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Assessing Capabilities of the High Energy Liquid Laser Area Defense System through Combat Simulations

Ryan S. Ponack

ASSESSING CAPABILITIES OF THE HIGH ENERGY LIQUID LASER AREA DEFENSE SYSTEM THROUGH COMBAT SIMULATIONS

THESIS

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AFIT/GOR/ENS/08-18

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AN ANALYSIS OF THE EFFICACY OF THE LCOM IN ESTIMATING MAINTENANCE MANPOWER PRODUCTIVE CAPACITY

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Abstract

High Energy Laser (HEL) technology continues to improve and its place in the battlefield is ever evolving. By combining the high energy delivery of solid state laser technology with the efficient thermal management of liquid laser technology, HELLADS has two main advantages over any HEL predecessors. 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 fire power 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 through a cost effective manner. Modeling and simulation supports this assessment as it yields itself easily to relatively low cost and robust testing methodologies. The challenge comes with building credible models through validation and verification of test parameters and scenarios. An Air Force Standard Analysis Toolkit model, the Extended Air Defense Simulation Model (EADSIM), is used in this study to meet these challenges. This research effort focuses on the assessment of the HELLADS operational capabilities through EADSIM. Of particular interest is the investigation of the envisioned HELLADS operational envelope and the potential advantages it offers over other HEL systems. Scenarios are applied to represent the Homeland Defense arena in which HELLADS is proposed to operate. Specifically this study explores what factors impact HELLADS effectiveness and suitability in the Homeland Defense scenarios examined.

Acknowledgments

I would like to express my appreciation to my faculty advisor, Dr. J.O. Miller for his insightful and helpful guidance throughout this research effort. I would also like to thank Mr. Rick Bartell for his HELEEOS support which was crucial in deriving output for my study. Thanks to analyst Tim Booher and his peers at A9 for their vital HELLAD configuration and parameter inputs. Finally, I would like to thank my wife for supporting, and putting up with, me throughout this process.

Ryan S. Ponack

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ASSESSING CAPABILITIES OF THE HIGH ENERGY LIQUID LASER AREA DEFENSE SYSTEM THROUGH COMBAT SIMULATIONS

I. Introduction

Background

Since the High Energy Laser Executive Review Panel (HELERP) released its Laser Master Plan for DOD in March of 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 (Department of Defense Laser Master Plan, 2000).

The Airborne Laser (ABL) test, planned for the end of 2008, will mark the first realistic test shot for a weapon of its type (Stephens, 2006). If this test is successful it will come a half century after the invention of the laser. 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 (Lamberson, 2004). According to a study, documented in the Air and Space Power Journal, HEL technology, now estimated at its 30 year point, seems to be on the cusp of a growth surge. In the figure below time is graphed versus a relative importance attribute which doubles every four years.

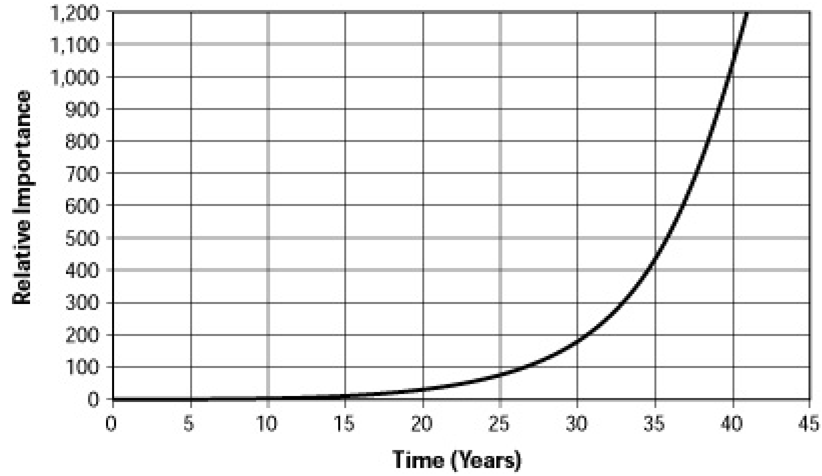

Figure 1. Typical Growth of Developing Technologies (Lamberson, 2004)

Part of this current trend in more rapid growth is the concept of using liquid lasers in place of chemical or solid state lasers used thus far. 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 ABL requires the Boeing 747 as a platform. This immense heat generation also limits firing time and increases down time 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, thus smaller platforms will be able to take advantage of HEL capabilities (Shachtman, 2005). The High Energy Liquid Laser Area Defense System (HELLADS) is the foremost program currently testing liquid laser technology.

