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Capability Assessment of the High-Energy Laser Liquid Area Defense System (HELLADS)

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High-energy Laser (HEL) technology continues to improve, and its planned place in the battlefield is ever evolving. The Defense Advance Research Projects Agency (DARPA)–envisioned HEL Liquid Laser Area Defense System (HELLADS) has two main advantages over any HEL predecessor. One, the configuration is small and light enough to be carried on more tactical aircraft such as fighters. Two, the thermal management greatly increases HEL firepower by increasing dwell time on target. To assess HELLADS operational capabilities, the test community has been challenged with how to effectively examine the advantages and limitations in a cost-effective manner. Where field testing is infeasible, modeling and simulation emerges as a relatively low-cost and robust assessment tool. Specifically, this research effort focuses on the assessment of operational capabilities for a yet-to-be-developed HEL weapon system patterned after HELLADS. An Air Force Standard Analysis Toolkit mission-level model, the Extended Air Defense Simulation Model (EADSIM), is used in this study along with the HEL End-to-End Operational Simulation (HELEEOS) to model atmospheric propagation. Of particular interest is the investigation of the envisioned HELLADS operational envelope and the potential advantages it offers over other HEL systems. Scenarios are developed to represent the homeland defense arena in which HELLADS is envisioned to operate.

KEYWORDS: Computer simulation, High-energy laser, Liquid laser, Mission-level combat modeling

Nomenclature

B	brightness, W sr^{-1}
c	target material specific heat capacity, J kg^{-1} K^{-1}
D	diameter of transmitting aperture, m
d	target material thickness, m
E_0	flux density, J m^{-2}
j	jitter (root mean square as a percent of λ/D)

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P	laser power, W
T_m	target material melting temperature, K
T_v	target material vaporization temperature, K
T_0	ambient temperature, K
ΔH_m	target material latent heat of fusion, J kg^{-1}
ΔH_v	target material latent heat of vaporization, J kg^{-1}
λ	laser wavelength, m
ρ	target material density, kg m^{-2}
τ	transmission (fraction of power transmitted over a given optical path), %
ω	wave front error (root mean square as percent of λ)

1. Introduction

Since the High Energy Laser Executive Review Panel (HELERP) released its Laser Master Plan for the Department of Defense (DoD) in March 2000, an increased level of laser research and testing has been conducted in an effort to make high-energy laser (HEL) weapon systems available to the warfighter. The HELERP recognized the importance of HEL technology in meeting challenging, offensive and defensive, weapon applications. To enhance HEL combat realization, the HELERP called for appropriate funding, new HEL technological management structures, support of an industrial base through program initiatives for new technologies and essential skills, and fostering cooperation with other agencies.[5]

History shows that revolutionary technological growth is rarely linear. For example, consider the drawn-out maturation of precision strike weapons, which were prototyped 35 years before they were operationally effective. According to a study documented in the *Air and Space Power Journal*,[10] HEL technology, now estimated at its 30-year point, seems to be on the cusp of a growth surge. In Fig. 1 time is graphed versus a relative importance attribute, which doubles every 4 years.

Part of this current trend in more rapid growth for HEL technology is the concept of using liquid lasers in place of chemical or solid-state lasers. Managing the enormous amount of thermal energy produced by solid-state lasers requires a significant cooling system. For example, the current chemical oxygen–iodine laser (COIL) technology used in the airborne laser (ABL) requires the Boeing 747 as a platform. This immense heat generation also limits firing time and increases downtime for cooling. By using a liquid exhibiting the same index of refraction as the gain media, a laser can potentially simultaneously fire and keep cool. This new technology greatly decreases the amount of space needed for HEL weapon systems, and thus smaller platforms will be able to take advantage of HEL capabilities.[18] The HEL Liquid Laser Area Defense System (HELLADS) is the foremost program currently testing liquid laser technology.

HELLADS hopes to be capable of delivering 150 kW of power with a weight goal of 5 kg/kW (Ref. 8). This puts HELLADS at approximately 750 kg, or 1,650 lb, an order of magnitude less than current laser weapon systems with similar power. This weight reduction enables tactical aircraft, such as fighters, bomber, tankers, and unmanned aerial vehicles (UAVs), to carry HELLADS.[7] This completely changes the way HEL can be utilized in the battlefield.

For the purposes of our study, we model an objective laser weapon system based on HELLADS design goals, realizing that laser development and aero-optic mitigation are far

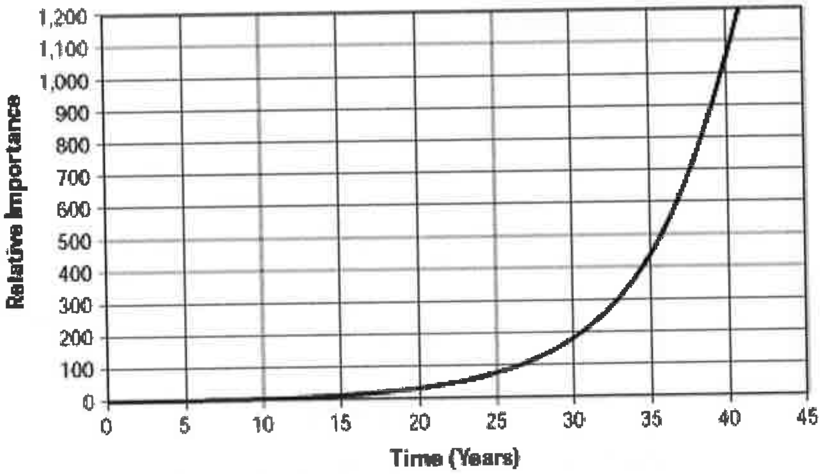

Fig. 1. Typical growth of developing technologies.[10]

from meeting our performance assumptions. This study focuses instead on demonstrating a simulation approach to effectively assess the operational capabilities of such a HEL weapon system. We obtain laser propagation inputs from the HEL End-to-End Operational Simulation (HEELEOS) model created by the Air Force Institute of Technology's (AFIT) Center for Directed Energy. HEELEOS derives a practical degree of fidelity in estimating laser energy delivery given three main areas of user inputs[3]: laser inputs such as wavelengths, beam power, beam quality, jitter, and exit aperture diameter; platform and target inputs such as speed, altitude, and relative spatial and geometric relationships; and environmental inputs such as atmosphere and aerosol types. The Extended Air Defense Simulation Model (EADSIM) uses the data provided by HELEEOS in appropriate scenarios to assess HELLADS air-to-air defensive capability against cruise missiles. Outputs are examined using analysis of variance (ANOVA) to identify driving operational factors, and linear regression techniques are used to build a predictive model. This work is an extension of previous research done at AFIT in the area of mission-level simulation of HEL weapons.[2,4]

The results of this study provide an initial look at the HELLADS operational envelope and are applicable to follow-on or further study of HELLADS operational effectiveness. The results may be used to adjust the proposed operational scenarios in which HELLADS can be used and also may be used in test planning procedures. Future developmental or operational testing results should be compared to the results and conclusion of this study. Any disparities in results should be investigated to improve the model for use in future studies.

