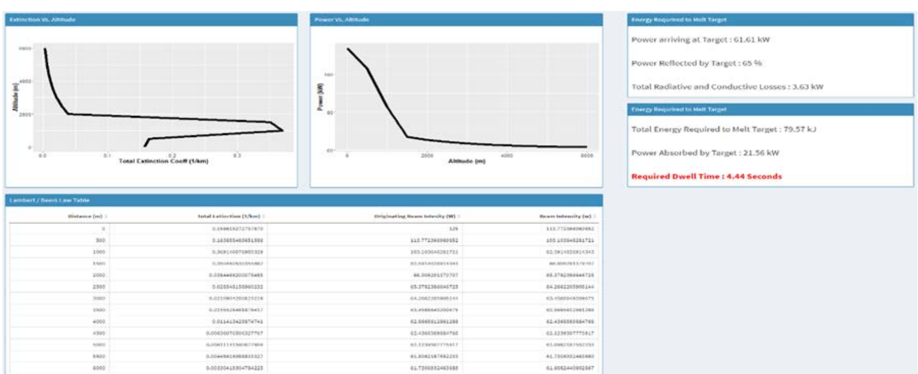
This research provided an overall evaluation of potential HEL threat and aimed to include all potential methods for protecting naval UAVs against HEL threats. The time limitation and broad focus of this study meant that certain aspects could not be concentrated on as strongly. The intent was to be all encompassing within the boundaries created, but there is further work needed to round out this topic. Future work in this area should be conducted at the classified level to include the most in-depth knowledge of adversarial threats and current naval UAV assets. Using this data and applying the modeling framework will assist in verifying a specific solution. Analyzing in this environment would allow for a more detailed model of active and passive countermeasure concepts and operational tactics. Furthermore, focusing on one particular type of UAV or a class of UAVs in a specific mission set will allow the focus to outline the best possible solution. The SWaP requirements are significant when considering additional systems on an aircraft. Depending on the type of UAV, this will vastly change the countermeasure technique; by focusing on one, this ambiguity can be clarified. The model also utilizes Beer-Lambert Law for its calculation. As stated in Chapter VI this is not accurate in all cases. This law assumes that the medium is linear, non-scattering, isotropic, and homogenous (Swinehart 1962). It assumes absorption and scattering are independent events (Gobrecht et al. 2015). Material that disperses the energy of the beam tends not to follow the exponential decrease in energy given by this calculation (McGunnigle, Dong, and Wang 2012). When conditions such as highly scattered material and rough surfaces are involved this does not produce accurate results (Gobrecht et al. 2015). Future work may analyze these conditions and determine an accurate way to account for these scenarios in the model. Future work may also include adding other atmospheric effects such as turbulence, thermal blooming, and diffraction into the calculation for the power lost due to the atmospheric effects. This will greatly increase the validity and accuracy of the model. Taking that a step further, future work could also include the addition of more wavelength options for the model. Only select, low interference, wavelengths appear in the model, in its current form. To be able to model different UAVs against different HEL threats, more wavelengths are required, along with the ensuing data that is specific to that wavelength. Future work could also expand on the model to include live data on the effectiveness of active countermeasures. This would increase the validity of the outcome of an encounter taking into account long dwell time cases. Overall, this study provides a foundation for future analysis of CDEWs integration with naval UAVs, which will enhance these findings.