Problem Statement

The goal of this study is to investigate the operational envelope of the HELLADS through modeling and simulation. Scenarios relevant to the proposed use of HELLADS are input into appropriate models. These scenarios explore various combinations of different factor configurations, such as platform and target parameters, HELLADS characteristics, and flight profiles, to examine HELLADS operational capabilities. This examination offers a first look at the theoretical limitations of HELLADS, providing a preliminary operational envelope where it can effectively carry out its mission. Laser atmospheric transport characteristics are input into the mission level model via a proven laser propagation model. Similar studies have previously been conducted using chemical laser inputs.

Research Objectives/Questions/Hypotheses

HQ USAF/A9, the USAF primary Study and Analysis group, has recently undertaken a Defense Advanced Research Projects Agency (DARPA) project to evaluate the military utility of HELLADS (HELLADS Military Utility Assessment, 2007). This study supports the HELLADS assessment by investigating the operational envelope of the proposed use of HELLADS. Laser propagation inputs are attained via the High Energy Laser End-to-End Operational Simulation (HEELEOS) created by AFIT's Center for Directed Energy. HELEOS derives a practical degree of fidelity in estimating laser energy delivery given three main areas of user inputs (Bartell and Allen, 2005).

1) Laser inputs, such as wavelengths, beam power, beam quality, jitter, exit aperture diameter.
2) Platform and target inputs, such as speed, altitude, and relative spatial and geometric relationships.

3) Environmental inputs, such as atmosphere and aerosol types, HELEEOS provides.

The mission level Extended Air Defense Simulation (EADSIM) model uses the energy delivery data provided by HELEEOS to investigate the HELLADS operational envelope. Appropriate scenarios will be run in EADSIM to assess HELLADS air-to-air defensive capability against various missiles and rockets. HELLADS Measures of Effectiveness (MOEs) will be evaluated using intended operational scenarios, but will also be evaluated beyond its proposed combat venues by *stretching* this operational envelope.

Research Focus/Scope/Methodology

HELLADS hopes to be capable of delivering 150kW of power with a weight goal of 5kg/kW (High Energy Laser Area Defense System, 2005). This puts the HELLADS at approximately 750 kg, or 1650 lbs, 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 UAVs to carry the HELLADS (HELLADS Military Utility Assessment, 2007). This completely changes the way HEL can be utilized in the battlefield.

Scenarios in EADSIM using these types of platforms are developed to assess the operational effectiveness of the HELLADS. Output will be examined and compared to expected values to ensure its accuracy. Analysis of Variance (ANOVA) is used to single out the driving input factors and linear regression techniques will be used to build a predictive model. Once a predictive model has been derived its responses will be compared to model outputs to ensure it is correct, and also to hone the predictive model to increase its accuracy. Once the "best" predictive model has been derived it will be used to examine HELLADS operational capabilities outside those proposed or intended.

Implications

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. It 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.

Preview/Overview

If successful, HELLADS will totally revolutionize HEL capability. It will greatly increase how the warfighter can apply HEL weaponry to gain considerable advantages over the adversary. Current HEL configurations require an enormous platform, limiting its engagement proficiency. By combining the high energy delivery of solid state laser technology with the efficient thermal management of liquid laser technology HELLADS will no longer have this limitation currently hindering HEL capabilities (Cohen and Knight, 2005:24).

The next four chapters give detailed information on investigating HELLADS capabilities. Chapter two summarizes applicable literature used in this research. Chapter three discusses the methodology used for the HELLADS assessment, including details concerning input data and model integration. Chapter four discusses analysis of the output data, including statistical procedures, Design of Experiments (DOE) methodology, ANOVA, and linear regression. Chapter five provides this study's conclusions and future, or follow-on, research and assessments.

II. Literature Review

Introduction

Before beginning the process of planning, executing, and analyzing a project some preliminary groundwork must be accomplished. A literature review delves into the generalities of the system under investigation and forms a starting point for further research. Understanding of how the concept has evolved through previous technological advances, and how it has been used and tested in the past, yields the researcher with a refined scope, from which the system under study can be better assessed.