In the remainder of this paper we first present some background on combat modeling and HEL modeling in particular with a focus on HEELEOS and EADSIM. Then we briefly discuss some previous research in the simulation of HEL weapons before detailing our study methodology, results, and conclusions.

2. Combat Modeling

Operations research is a lever to support decisions, and a combat model aspires to aid this process by achieving a realistic representation of the operations as they pertain to the

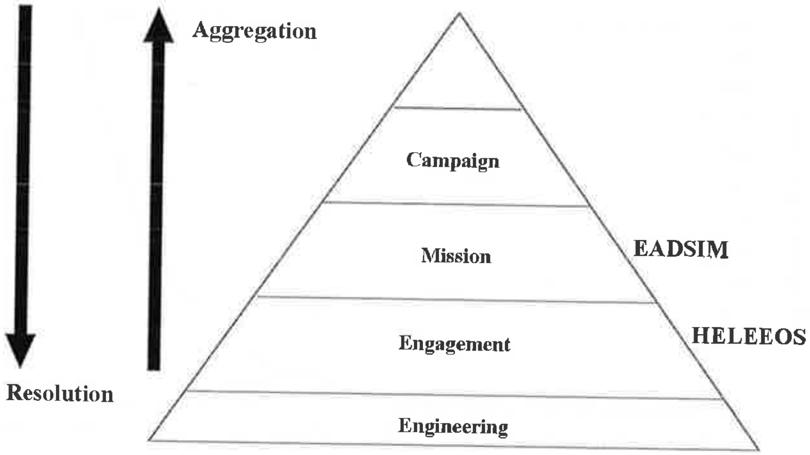

Fig. 2. DoD modeling and simulation pyramid.

specific agendas under investigation.[9] Although no two combat simulations will be exactly alike, the general type of scenario they are built to model can be stratified into different levels. Naturally, models used to assess the damage done by a single attack or the nature of a one-on-one scenario require a higher fidelity of interactions than do models simulating a campaign or mission–level battle. To this end, combat models are classified into a hierarchy based on their degree of resolution. Figure 2 shows the model hierarchy used by the DoD and where HEELEOS and EASDIM fall.

Aggregation increases as you go up the pyramid, and resolution, or fidelity, increases as you go down the pyramid. At the bottom, engineering level, physical phenomena are modeled via mathematical and physical sciences, such as the effects of gravity, atmosphere, propagation, and laser power delivery. Farther up the pyramid the levels use the engineering conclusions as the basis to perform one-on-one, one-on-few, and few-on-few to simultaneously model engagements or missions. These models also employ other attributes, such as command and control characteristics, to realistically simulate the types of engagements being investigated.

The goal of simulating HEL is to supplement live tests by gauging how laser effects and target responses change via assessing target interactions in operationally relevant engagement environments.[1] Techniques traditionally used for simulating conventional kinetic weapon systems such as missiles and bombs cannot be used to simulate laser weapon systems. Physical effects, such as gravity and drag, that drive kinetic weapon system simulations do not apply to the natural physics that affect laser energy. Whereas kinetic weapons need to be dropped, fired, or launched and given a time window to fly, lasers arrive at the aim point instantaneously with high precision. However, laser weapons must also remain fixed, or dwell, on a precise aim point over some finite period of time to deposit enough energy on the target for the desired effect.

Models simulating laser effects take into consideration environmental effects that most directly influence delivery of laser energy to a target. The most significant are thermal blooming, molecular and aerosol absorption/scattering, and turbulence.[20,22] Thermal blooming, or defocusing, is a nonlinear thermal distortion caused by the interaction of laser radiation and the heating of the propagation path by radiation absorption. A laser beam increases the temperature of the air, resulting in decreased density, and refractive index, of the local air. This distortion causes defocusing of the beam wave front known as thermal blooming. In addition to thermal blooming, water vapor and other molecules between the laser source and its intended target scatter and absorb laser energy, significantly decreasing the power. Thermal fluctuations in the air, dependent on the changes caused by laser energy, also affect laser propagation. Different air temperatures possess different refractive indexes; thus thermal changes can cause the laser beam to spread and wander. Beam characteristics such as wavelength and power can be adjusted to minimize adverse effects caused by thermal blooming, scattering, absorption, and turbulence. Certain wavelength and power combinations function better for given atmospheric conditions, maximizing the laser energy delivered to the target. Target characteristics and the intended effect on the target are also taken into account when choosing laser beam wavelength and power. Long et al.[12] demonstrated the benefit of intentionally focusing a laser beam beyond the target in air-to-ground scenarios to improve peak irradiance on the target through a reduction in thermal blooming. Adaptive optics have proven to lessen the degrading effects of turbulence.[20]

HEELEOS obtains input from the user to include beam wavelength, power, slant ranges, platform and target characteristics, and atmospheric conditions to estimate laser power delivery to the target. For our study HEELEOS output is in the form of power propagation tables (formatted for use in EADSIM), with peak irradiance at the target as a function of slant range, altitude, and other selected weapon platform and target characteristics. EADSIM is a mission-level simulation used by combat developers, materiel developers, and operational commanders to assess the effectiveness of theater missile defense and air defense systems against the full spectrum of extended air defense threats. The simulation incorporates many factors to simulate air-to-air engagements, including multitier engagements, theater ballistic missiles in all phases, passive defense, infrared signatures, and radar signatures, to formulate the probability of kills for given scenarios. Previous HEL studies using EADSIM have used instantaneous flight time missiles in lieu of explicitly modeling laser energy propagation and delivery to the target. However, recent versions of EADSIM have the ability to model actual laser weaponry characteristics as briefly discussed below.[6]

EADSIM Version 13 used in this study incorporates a laser rule set, capable of simulating directed energy weapons (DEW) on air, space, and ground platforms against various target types. The entire engagement timeline for DEW is modeled and includes simulation of laser slewing, laser warming, power propagation losses, and target destruction. Targets are engaged via user inputs for threat prioritization logic, such as ballistic boost phases and defense of preset laser protection zones.