APPENDIX: MODELING CODE IN “R”









Code:

```
library(shiny)
library(DT)
library(shinydashboard)
library(shinyBS)
library(readxl)
library(shinyjs)
library(leaflet)
library(reshape2)
library(ggplot2)
library(scales)

rm(list=ls())

######Data Import###
#
#
# dat <<- read_excel("DASH.xlsx",
#                  sheet = "TRAINERS")

refdata <<- read_excel("Refdata.xlsx", sheet = "Ref")

####################
## UI ##
####################

update

#Create GUI
ui <- dashboardPage( title = "HEL Propagation Calculator",
                 dashboardHeader(title = "HEL Calc"),
                 dashboardSidebar(disable = TRUE,
                         sidebarMenu( id="tabs",
                                 menuItem("Main View", tabName = "lvl0"),
                                 menuItem("Map View", tabName = "lvl1"),
                                 menuItem("Data View", tabName = "lvl2"),
                                 menuItem("Results View", tabName = "lvl3")

                         ), collapsed = TRUE),

                 dashboardBody( tags$head(tags$link(rel = "shortcut icon", href =
"favicon.ico")),

                        tabItems(
```

```
# Import or Nominal
tabItem(tabName = "lvl0",
      fluidPage( useShinyjs(),
            h1("HEL Propagation Calculator", tags$img(src = "NAVAIR_SEAL (3).png", width =125, height= 125, align = "right"),tags$img(src = "navy.png", width =125, height= 125,  align = "right")),

            br(),br(),br(),br(),br(),br(),

            column(2),column(4, box(title = "Use Nominal Atmospheric Values?", width = 12, height = 230, status = "primary", solidHeader = TRUE, br(), br(), br(), bsButton("main1", label = "Go!", icon = icon("fighter-jet"), size = "large", block = TRUE))),column(4, box(title = "Use LEEDR Import?", width = 12, height = 230,status = "primary", solidHeader = TRUE, fileInput("file1","Choose CSV File", multiple = FALSE, accept = c("text/csv","text/comma-separated-values,text/plain",".csv")), br(), bsButton("main2", label = "Go!", icon = icon("fighter-jet"), size = "large", block = TRUE)))

      )
),




# US Map tab content
tabItem(tabName = "lvl1",
      fluidPage( useShinyjs(),
            h1("Choose Location for Localized Atmospheric Data", tags$img(src = "NAVAIR_SEAL (3).png", width =125, height= 125, align = "right"),tags$img(src = "navy.png", width =125, height= 125,  align = "right")),

            br(),br(),br(),br(),br(),br(),

            box(title = "US MAP", width = 12,status = "primary", solidHeader = TRUE,  leafletOutput("usmap",height = 725)),
            bsButton("main3", label = "Back to Homepage", icon = icon("fighter-jet"), size = "large", block = TRUE)

      )


),
```

```
# Data tab content
tabItem(tabName = "lvl2",
    fluidPage( useShinyjs(),
        h1("Data Input for HEL Calculator", tags$img(src = "NAVAIR_SEAL (3).png", width =125, height= 125, align = "right"),tags$img(src = "navy.png", width =125, height= 125,  align = "right")),
        br(),
        h2("Valid for HEL wavelengths of - 1 \u03BCm, 1.6 \u03BCm, 2.1 \u03BCm, or 4 \u03BCm"),
        br(),br(),br(),br(),br(),br(),

        column(1),column(4, box(title = "Power Input", width = 12,height = 140,status = "primary", solidHeader = TRUE, numericInput("pow", "Originating Power (kW)",0,min=0))),column(6, box(title = "UAV Group Selection - This Sets Altitude of Target", width = 12,height = 140,status = "primary", solidHeader = TRUE, column(8,radioButtons("gro","UAV Group",inline = TRUE, c("Group 1"=1,"Group 2"=2,"Group 3"=3,"Group 4"=4,"Group 5"=5))),  column(4,br(),bsButton("help1", label = "UAV Group Help", icon = icon("fighter-jet"), size = "large")))),
        br(),br(),br(),br(),br(),br(),br(),br(),