In the past decade HEL technology has advanced substantially and there are currently many programs, in all services, using, or testing, HEL capabilities. One of the most notable is the Army's Tactical HEL (THEL). The ground based THEL has proven effective against intercepting single, and salvos of, Rockets, Artillery and Mortars (RAM). The Army is currently developing and testing the Mobile THEL (MTHEL) which is a transportable, ground based THEL, intended to target, not only RAM, but also UAVs, cruise missiles, ballistic missiles, satellites, battlefield optics and sensors, helicopters, and ground attack aircraft (Souder and Langille, 2004:4). After detecting such enemy attacks there is only a matter of seconds, or less, to counter. Fly out times make kinetic counter-measures, defeating rockets with rockets, an infeasible solution. Once an air attack is detected, acquired, and tracked HEL weaponry engages the target at the speed of light. This instantaneous reaction time makes it a much more practicable solution for defeating high speed air attacks. The Army has proven THEL and MTHEL ability to defeat high speed air attacks. The HELLADS mission is also to defeat these types of attacks however, it will do so via air-to-air instead of ground-to-air.

The Air-borne Laser (ABL) was the first concept of using an air-to-air laser weapon system to defeat air attacks. It uses a complex system of sensory, targeting, and lasing technologies to laze down ballistic missiles while they're in their boost phase. It uses four different types of lasers, each with a specific purpose. After detecting a boosting, ballistic missile it uses one laser to track, a second laser to aim, a third laser to measure the amount of atmospheric disturbance between the aircraft and missile, and a fourth, a HEL, to irradiate the missile. In this case the HEL is a Chemical Oxygen Iodine Laser (COIL). The COIL, invented by the Air Force Research Laboratory (AFRL) in 1977, uses a mixture of chemicals and chemical gases to excite oxygen. *Excited* iodine gas is then produced by injecting iodine into the *excited* oxygen. When the iodine returns to its normal state it produces flashes called photons. These photons are then amplified to produce the laser beam (Airborne Laser, 2003). The ABL is reported to have a range of more than 200 miles, however, to generate this type of power it needs six COIL modules, each the size of an SUV and weighing 6,500 pounds (Airborne Laser, 2003). Only large aircraft, like the current ABL platform, a 747, can carry such a weight. By being light enough to be carried by fighters, HELLADS will provide enough power and maneuverability to defeat close to medium range air targets.

The Advanced Tactical Laser (ATL) is a HEL that uses a very similar COIL, but its primary mission is striking closer tactical targets. The ATL uses a modified C-130 as its platform. Equipped with HEL appropriate sensory and tracking systems it uses a turret, protruding from a 50 inch diameter hole in the belly of the aircraft, to strike at ground targets (Advanced Tactical Laser, 2006). Potentially, the precision, speed, and range of the ATL, will allow it to strike targets with minimal collateral damage from a range of 15 kilometers. This stand-off type attack, made capable by the ATL, enables covert attack possible outside of the range of small arms fire and shoulder-launched anti-aircraft missiles. Using 100 to 300kW of power the ATL can emit a four inch diameter beam that can cut through metal in less than five seconds, from nine miles away (Advanced Tactical Laser, 2005). With a similar power output, but lighter payload, the HELLADS aspires to have comparable capabilities against air targets.

Yet another current HEL program is the Joint High Power Solid State Laser (JHPSLL). The JHPSLL is currently entering its third phase of development and hopes to soon demonstrate 100kW power generation which is intended to be used for a wide variety of missions including defense against RAM, anti-tank guided missiles, rocket propelled grenades, and man-portable SAMs (Joint High Power Solid State Laser, 2005). The JHPSLL uses solid state laser technology to generate its beam and it is intended to be mobile like the MTHEL.

HEL power can be generated from solids, fibers, chemicals, or liquid. Solid state lasers use a crystalline or glass, fiber lasers use fibers, chemical laser use a mixture of chemicals, such as the COIL used in the ABL, and liquid lasers use a solid and a liquid to produce laser beams. Although the aforementioned use different materials, the means of power generation follows the same basic premise, see figure below.