The engagement process is represented via the battle management phases, which consist of target selection, through threat assessment and laser-to-target assignment procedures, and launch/lase phases, which represent HEL delivery once the decision to engage has been reached. Figure 3 illustrates this engagement process.

3. Previous HEL Simulation Research

Capt. Maurice Azar[2] constructed a scenario using a single advanced tactical laser (ATL) platform engaging multiple cruise missile targets to evaluate the capabilities of EADSIM to model the combat effectiveness of a HEL system and to identify data requirements and sensitivity of simulation results to variations in model input parameters. His study modeled

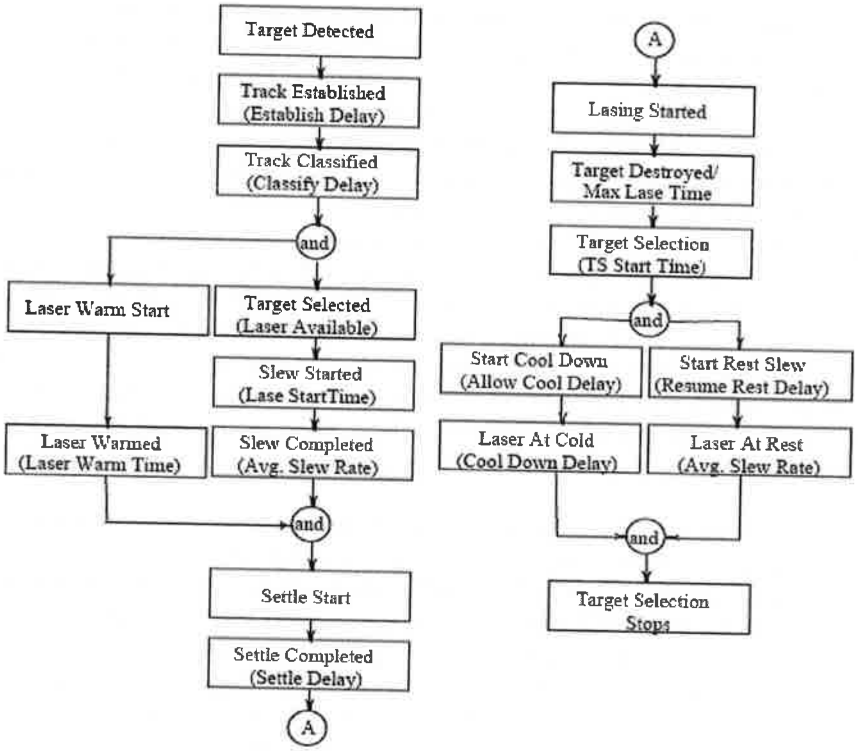

Fig. 3. Laser engagement timeline.[6]

beam propagation indexed by target range using the brightness equation, a first-order approximation of propagation. The result is a magnitude of intensity propagated through an atmosphere under specific conditions. Based on Tyson's definition,[21]

$$B \approx \left\{ \frac{\pi D^2 P}{4\lambda^2} \right\} \left\{ e^{-\left(\frac{2\pi\omega}{\lambda}\right)^2} \right\} \left\{ \frac{1}{1 + \frac{\pi^2}{2}\left(\frac{j}{\lambda/D}\right)^2} \right\} \tau. \tag{1}$$

For Capt. Azar's study, two propagation tables using Eq. (1) were generated based on jitter: the first to represent the case of no jitter with a mild wave front error of 0.2 times the wavelength and the second using a factor for jitter of $2.205 * \lambda$ to describe conditions of vibration and other motion on the laser platform that would cause the expected incident laser beam spot size to be five times larger than in the case with no jitter.

Capt. Mike Cook[4] undertook an effort paralleling Capt. Azar's but with two major differences. As opposed to using the brightness equation, power propagation tables were constructed using HELEEOS, and in this effort ATL effectiveness against ground, as opposed to air, targets was assessed.[4] Using power propagation input from HELEEOS is actually preferred over using a brightness equation as HEELEOS explicitly accounts for thermal blooming and jitter. Capt. Cook compared irradiance levels, at different slant ranges, calculated by the brightness equation and HELEEOS. Irradiance calculated by HELEEOS was found to be much less, due to thermal blooming, than the irradiance calculated by the brightness equation (Fig. 4).

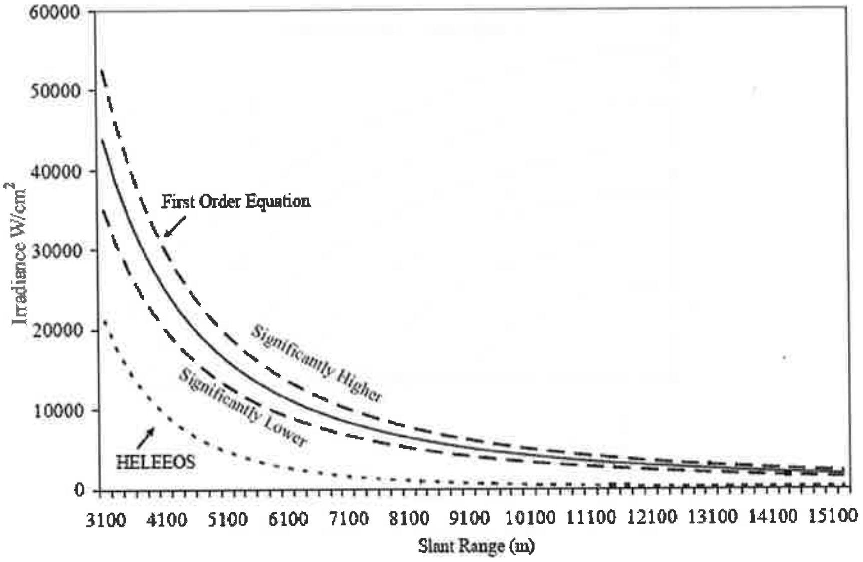

Fig. 4. Power comparison with thermal blooming.[4]

Capt. Cook[4] also noted the brightness equation's inability to properly represent degradation of HEL effectiveness due to jitter. Turbulence-induced jitter and vibration-induced jitter adversely affect HEL's ability to hit a target.[11] As Fig. 5 shows, depending on beam quality and wave front error, jitter plays a significant role in hitting a target. This graph shows the allowable amount of jitter. If these thresholds are exceeded, a HEL's ability to place an effective amount of energy on a target greatly decreases.