        column(1),column(4, box(title = "Range Input", width = 12,height = 360,status = "primary", solidHeader = TRUE, numericInput("dis", "Horizontal Distance to Target (m)",0,min=0), tags$img(src = "tri.png", width =500, height= 166))),column(6, box(title = "HEL Target Material Type Selection - 10x10x1 cm Target", width = 12,height = 200,status = "primary", solidHeader = TRUE, column(8,radioButtons("typ","Material Type",inline = TRUE, c("Aluminum"="Aluminum","Annealed Chromium"="Annealed Chromium","Iron"="Iron","Silver"="Silver","Gold"="Gold","Platinum"="Platinum","Palladium"="Palladium","Copper"="Copper","Lead"="Lead","Tin"="Tin", "Nominal" = "Nominal")), br(), checkboxInput("checks","Use Bragg Mirror Coating?")), column(4,br(),bsButton("help2", label = "Material Type Help", icon = icon("fighter-jet"), size = "large")))),column(6, box(title = "Weather Conditions (LEEDR Import will Overwrite)", width = 12,height = 140,status = "primary", solidHeader = TRUE, column(8,radioButtons("wea","Weather Conditions",inline = TRUE, c("Clear"="Clear","Cloudy"="Cloudy","Foggy"="Foggy"))), column(4,br(),bsButton("help3", label = "Weather Conditions Help", icon = icon("fighter-jet"), size = "large")))),


        bsModal("grohel", h2("UAV Group Help"), "help1", size = "large",tags$img(src = "group.png", width =800, height= 600)),
        bsModal("typhel", h2("Material Type Help"), "help2", size = "large",tags$img(src = "mats.png", width =800, height= 600)),
        bsModal("weahel", h2("Weather Conditions Help"), "help3", size = "large",tags$img(src = "weat.png", width =800, height= 600)),
```

```
bsButton("main5", label = "Run!", icon = icon("fighter-jet"), size = "large", block = TRUE),
br(),br(),br(),
bsButton("main4", label = "Back to Homepage", icon = icon("fighter-jet"), size = "large", block = TRUE)


)
),

# Results page
tabItem(tabName = "lvl3",
fluidPage( useShinyjs(),
h1("HEL Propagation Calculator", tags$img(src = "NAVAIR_SEAL (3).png", width =125, height= 125, align = "right"),tags$img(src = "navy.png", width =125, height= 125,  align = "right")),

br(),br(),br(),br(),br(),br(),

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column(4,box(title = "Energy Requrired to Melt Target", width = 12, status = "primary", solidHeader = TRUE,h3(textOutput("Tarp")),br(),h3(textOutput("Tref")), br(), h3(textOutput("Tlost"))),box(title = "Energy Requrired to Melt Target", width = 12, status = "primary", solidHeader = TRUE,h3(textOutput("Te")),br(),h3(textOutput("Tabs")),br(),h3(div(tags$b(textOutput(" Tdwell"), style = "color: red"))))),


column(8, box(title = "Lambert / Beers Law Table", width = 12, status = "primary", solidHeader = TRUE,DT::dataTableOutput("tbl1"),style="font-size:110%")),
column(4,box(title = "Active Countermeasure - Choosing an Option will Recalculate Kill Chance", width = 12, status = "primary", solidHeader = TRUE,radioButtons("act","Active Countermeasure Choice",inline = TRUE, c("None"="None","Threat Warning / Tactical Maneuvers (30% Success)" = "TW","Swarm Tactics (70% Success)"="Swarm"))), box(title = "Kill / No Kill", width = 12, status = "primary", solidHeader = TRUE, h3(textOutput("infos"), br(),uiOutput("kill"),align = "center"))),
```

```
                                        bsButton("main7", label = "Back to Inputs", icon =
icon("fighter-jet"), size = "large", block = TRUE),
                                        bsButton("main6", label = "Back to Homepage", icon
= icon("fighter-jet"), size = "large", block = TRUE)
                                  )
                            )

                            ### Tab Items ###
                          )
              )
              ### Close UI ###0
)


####################
##SERVER##
####################


#Code behind the GUI
server <- function(input, output, session) {


  ##################################################        LEEDR        Import
##################################################
  site <<- "import"

  getData <- reactive({

    inFile <- input$file1

    if (is.null(input$file1))
      return(NULL)

    read.csv(inFile$datapath, header=TRUE, sep=",")