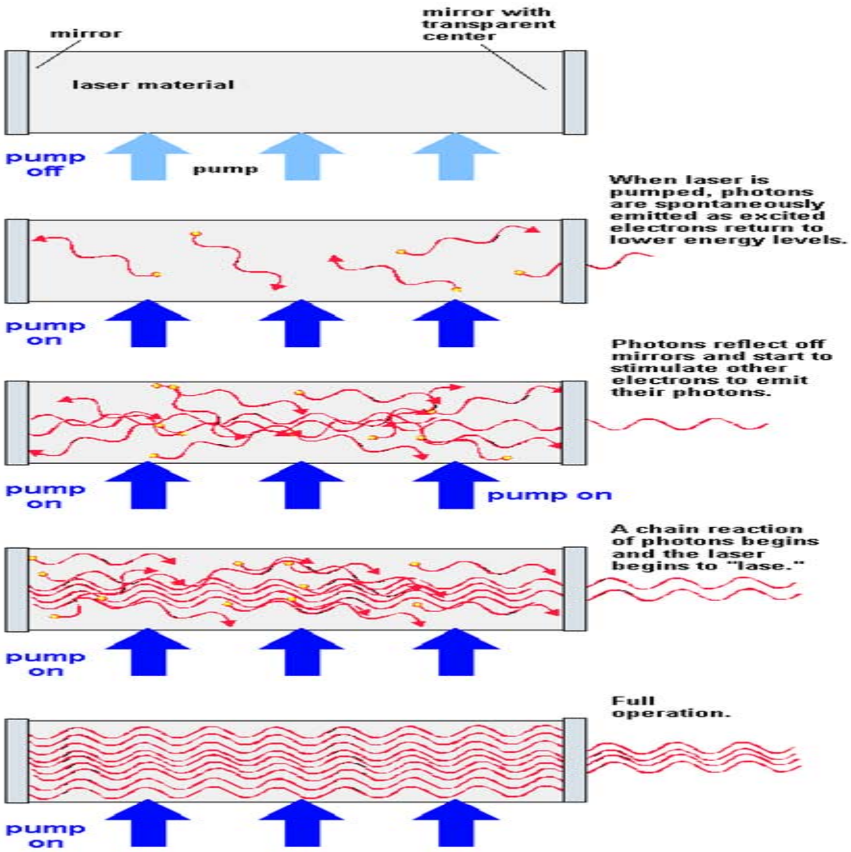

Figure 2. Laser Basics (How Does It Work?, 2001)

By pumping the medium, solid, fiber, chemical, or liquid, with light or electricity, the ions in the material become *excited*, causing them to jump to higher orbits. When the electrons drop back to lower energy levels they release a photon or quantum of light. This process continues until the light waves' strength builds and passes through the medium. Mirrors reflect the light back and forth in the tube, creating a chain reaction which causes the laser to laze (Coherent Light and Its Emissions in Lasers, 2007). Although solid state lasers and fiber lasers are not as powerful as chemical lasers they offer the potential of being more suitable for a wider range of applications due to their compactness and their ability to function on electrical energy alone (McHale, 2006).

Lasers generate an immense amount of thermal energy, limiting their laze time and thus their capabilities. HELLADS uses a solid state laser in conjunction with a liquid to lessen excessive heat generation, allowing it to laze longer.

HELLADS will undoubtedly enhance HEL weapons' capability. According to DARPA director, Dr. Tony Tether, "a unique cooling system might allow the system to be 10 times lighter, significantly smaller, and approximately half the cost of current developmental HEL systems." (Tether, 2003).

The HELLADS low weight and superb cooling efficiency will enable it to achieve previously impossible tasks for this type of weapon system. It will enable tactical aircraft, such as fighters, to be equipped with a continuous lazing capability to target threats such as cruise missiles, aircraft, UAVs, low altitude missiles, rockets, artillery, mortars and SAMs (Robinson, 2007:20).

The HELLADS program is currently set up into five phases (High Energy Laser Area Defense System, 2005). The first phase evaluated feasibility issues of the HELLADS, including platform integration, carry employments, signature effects, cueing employment, target classifications, range, and firing methodologies. This was accomplished through satisfying critical parameters by a subscale liquid laser demonstration. Phase two spans four years and will attempt to demonstrate a HELLADS comparable system's ability to deliver 100kW of power. In 2004 HELLADS began its third phase which consisted of a laboratory demonstration of a subscale prototype laser with comparable geometries and attributes of the proposed operational HELLADS configuration (Request for Information, 2004).