Perfect beam quality is one, and higher numbers denote decreased beam quality. HELEEOS reflects the degradation on the ability to accurately hit a target when jitter values of greater than 5 μrad are input into a model simulating a solid-state laser, which is typically given a beam quality of two. As can be seen in Fig. 5, lower beam quality and greater wave front error decrease the allowable jitter. Like Capt. Azar's research, this study also gives insights into the importance of single factors as they apply to affecting a HEL's ability to destroy targets but also on how they affect average dwell time. These factors included power level, vulnerability level, target selection priority, weapon altitude, propagation, and weapon velocity.

4. Methodology

EADSIM offers four ways in which to specify probability of kill (P_k) for HEL weapons. Because HELEEOS outputs values as intensity or irradiance, the EADSIM intensity methodology for computing target lethality is used in our study. HELEEOS provides irradiance values as a function of altitude and slant range in the form of power propagation tables. Applicable inputs in HELEEOS are selected to generate applicable irradiance values for EADSIM to utilize.

HELEEOS offers different site locations, representing true atmospheric conditions, which can be utilized by the user. These locations represent the typical atmospheric

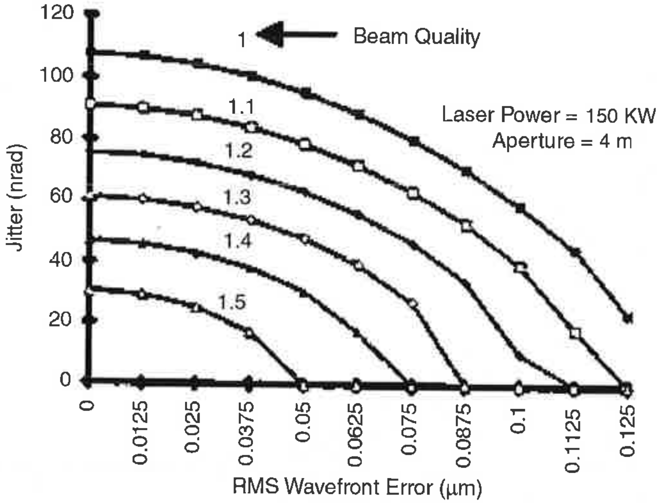

Fig. 5. Allowable jitter, 150-kW system.[16]

conditions such as temperature, pressure, water vapor content, and optical turbulence as they relate to laser beam power loss, otherwise known as layer extinction. For the purpose of this study coastal areas are chosen to mirror HELLADS CONOPS.

HEL weaponry exhibits unique operational advantages over kinetic weaponry; however, it does not come without a caveat that is often not fully accounted for when HEL assessments are conducted. In addition to atmospheric conditions previously mentioned, we need to assume that the laser beam can reach the target. This condition is designated as cloud-free line of sight (CFLOS) in HELEEOS. Lasers are not capable of going through clouds; thus all assessments, although they may reflect different atmospheric and aerosol environments, are conducted under the assumption that the laser reaches the target, with some degree of degradation caused by these environments. Therefore it is important for the reader to understand that this assessment is applicable only when CFLOS exists. HELEEOS offers a worldwide probability of CFLOS.

In general CFLOS probability is highest when the platform and target are at the same altitude. This probability decreases as the platform and target altitude difference increases, due to the fact that more vertical space corresponds to a higher chance of cloud interference. For our scenario settings the highest CFLOS probability, 50%, occurs when the platform is at 3,000 m and the target altitude is 1,500 m. This probability decreases as the vertical distance of the platform to the target increases, with the lowest value occurring when the platform and target are at 10,000 and 500 m, respectively.

Although relatively close altitudes increase CFLOS, they are not necessarily conducive to higher peak irradiance values. Angle plays a large role in peak irradiance, and more oblique angles, occurring when the platform and target altitude are relatively close, result in lower peak irradiance values. For this reason it is advantageous for the platform to be in a position high enough above the target to mitigate peak irradiance degradation caused by oblique angles.

In a maritime environment, laser beam degradation from aerosols can also be significant. Aerosol volume decreases as altitude increases, and in general aerosols will have a negligible

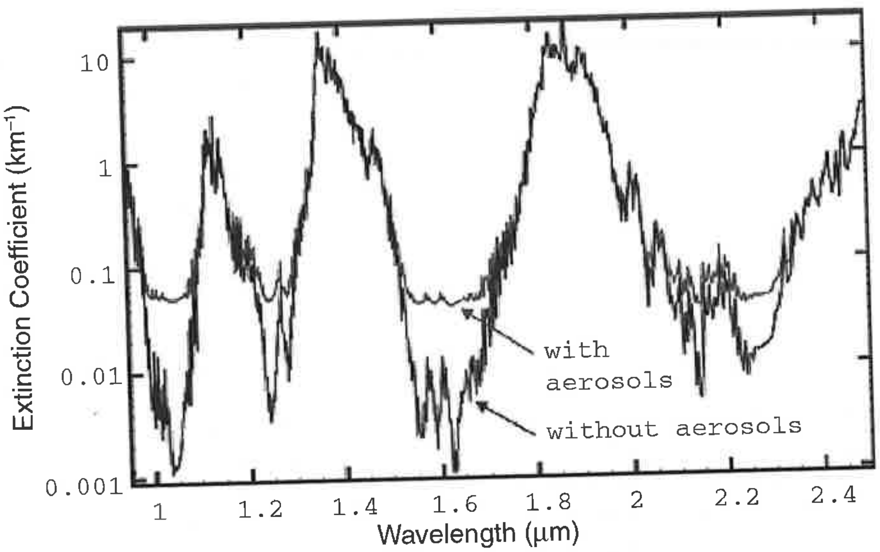

Fig. 6. Extinction coefficient vs wavelength.[20]

effect on laser engagements occurring above the boundary layer (approximately 500 m). However, laser effectiveness degrades for engagements occurring below this threshold. The volume of aerosols that adversely affects the laser beam depends on where, geographically, and on when, seasonally, the engagement is taking place. For obvious reasons, ocean areas tend to have more aerosols, in the form of water vapor and salt, than land areas under this boundary layer. In general summer will have more aerosols than winter; however, because this particular study occurs over the ocean, the differences between summer and winter are too subtle to have a significant impact on the peak irradiance.