  })



  ##################################################          US           MAP
##################################################

  output$usmap <- renderLeaflet({
```

```
  leaflet(options = leafletOptions(trackResize = F,scrollWheelZoom =
FALSE,zoomDelta=.1,wheelPxPerZoomLevel = 120, zoomSnap=.1, dragging = F,
doubleClickZoom = FALSE)) %>%
   addTiles( urlTemplate = "/USMAP_Dash/{z}/{x}/{y}.png",options =
providerTileOptions(tms = TRUE, noWrap = TRUE)) %>%
    setView(lng = -17, lat = -8, zoom = 2.6) %>%

   addMarkers(lat =-8, lng = 113, layerId = "e") %>%
   addMarkers(lat = -40, lng = 90, layerId = "se") %>%
   addMarkers(lat = -20, lng = -159, layerId = "sw")

 })

  observeEvent(input$usmap_marker_click, {

    #if (input$usmap_marker_click$id == "e") {updateTabItems(session, "tabs", "lvl1")},
    if (input$usmap_marker_click$id == "se") {leafletProxy("usmap") %>%
                                  flyTo(lat=-32,lng=85,zoom=4)
                                  delay(800,updateTabItems(session, "tabs", "lvl2"))}
    #if (input$usmap_marker_click$id == "sw"){updateTabItems(session, "tabs", "lvl1")},
    site <<- input$usmap_marker_click$id
  })


 ##################################################### Results
#################################################

  ## Data Valadation##

  observeEvent(input$main5, {
  if(input$pow <= 0 |input$dis <= 0){showModal(modalDialog(title = "Data Validation",
div(tags$b("Please enter a value greater than 0 for Power and Range", style = "color: red")),
easyClose = TRUE))}

    else {
     updateTabItems(session, "tabs", "lvl3")

     powe <<- input$pow
     distance <<- input$dis
     mats <<- input$typ

    ## Get Altitude ##
     if (input$gro == 1) {alt <<- 500}
     if (input$gro == 2) {alt <<- 1500}
     if (input$gro == 3) {alt <<- 6000}
```

```
 if (input$gro == 4) {alt <<- 6000}
 if (input$gro == 5) {alt <<- 10000}
## Calc Distance to target ##
 z <- alt^2 + distance^2
 z <- sqrt(z)
 angles <- asin(alt/z)


## Get LEEDR or Nominal Weather Data ##
 if(input$wea == "Clear") {jaxdata <<- read_excel("Refdata.xlsx", sheet = "Jax")} else
{jaxdata <<- read_excel("Refdata.xlsx", sheet = "Jaxcloudy")}
 if (site == "se") {weatdata <- jaxdata[,c(1,3,7)]}
 if (site == "import") {weatdata <- leedr[,c(1,3,7)]
          names(weatdata)<- c("Distance (m)","Aerosol Extinction
(1/km)","Molecular Extinction (1/km)")}
 weatdata$"Total Extinction (1/km)" <-weatdata$`Aerosol Extinction (1/km)` +
weatdata$`Molecular Extinction (1/km)`
 weatdata <- weatdata[,c(1,4)]
 names(weatdata) <- c("Distance (m)","Total Extinction (1/km)")

 data <- weatdata
 data$"Originating Beam Intesity (W)" <- 0
 data$"Beam Intensity (w)" <- 0

 data[1,3:4] = powe
 data[2,3] = data [1,4]

 if (input$gro == 1) {data <- data[1:2,]}
 if (input$gro == 2) {data <- data[1:4,]}
 if (input$gro == 3) {data <- data[1:13,]}
 if (input$gro == 4) {data <- data[1:13,]}
 if (input$gro == 5) {data <- data}


## Itterate every 500ft and calc power loss ##
 steps <- (500/sin(angles))/1000

 for (row in 1:nrow(data)){
   data[row,4] = data[row,3] * exp((-data[row,2])*steps)
   data[row+1,3] = data[row,4]
 }

 dataa <<- data[-nrow(data),]

 x<-dataa[nrow(dataa),ncol(dataa)]
```

```
#x<<-x$`Beam Intensity (w)`


## Power charts ##
output$plot1 <- renderPlot({
  ggplot(dataa) + geom_path(aes(x=dataa$`Total Extinction (1/km)`,y=dataa$`Distance (m)`), size = 2)+ theme(axis.text.x=element_text(size=14), axis.text.y=element_text(size=14),
axis.title=element_text(size=16,face="bold",vjust=35)) + labs(x= "Total Extinction Coeff (1/km)", y= "Altitude (m)")
})
output$plot2 <- renderPlot({
  ggplot(dataa) + geom_path(aes(y=dataa$`Beam Intensity (w)`,x=dataa$`Distance (m)`), size = 2)+ theme(axis.text.x=element_text(size=14), axis.text.y=element_text(size=14),
axis.title=element_text(size=16,face="bold",vjust=35)) + labs(x= "Altitude (m)", y= "Power (kW)")