Phase four will employ a ground-based system analogous to the final HELLADS configuration meeting the 5kg/kW, weight to power, specifications. This ground based system will also demonstrate the ability to fit the appropriate technology into a compact design, small enough to be carried on a specified tactical aircraft. Phase five will concentrate on the engineering, formulation, and integration needed to accomplish a HELLADS shot from an aircraft. Interoperability with the platform and HELLADS will be tested in the ability to acquire and track targets and in controlling beam and fire attributes (High Energy Laser Area Defense System, 2005).

HQ USAF/A9F planned military utility assessment of HELLADS is also split up into five phases that reasonably resemble the five phases listed above. Through the use of modeling and simulation, this study addresses questions regarding specific HELLAD capabilities and isn't necessarily tied to any one phase.

The primary focus will be on HELLADS capabilities and limitations as they pertain to physical measures such as range, number of shots, time on target, and probability of kill, or target degradation. These measures will be calculated over different combination sets of possible or relevant scenarios, given HELLADS intended platforms, power, firing characteristics, and targets. The proposed use of the HELLADS is in the Homeland Defense CONOPS arena and scenarios in this study reflect that.

Modeling and Simulation

The Defense Modeling and Simulation Coordination Office (DMSCO) lays the groundwork for all M&S work done for DoD . It sets specific guidelines to be followed and performs appropriate corporate level functions necessary to foster cooperation, synergism, and cost-effectiveness among the M&S activities of the DoD Components. It works to foster interoperability, reuse, and affordability of M&S and the responsive application of these tools to maximize capabilities available to the warfighter and to enhance attributes of DoD operations (Mission Statement, 2006).

Ideally every system would be thoroughly tested operationally before ever going to the field. However, due to the financial enormity of this idealistic approach, other, less financially obligating, means of testing are necessary. Modeling and simulation provides a comparably low cost testing platform and can also be used for a wide scope of testing that would not be realistic, or possible, in the operational test theater. Scenarios and excursions otherwise untestable can be examined through modeling and simulation. Historically, a model has been defined as being a "physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process" and a simulation has been defined as a "method of implementing a model over time" (Hughes, 1997:4).

Simulation types are classified by broad taxonomies, classifying them relative to their purpose, degree of aggregation, and by durability (Miller, 2007). The type of simulation used in this research is classified in purpose as a constructive model; one in which simulated people operate simulated systems. The simulation executes an assigned scenario using data input from the model user and produces output data which then can be analyzed to assess the overall effectiveness of the system under the prescribed subject matter. These models are also defined as descriptive, another purpose classifier, or models that facilitate decisions through inference. Descriptive models use a set of appropriate inputs to analyze the relative outputs and evaluate alternatives based on the cause and effect of the input/output relationships.

For degree of aggregation, the actual models used in this study fall under the mission and engagement level portions of the pyramid, discussed in the next section. Engagement output data from HELEEOS, an engagement level model, will be used as inputs for EADSIM, a mission level model.

Lastly these models are classified by durability as standing models, or legacy models. Standing models are legacy models which have been used extensively in the past and are operated, maintained, and improved on a continual basis (Hughes, 1997:9). Some of these models are accepted by the analytical community and become part of the Air Force Standard Analysis Toolkit (AFSAT). AFSAT serves as a benchmarked set of models which can be used for various levels of aggregated engagements. AFSAT highlights appropriate standing models and their use for given analytical purposes. In this manner AFSAT prevents analysts from *re-inventing* the wheel, moderates the model population, and, to some extent, streamlines the modeling and simulation analytical process (Air Force Standard Analysis Toolkit, 2006).

Hierarchical Process

Every model is applied for its intended purpose to assess a system in a specific scenario. Operations research is a lever to support decisions and a model aspires to aid this process by achieving a realistic representation of the operations, as they pertain to the specific agendas under investigation (Hughes, 1997:4). Although no two 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, models are classified into a hierarchy exemplifying their degree of resolution. Figure 3 shows the model hierarchy used by DoD.