This study investigates HELLADS capabilities for homeland defense in a maritime environment and considers performance on the upper edge of, and above, this boundary layer. Regarding HEL effectiveness, this type of scenario is potentially very degrading. However, the degradation caused by aerosols depends on beam wavelengths, with specific wavelengths mitigating these effects. Figure 6 shows the extinction coefficient, i.e., the sum of scattering and absorption, as a function of wavelength. Figure 6 was generated by data representative of a midlatitude maritime, summer environment with 50 km of visibility, which closely resembles the scenario used in this study. The graph shows troughs at wavelengths around 1, 1.6, and 2.2 μm, signifying their superiority in maritime environments, regarding extinction due to aerosols.

In terms of atmospheric turbulence modeled for this study, we use the Hufnagel Valley 5/7 profile setting for HEELEOS. Table 1 lists all the HEELEOS input settings used in modeling beam propagation for our study. Initial settings, including distance from platform, relative azimuth to next object, and distance from last object, are also available to tweak engagement orientation. Given the 1.07-μm wavelength (very close to the first trough in Fig. 6) used in this study, there is little absorption and likewise little thermal blooming. Geometry affects thermal blooming, but because there is very little thermal blooming associated with this wavelength, geometry is not a significant factor in calculating irradiance for these settings.

Our study uses a baseline scenario with HEELEOS parameters shown in Table 1. Parameters with more than one value under the "Setting" column, are important factors we

Table 1. HELEEOS input settings

Parameter	Initial setting
Scaling law	Share
Aero-optic model	Conformal aperture
Aerosol type	Advanced Navy aerosol
Turbulence profiler	HV 5/7
Atmosphere type	Ocean summer: Lat 38, Lon −74
Turbulence multiplier	1 (default)
Wind model	Expert
Wind percentile	50% (average)
Wind direction	90 (east)
Platform altitude, m	3,000, 6,500, 10,000
Platform velocity heading	0 (north)
Platform initial distance from platform	—
Platform horizontal velocity, m/s	200, 250, 300
Platform acceleration heading	—
Platform initial relative azimuth to next object	315 (NW)
Target altitude, m	500, 1,000, 1,500
Target velocity heading	270 (west)
Target distance from last object, m	25,000
Target horizontal velocity, m/s	200
Target vertical velocity, m/s	0
Target acceleration heading	N/A
Target vertical acceleration	N/A
Target horizontal acceleration	N/A
Engagement dwell time	N/A
Number of steps in	N/A
Susceptible target width	N/A
Susceptible target length	N/A
Target damage threshold	N/A
Laser wavelength, μm	1.07
Relative obscuration	0.1 (Default)
Beam quality	1.3
Wave front error	0
Total system RMS jitter	0
Laser type	Continuous wave
Laser propagation model	Top hat
Adaptive optics	Med (No AO, average tracking system)
Exit aperture diameter, m	0.3
Magazine depth	N/A

identified to vary in exploring the HELLADS operational envelope. The parameter settings selected offer a glimpse at how different factors impact HELLADS overall effectiveness in different situations. Factor levels are chosen to represent realistic scenarios for this type of engagement, as discussed in the following section. Design of experiments (DOE) is implemented to answer several important questions regarding input factors and response variables (for our study also referred to as measures of effectiveness, MOE). The purpose of a DOE is to accurately estimate which input factors, or combination of factors, have the most effect, or desirable effect, on a response variable under examination. Once the most influential input factors have been discovered, achievement of the desired response can be investigated by changing the settings of these input factors.[14]

After using DOE to set up the simulation experiments and conducting the runs, an ANOVA is often used to calculate which factors, and/or factor interactions are significant. A significant factor, or factor interaction, is one whose variability is a large proportion of the overall variability. In other words, variability is calculated for each factor and appropriate factor interactions and compared to the overall variability of the experiment. Those factors with relatively large variability would be considered statistically significant influencers on the response variable.

In addition to ANOVA, linear regression can be used to formulate a prediction equation. Linear regression estimates regression coefficients for each significant factor or factor interactions and incorporates them into a function of the response variable. A regression coefficient can be thought of as a weight designation for each significant factor. If the factor decreases the response variable, it will be given a minus notation in the prediction equation; likewise it will be given a positive notation if it has a positive effect on the response variable. Also, the amount of significance a factor has on the response variable will be reflected in the regression coefficient pertaining to that particular coefficient. For example, a more significant factor will be given a regression coefficient with a higher value. By using regression coefficients to represent the expected change in the response variable per unit change in each of the significant factors when all other factors are held constant, linear regression provides a function possible for predicting the response for a given set of significant factor inputs (Ref. 14, p. 67).

5. Scenario Details and Study Factors

The scenario considers a situation in which cruise missiles targeted at a coastal airbase are detected off the coast and a fighter is scrambled to intercept them before they reach the coastline. We initiate the scenario when the first cruise missile is roughly 322 km off the coast line, with the fighter flying directly at the group of cruise missiles. Laser engagement begins when the fighter is approximately 90 km directly in front of the first cruise missile. This scenario allows the fighter to begin lasing on the incoming cruise missiles while flying head-on with them. When the fighter passes the group of targets, it turns 180 deg and follows the cruise missiles, at which time the cruise missiles turn in an attempt to evade the chasing fighter (simple to implement in EADSIM to mimic terrain following movements by the cruise missiles). The fighter reacts to the evasion maneuver by mimicking the evasion pattern of the cruise missiles and continues to engage them. The total simulated scenario time is 1,000 s, and the salvo of nine cruise missiles comes in three groups of three, with each group starting at a different time (0, 100, and 180 s after scenario start time) from approximately the same location.