})
output$tbl1 <- DT::renderDataTable({
  DT::datatable(dataa[,],rowname = FALSE,selection = 'single', options = list(dom = 't', pageLength = 25, lengthChange = FALSE), class = 'cell-border strip hover')
})



## Energy to Melt ##

sbc <- 5.670374419 *10^-8
t0 <- 300
mass <- .1

matdata <- refdata[refdata$Material == mats,]

Q1 <- matdata$Cp * mass * ((matdata$Tmelt-273.15)-(t0-273.15))
Q2 <- mass * matdata$H
QT <- (Q1+Q2)/1000

Pr <- matdata$e * sbc * (pi*.1^2) * (matdata$Tmelt^4-t0^4)
Pc <- (matdata$k * ((2*pi*.01*.005)+(pi*.01^2))*(matdata$Tmelt-t0))/.05
Pt <- (Pr+Pc)/1000

if(input$checks == TRUE){refects <- .99}else{refects <- matdata$Reflectivity}
Pab <- x*(1-refects)

if(Pab-Pt>0){dwell <- QT/(Pab-Pt)} else {dwell <- 0}
```

```
output$Tarp <- renderText({paste(" Power arriving at Target : ", round(x,2) , " kW")})
output$Te <- renderText({paste(" Total Energy Required to Melt Target : ",
round(QT,2) , " kJ")})
output$Tlost <- renderText({paste(" Total Radiative and Conductive Losses : ",
round(Pt,2) , " kW")})
output$Tref <- renderText({paste(" Power Reflected by Target : ", refects*100 , "
%")})
output$Tabs <- renderText({paste(" Power Absorbed by Target : ", round(Pab,2) , "
kW")})
output$Tdwell <- renderText({paste(" Required Dwell Time : ", if(dwell == 0){"Not
enough Power to Melt"}else{paste(round(dwell,2), " Seconds")})})

if(dwell == 0) {timer <<- 6 }else{timer <<- dwell}



observeEvent(input$act, {
  if (input$act == "None"){
    output$kill <- renderUI({
      if(timer <= 5) {tys <<-1
      tags$img(src = "kill.png", height=200, width = 200, align = "center")}
      else {tys <<-2
      tags$img(src = "safe.png", height=200, width = 200, align = "center")}
    })
  }

  if (input$act == "TW"){
    output$kill <- renderUI({
      rn <- round(runif(1,min=0,max=100),0)
      print(rn)
      if(timer <= 5 & rn <= 70) {tys <<- 3
      tags$img(src = "kill.png", height=200, width = 200, align = "center")}
      else {tys <<- 4
      tags$img(src = "safe.png", height=200, width = 200, align = "center")}
    })
  }

  if (input$act == "Swarm"){
    output$kill <- renderUI({
      rn <- round(runif(1,min=0,max=100),0)
      print(rn)
      if(timer <= 5 & rn <= 30) {tys <<-5
      tags$img(src = "kill.png", height=200, width = 200, align = "center")}
      else {tys <<- 6
```

```
        tags$img(src = "safe.png", height=200, width = 200, align = "center")}
       })
      }

      output$infos <- renderText({
            if(tys == 1) {paste(" Target Killed Due to Dwell Time and No
Countermeasures Used")}
            else if (tys ==2) {paste(" Target Safe Due to Long Dwell Time")}
            else if (tys ==3) {paste(" Target Killed Due to Dwell Time and Failed
Maneuvers")}
            else if (tys ==4) {paste(" Target Safe Due to Successful Maneuvers")}
            else if (tys ==5) {paste(" Target Killed Due to Dwell Time and Failed
Swarm")}
            else if (tys ==6) {paste(" Target Safe Due to Swarm")}
            else (paste("Please Select a Countermeasure"))

            })

     })

  }
  })


  ################################################## Lvl 1 - Base Map
##################################################

 ### Begining Choice ###
  observeEvent(input$main1, {updateTabItems(session, "tabs", "lvl1")})
  observeEvent(input$main2, {leedr<<-getData()
                   site<<-"import"
                   updateTabItems(session, "tabs", "lvl2")})
  observeEvent(input$main3, {updateTabItems(session, "tabs", "lvl0")})
  observeEvent(input$main4, {updateTabItems(session, "tabs", "lvl0")})
  observeEvent(input$main6, {updateTabItems(session, "tabs", "lvl0")})
```

```
  observeEvent(input$main7, {updateTabItems(session, "tabs", "lvl2")})



 ######### close server #########

 session$onSessionEnded(stopApp)

}


####################
## SHINYAPP##
####################
```

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