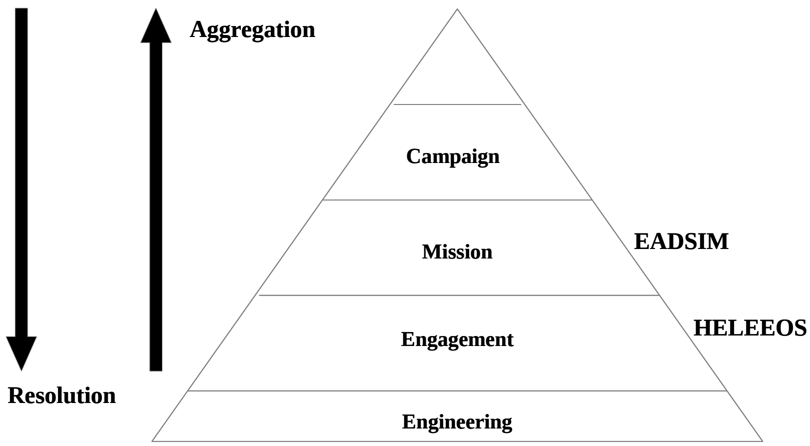

Figure 3. DOD M&S Pyramid

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 type of engagements being investigated.

HEL Modeling and Simulation Challenges

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 (Appropriation/Budget Activity, 2007:25-27). Models traditionally used for simulating conventional kinetic weapon systems such as bullets, missiles, bombs, and artillery, cannot be used to simulate laser weapon systems. Physical effects, such as gravity and drag, which drive kinetic weapon system simulations do not apply to the natural physics that affect laser energy. Projectile weapons, for the most part, cannot function autonomously after they've been employed. Aiming points are derived using formulas that take into account such things which do not influence laser propagation. 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.

Models simulating laser effects take into consideration environmental effects that most directly influence laser power delivery to a target. The most significant are thermal blooming, molecular and aerosol absorption/scattering, and turbulence (Zimet, 2002; Sprangle and others, 2004). 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 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. This distortion can be decreased by using specific beam wavelengths which are scattered, and absorbed, less in various atmospheric environments (Sprangle and others, 2004).

Atmospheric conditions have a great effect on HEL weaponry. Whereas the trajectory of traditional projectile weapons are not effected by water vapor, fog, and clouds, a laser beam cannot effectively propagate through these types of adverse environments. Water vapor and other molecules between the laser source and its intended target scatter and absorb laser energy, significantly decreasing its power. Thermal fluctuations in the air, dependent on the changes caused by laser energy, also effect laser propagation. Different air temperatures possess different refractive indexes, thus thermal changes can cause the laser beam to spread and wander. Adaptive optics have proven to lessen the degrading effects of turbulence (Sprangle and others, 2004).

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.

All these factors are unique to modeling laser effectiveness and thus present a whole new set of challenges for accurately estimating laser degradation and laser efficacy. HEELEOS, mentioned in the introduction, obtains input from the user, such as, beam wavelength, power, slant ranges, platform and target characteristics, and atmospheric conditions, to estimate laser power delivery to the target, and consequently, influence probability of kill estimation calculated in EADSIM (Bartell and Allen, 2005).

Output from HEELEOS can subsequently be incorporated as inputs into EADSIM, also discussed earlier, to examine mission level scenarios, such as, one-on-few and few-on-many scenarios. For this research scenario set up will be based on the intended use of HELLADS provided by A9, and EADSIM results will provide estimations for HELLADS capability and limitations, including number of shots, time availability, range, platform configurations, and target classes.

EADSIM

EADSIM is a workstation-hosted, system-level simulation which is 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. EADSIM provides a many-on-many theater-level simulation of air and missile warfare, an integrated analysis tool to support joint and combined force operations, and a tool to provide realistic air defense training to maneuver force exercises at all echelons (EADSIM Methodology Manual for Version 13.00, 2005).

EADSIM incorporates many factors to simulate air-to-air engagements, including multi-tier engagements, Theater Ballistic Missiles in all phases, passive defense, infra-red signatures, and radar signatures, to formulate probability of kills for given scenarios. Studies using EADSIM similar to this one have traditionally used high speed missiles in lieu of laser energy. However, recent versions of EADSIM have the ability to model actual laser weaponry characteristics as briefly discussed below.

The current version of EADSIM incorporates a Laser ruleset, 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/laze phases, which represent HEL delivery once the decision to engage has been reached (EADSIM Methodology Manual, 2006:4.7.33-1). Figure 4 illustrates this engagement process.