Fighters can effectively operate at a wide range of altitudes; however, for this particular study, considering the intended targets' typical altitude, flight levels range from 3,000, 6,500, and 10,000 m with a set altitude within each design point. Higher altitudes, although they increase slant ranges, offer more-acute angles, which result in higher peak irradiance values and also allow the HELLADS weapon a larger area of coverage. Platform velocity ranges from 200, 250, and 300 m/s. Weapon configuration also plays a role, albeit indirect, in peak irradiance. A HEL delivered by a slewing turret potentially has the advantage of engaging targets in a 360-deg field of view. For this study a pod, or conformal aperture, is used to resemble the proposed HELLADS configuration. This configuration's shortcoming is the degrading effect airflow has on the laser beam when shooting with the wind, which arises anytime lasing occurs in a direction greater than ±90 deg from the trajectory of the platform. When firing into the wind, the optical aberration expected looking forward into the flow is primarily focus, which we assume can be corrected (we do not explicitly account for aero-optic effects). Employing a conformal aperture for laser beam delivery does limit HELLADS engagement, namely with regard to line of sight (LOS). For this reason the target must be in the conformal aperture LOS before it can be engaged. However, the agility of the fighter platform should compensate for this configuration's LOS restrictions. In addition, a slewing capability is incorporated for the pod with settings of ±30 and ±60 deg.

Targets in this study consist of cruise missiles, which are typically low flying, and applicable altitudes of 500, 1,000, and 1,500 m with a velocity of 200 m/s were chosen. The ability for a laser to burn through (or otherwise destroy) a target depends on laser characteristics such as power density, peak power, irradiation wavelength, and pulse features, as well as on target characteristics, such as material density and heat capacity.[13]

According to some experts, there are four main ways to kill a target via HEL.[19] These include causing the target to explode by sufficient heating; damaging the structure causing the target to deflect, abort, or disintegrate; damaging the guidance systems, causing diversion; and damaging the sensor systems. Applicable settings for these factors are input into HELEEOS to calculate irradiance values, which are then applied by EADSIM to calculate absorption, power reflection, heat conduction, and heat diffusion, which ultimately decide when the target is defeated. EADSIM offers three different aim points for a cruise missile: nose, fuselage, and wing. In this study it is assumed that burn through at any of these aim points will cause failure and result in a kill. A material damage study conducted at the Naval Postgraduate School (NPS) in 2000 investigated the amount of energy required to burn through a generic cruise missile. It used the following equation, along with physical characteristics of aluminum, to calculate laser intensity required to bring aluminum to vaporization temperature:

$$E_0 = \rho d(c[T_m - T_o] + \Delta H_m + c[T_v - T_m] + \Delta H_v), \qquad (2)$$

where E_0 is the required flux density, ρ is the density, d is the material thickness, c is the specific heat, T_m is the melting temperature, T_o is the ambient temperature, T_v is the vaporization temperature, ΔH_m is the latent heat of melting, and ΔH_v is the latent heat of vaporization.[13] Table 2 shows specific values for these variables used in the NPS study.

Using 3 cm for d and an ambient temperature of 25°C, Eq. (2) yields a flux density of 113,234 J/cm^2 and is accurate if the material being targeted absorbs all the energy deposited by a laser; however, this is an unreasonable assumption. Different materials have different absorption rates. The NPS study used a 50% absorption rate for aluminum, resulting in a flux density of 226,468 J/cm^2 needed to vaporize the target. To mirror units used in EADSIM

Table 2. Aluminum properties

Property	Value
ρ (kg/m^3)	2,700
d (cm)	3
C (J/kg-K)	896
T_m (K)	855
T_o (K)	300
T_v (K)	2,570
ΔH_m (J/kg)	400,000
ΔH_v (J/kg)	10,800,000

Table 3. EADSIM scenario factor settings

Factor	Low	Med	High	Designator
Platform altitude (m)	3,000	6,500	10,000	A
Platform velocity (m/s)	200	250	300	B
Target altitude (m)	500	1,000	1,500	C
HELLADS LOS (deg)	±30	N/A	±60	D

calculations, this flux density is converted to 226,468 W·s/cm^2. This is an approximation of the amount of energy or irradiance that is expected to defeat a cruise missile. Required dwell time can then be simply calculated by the following equation:

$$T_d = \frac{E_0}{\text{Irradiance}}. \tag{3}$$

Units cancel out, leaving the dwell time, T_d, required to destroy the target in terms of seconds. In this manner it is possible to conservatively (from the HEELADS viewpoint) estimate how long it will take, given certain inputs, to destroy a cruise missile in EADSIM. EADSIM models uncertainty for this damage process by incorporating a random number draw to adjust the lethal energy levels required.

6. Results

Table 3 shows the settings for the EADSIM scenarios using our DOE with three factors at three levels and one factor at two levels. This table includes letter designators for each factor used in later tables and equations. Note that target velocity is set at 200 m/s across all design points. A full factorial, in which all combinations of every setting are represented as in this experiment, results in $3^3 \times 2^1$ or 54 design points or scenarios. Each of the 54 design points was run five times using the Monte Carlo feature in EADSIM, resulting in 270 individual EADSIM runs.

The full regression model constructed from our DOE consists of four main effects, six two-way interactions, four three-way interactions, and one four-way interaction to be considered, resulting in the model

$$\begin{aligned} y_{hijkl} = {} & \mu + \tau_h + \beta_i + \gamma_j + \varphi_k + \tau\beta_{hi} + \tau\gamma_{hj} + \tau\varphi_{hk} + \beta\gamma_{ij} + \beta\varphi_{ik} + \gamma\varphi_{jk} + \tau\beta\gamma_{hij} \\ & + \tau\beta\varphi_{hik} + \tau\gamma\varphi_{hjk} + \beta\gamma\varphi_{ijk} + \tau\beta\gamma\varphi_{hijk} + \varepsilon_{hijkl}, \end{aligned} \tag{4}$$

Table 4. ANOVA of all effects with kills as MOE.

Source	SS	DF	MS	F	p-value prob $>F$	Significance
Block	12.57	4	3.14			
Model	1,240.30	53	23.40	26.30	<0.0001	Significant
A	850.50	2	425.25	477.93	<0.0001	Significant
B	116.72	2	58.36	65.59	<0.0001	Significant
C	112.03	2	56.01	62.95	<0.0001	Significant
D	34.13	1	34.13	38.36	<0.0001	Significant
AB	13.48	4	3.37	3.79	0.0054	Significant
AC	21.04	4	5.26	5.91	0.0002	Significant
AD	1.36	2	0.68	0.76	0.4681	
BC	24.21	4	6.05	6.80	<0.0001	Significant
BD	0.69	2	0.34	0.39	0.6795	
CD	6.76	2	3.38	3.80	0.0240	Significant
ABC	26.72	8	3.34	3.75	0.0004	Significant
ABD	8.76	4	2.19	2.46	0.0465	Significant
ACD	13.56	4	3.39	3.81	0.0052	Significant
BCD	4.56	4	1.14	1.28	0.2789	
$ABCD$	5.80	8	0.72	0.81	0.5902	
Residual	188.63	212	0.89			
Cor. total	1,441.50	269				

where $h = 1, 2, 3$, $i = 1, 2, 3$, $j = 1, 2, 3$, $k = 1, 2$, and $l = 1, 2, 3, 4, 5$. Here μ represents the overall mean of our response variable or MOE from EADSIM, τ represents the effect due to platform altitude, β represents the effect due to target altitude, γ represents the effect due to platform velocity, φ represents the effect due to HELLADS LOS, and ε represents the effect due to error. Note that this model is general in that it does not show possible quadratic effects.