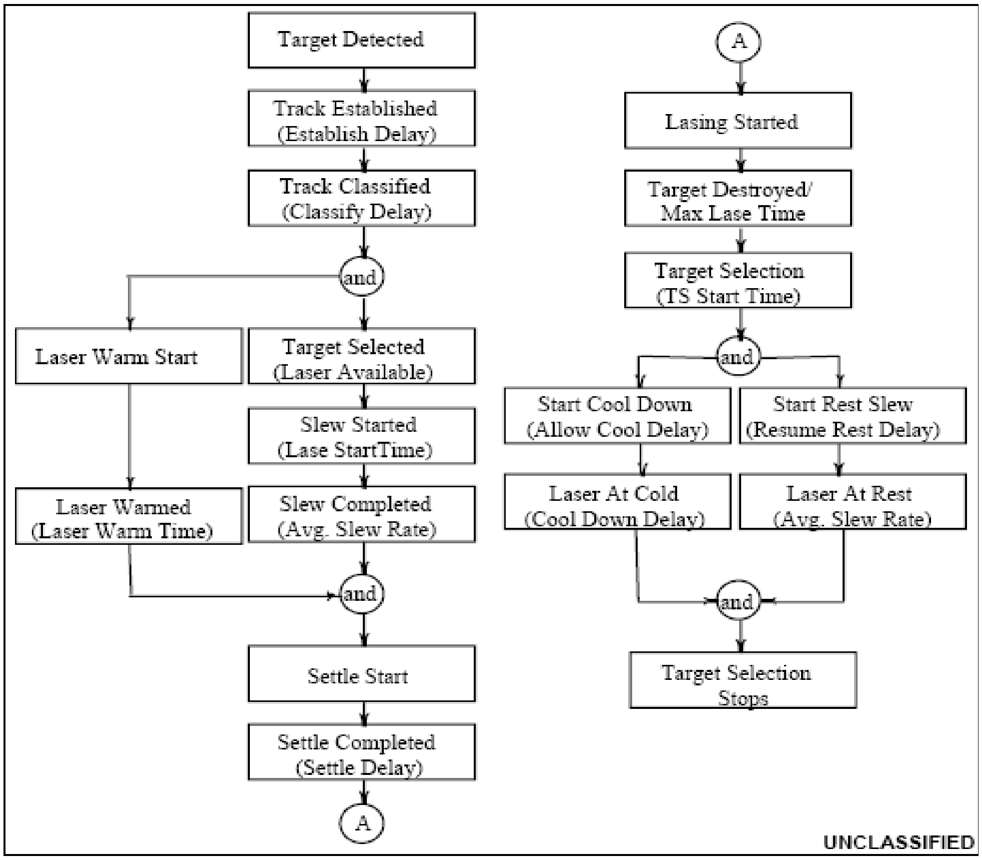

Figure 4. Laser Engagement Timeline (EADSIM Methodology Manual)

The decision to engage is based on several factors including, time on track, friend or foe identification, local track, and target criteria. Once a target is selected for engagement a turn-to-target decision is made, based on laser-target geometry and target angle thresholds. Once a target meets the Line-of-Sight (LOS) thresholds range, laser slewing, warming and settling times are then modeled (EADSIM Methodology Manual, 2006:4.7.33-18). EADSIM offers four lethality modeling options to specify probability of kill (Pk). The intensity and fluence models apply user inputs as their values and calculate Pk via a random number draw representing the targets survivability percentile. The damage required to effectively kill the target is determined, based on the random number draw, by using maximum and minimum vulnerability criteria for the engaged target (EADSIM Methodology Manual, 2006:4.7.33-22).

The HEL Vulnerability Module (VM) interface requires no inputs from the user, rather it looks up vulnerability data defined in the VM for specific targets and aimpoints. The Pk calculation for the actual engagement occurs from a random draw, unless otherwise specified in the planning process by the user (EADSIM Methodology Manual, 2006:4.7.33-39).

The shared object option calculates Pk via a user developed algorithm to process an engagement. EADSIM calls the shared object function and uses the provided lethality information to determine target destruction. This lethality modeling option is similar to the HEL VM, but is more labor intensive as it requires the user to create an algorithm to derive data which HEL VM already provides (EADSIM Methodology Manual, 2006:4.7.33-32).