To determine which factors significantly affect the MOE, an ANOVA was conducted investigating all main effects and interactions. Using the number of cruise missile killed (hereafter referred to as kills) as the MOE, the ANOVA in Table 4 was generated, with A, B, C, and D representing platform altitude, target altitude, platform velocity, and HELLADS LOS, respectively.

Terms in Table 4 with a p-value of less than 0.05 are considered influential on the response and are statistically significant at an alpha level of 0.05. This ANOVA table shows platform altitude, target altitude, platform velocity, HELLADS LOS, platform altitude*target altitude (factor interactions denoted using this notation), platform altitude*platform velocity, target altitude*platform velocity, target altitude*HELLADS LOS, platform altitude*target altitude*platform velocity, platform altitude*target altitude*HELLADS LOS, and platform altitude*platform velocity*HELLADS LOS to be significant for number of kills. The remaining two- and three-way interactions were not found to have a significant effect on kills and are rolled up into the error term. Doing so and reanalyzing the model results in the same factors and interactions being statistically significant at the same alpha level. The adjusted R^2 value of .8350 means that this model is explaining 83.5% of the variation about the mean. Although this model fits the data nicely, it consists of 11 factors including 7 two- or three-way interactions. In regression, parsimony is sought to attain a model that adequately

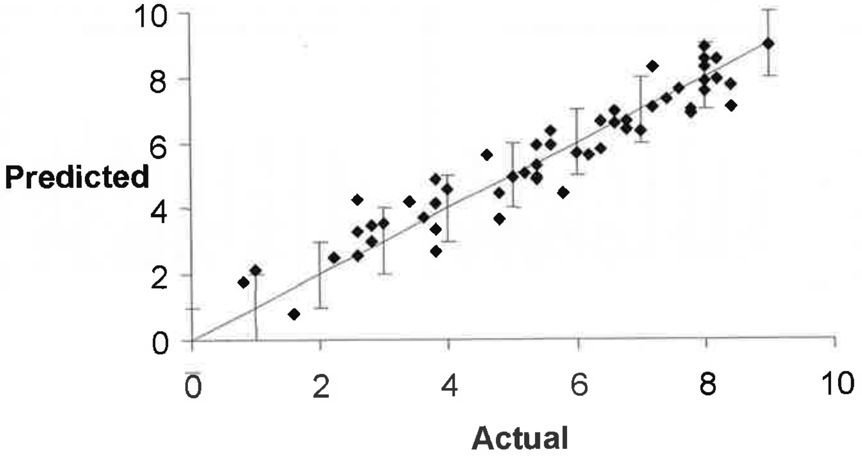

Fig. 7. Predicted versus actual average kills.

fits the data, but with a minimum number of factors. In other words any data set could be fitted perfectly using all main and interaction effects; however, this would not be considered a good model. Basically, the analyst should be willing trade a higher adjusted R^2 value for fewer terms in determining the final model.

Using this mind set, the significant two- and three-way interactions could be eliminated to investigate how this affects model efficiency, or more specifically the adjusted R^2 and lack of fit. First the three-way interactions are dropped from the model, resulting in an adjusted R^2 of .8099, which we still consider adequate. Next only the main effects are considered, resulting in an adjusted R^2 of .7732, which we again consider adequate.

Because a model using only main effects can adequately explain our data, the next step in analyzing the data is to ensure that certain assumptions hold, these being the assumptions of data normality, data independence, and the error term, ε, having zero mean and constant variance. All of these assumptions can be checked by analyzing the residuals, or the differences in observed values and fitted values. See Ponack[17] for detailed results showing that these assumptions hold.

Now we can use the results from our ANOVA to build the following prediction equation for kills:

$$(y+1)^{1.29} = 11.46 + 4.67A + 0.071A^2 - 1.94B + 1.01B^2 - 1.85C + 0.42C^2 + 0.79D \tag{5}$$

where y is calculated as the expected number of kills given the levels of the factors. The levels of factors used in this design are shown in Table 4. Recall that A, B, C, and D represent platform altitude, target altitude, platform velocity, and HELLADS LOS, respectively. To illustrate the use of Eq. (5), consider that we want to predict how many kills are expected when the platform is flying at 3,000 m and a speed of 300 m/s; the target is flying at 1,000 m; and the HELLADS LOS is ±30 deg. Solving for y results in an expected number of kills of 8.3. The average number of kills from our EADSIM runs for these factor levels is eight. Using this methodology Fig. 7 was created to show actual versus predicted values for the average number of kills for each of the 54 design points.

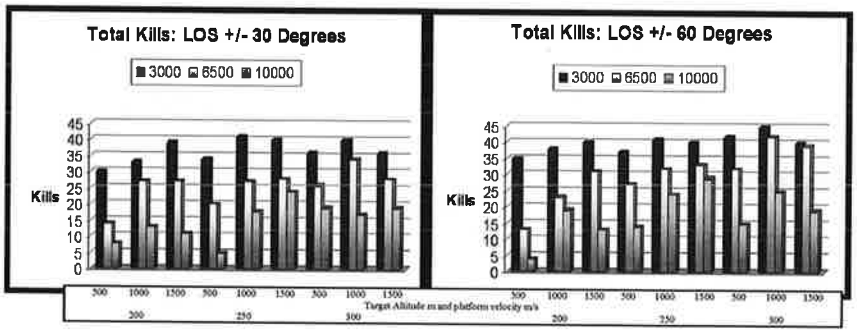

Fig. 8. Total kills over all factor settings.

The error bars show, in general, that the predicted values are rarely outside of ±1 of the actual average kills. It should also be noted that a basic correlation between factors and kills can be summarized by Eq. (5). Platform altitude has a negative correlation with mean kills: the higher the altitude the lower the kills; target altitude has a postive correlation with mean kills: the higher the altitude the higher the kills; platform velocity has a positive correlation with mean kills: the higher the velocity the higher the kills; and LOS also has a positive correlation with mean kills: the higher the LOS the higher the kills. From Eq. (5) we can also distinguish the most to least influential factors by the coefficients they possess: the higher the coefficient, the more influence that factor has on mean kills. The most to least influential factors are platform altitude, target altitude, platfrom velocity, and LOS, respectively. Also note that target altitude and platfrom velocity are very similar in terms of how much they influence mean kills.

The next step in the analysis is to get an overall sense of where HELLADS is most effective. Figure 8 shows the total kills for each factor level. Lower platform altitude, or more generally the closer the altitude of the platform and target, as long as it is enough to give the platform a practical shot, the higher the kill count. The only caveat on this general observation is that when the platform velocity is greater than that of the target it appears to lower the kill count if their respective altitude difference is under 2,000 m. This is apparent by the drop in kills, when the platform is flying 50 m/s faster than the target with an altitude difference of 1,500 m for both LOS settings. A positive correlation can also be seen between platform velocity and kill count, except for the case in which the platform and target are at 10,000 and 1,500 m, respectively. In general a higher platform-to-target-velocity ratio gives the platform an advantage because it can more easily get the target in range once it is detected. Our study considered constant platform and target velocity for each design point. In a realistic engagement, the fighter could vary its speed to maximize time on target and consequently probability of kill.

Analysis of the number of kills also showed, regardless of target altitude and HELLADS LOS, that lower platform altitudes and higher platform velocities increased the number of kills. Because these two factors are directly under a pilot's control, they can be adjusted to create an engagement, when target altitude and LOS are known variables, which should maximize HELLADS effectiveness.

In addition to the number of kills, average lase time was also analyzed as an MOE. Performing a similar ANOVA to average lase time resulted in platform altitude, target altitude, and platform velocity being significant. All lase times were utilized for this analysis,

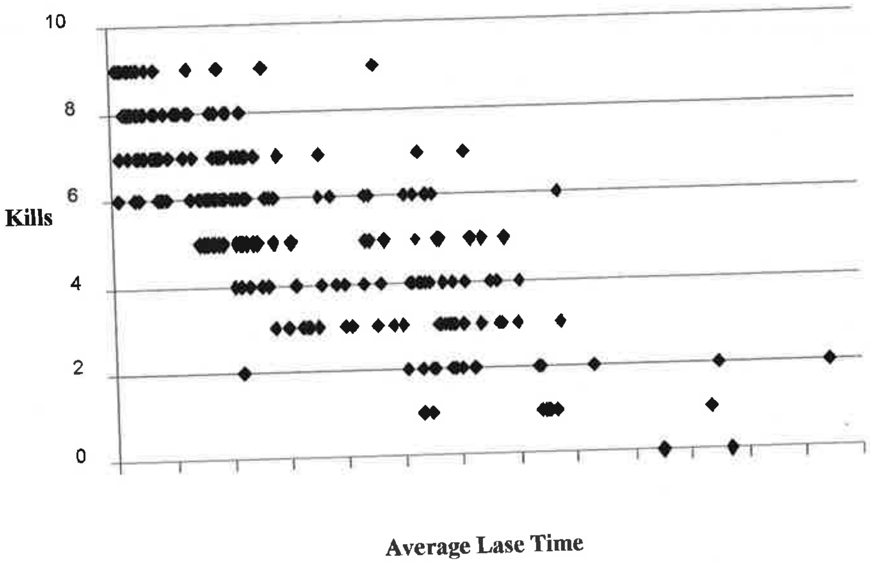

Fig. 9. Average lase time versus kills.

even if the lase did not result in a kill. HELLADS LOS was not found to be a significant factor; thus, it was not considered as a factor in this ANOVA. The two levels of LOS were absorbed into the design, giving 10 replications, instead of 5 for each LOS, at each design point. This is often referred to as collapsing the design in DOE. It allows the analyst to ignore insignificant factors, resulting in more replications for the reduced number of design points. In this case because LOS was not found to be significant it was left out, decreasing the number of design points by a factor of 2, from 54 to 27. The 27 design points are all the possible combinations of those factors found to be significant. Now the 270 runs are a result of a full 3^3 factorial design with 10 runs at each of the 27 design points.

The three two-way interactions, as well as the three-way interactions, were also found to be significant, but with much less influence. A simple comparison was accomplished by analyzing the values over each main effect factor to see how they affected average lase time. The only main effect practically influential on average lase time was platform altitude (see Ref. 17 for more details). Analysis also indicated a negative correlation between the number of kills and average lase time as shown in Fig. 9. The higher the platform altitude setting, the more lase time was required to defeat a target. As explained in the HELEEOS output analysis, increased altitude differences between the platform and target consequently increase the slant range, thus leading to a lower peak irradiance value, and ultimately a reduced P_k for these particular scenarios. Higher average lase times found in these scenarios can be attributed to the corresponding lower kill counts. Lower average lase times actually indicate that the HELLADS platform is firing, and destroying the target more quickly, which again happens when the platform is relatively low, where the slant ranges are smaller and peak irradiance values are higher.

7. Conclusions

This study revealed the most influential factors on HELLADS performance and also identified settings that increased HELLADS P_k. From most to least influential, these factors were platform altitude, target altitude, platform velocity, and LOS. The results also showed that regardless of target altitude and LOS, lower platform altitudes and higher platform velocities maximized HELLADS effectiveness. Keep in mind that a lower platform altitude is relative to the target altitude. Thus, to maximize effectiveness a lower platform altitude would be one that is relatively similar to the target altitude, perhaps 500–800 m above the target altitude. This ensures that HELLADS can be in a position to engage targets in a scenario that has smaller slant ranges.

This research gives a reasonable estimation of where HELLADS will be effective given certain parameters. The two main advantages that HELLADS brings to the warfighter are increased maneuverability and continuous lase time. Employing this type of technology on a fighter aircraft increases the engagement envelope and does not require constant loitering. A HELLADS-equipped fighter could scramble to a location and use its superior speed and agility to maximize HELLADS lethality. One of these advantages, continuous lase time, could actually be tested in future research more completely. This study revealed that longer average lase times were synonymous with fewer kills. However, if certain input factors were varied, such as power, longer lase times may prove to have an enormous benefit.

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