Power propagation greatly influences laser lethality as it effects deposited energy on the target (EADSIM Methodology Manual, 2006:4.7.33-29). Energy deposition is a function of beam spread and peak intensity, both of which depend upon power propagation. EADSIM determines the effect power propagation has on the deposition of target energy by power propagation look up tables which will be provided by HELEEOS.

Analysis Techniques

Design of Experiments (DOE) is implemented to answer several important questions regarding input factors and response variables. Before starting an experiment one should take into consideration all appropriate input factors, both controllable and uncontrollable. The purpose of an experiment is to accurately estimate what 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. Bias due to uncontrollable factors, and noise, can also be estimated and minimized through replication, randomization, and an experimental design known as blocking (Montgomery, 2001:12).

Replication provides the experimenter with an estimate of the experimental error and also the means to more accurately estimate the response variable(s) under investigation. In some cases, operationally testing very expensive weapons for example, it may be difficult or impossible to replicate. However, for this study, which utilizes modeling and simulation, replication will not be a problem.

Randomizing input factor settings and the order in which the runs are accomplished average out extraneous noise, greatly increasing the validity and confidence of experimental conclusions. By spreading out uncontrollable factors randomly throughout the design, their influences will be evenly spread out, minimizing their effects on the response variable and avoiding the possibility of skewing the data, potentially leading the experimenter to make invalid conclusions concerning input factor influences on the response variable of time to complete the task. Randomization also validates the assumption of independent random variables needed to make statistically sound conclusions.

Blocking is a design strategy used to further minimize the variability caused by nuisance factors, those factors which have influence over the response variable but are not necessarily important to the experiment. When blocking, the experiment is set up so that effects due to a nuisance factor can be completely discerned from effects due to factors of interest. A good example of this is a design strategy which blocks on day, where day was not pre-selected as a factor of interest. If we were running an experiment which took more than one day the test would be set it up so that relatively homogeneous runs were run for each block (day). In this manner we would be interested in examining the variability within blocks (days), and not concerned with variability between blocks (days), since day was predetermined to not be a factor of interest. If the runs done in each block (day) were not homogeneous it would be impossible to make inferences on what factor(s) influenced the response variable under investigation. In other words the variability from blocks would be confounded with other factors, rendering any conclusions made, concerning factor influence on the response variable, invalid.

After using DOE to set up the experiment, and conducting the runs, an analysis of variance (ANOVA) is often used to calculate what factors, and/or factor interactions, are significant. A significant factor, or factor interactions, is one whose variability is a large proportion of the overall variability. In other words variability is calculated for each factor, and possibly 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, and 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 affect 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 of predicting the response for a given set of significant factor inputs (Montgomery and others, 2004:67). Prediction equation accuracy will be tested and optimized by comparing it to model results with applicable input factors.

Previous Research

This research effort expands upon three recent theses written by AFIT students which all used EADSIM to assess HEL capabilities. These theses provided the EADSIM framework for this particular study.

Research of Captain Maurice Azar

Prior to this research, in 2003, the assessment of HEL capabilities was generally done using several stand alone engineering models that only addressed small portions of a HEL weapon system (Azar, 2003:1-2,1-3). This research assessed EADSIM's ability to assess ATL capabilities against cruise missiles and provided measures of effectiveness for the model, and the means by which they could be applied and aggregated into higher level models, such as the campaign model, THUNDER (Azar, 2003:1-4). THUNDER is a theater level combat model that is designed to guide policymaker decisions, by evaluating issues involving the utility and effectiveness of air and space power in a campaign level scenario (Aerospace Systems Survivability, 2001:60).

EADSIM was used to simulate an ATL mounted on a C-130 flying in a circular pattern, with radius of 5 km, at 15000 meters, and 150 knots engaged nine cruise missiles, flying due south, at 100 meters AGL, and at 400 knots (Azar, 2003:3-2). This study did not use HELEEOS to generate power propagation tables as this study does; rather Captain Azar used a Tyson's first order brightness equation to produce applicable inputs for EADSIM (Azar, 2003:3-15; Tyson, 1998:24):

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

where

B = *Brightness (watts / steradian)*

D = *Diameter of transmitting aperture (meters)*

P = *Power of laser (Watts)*

λ = *Wavelength (meters)*

ω = *Wavefront error (root mean square as percent of λ)*

j = *Jitter (root mean square as a percent of λ / D)*

τ = *Transmission of atmosphere (percent)*

Table 1. Brightness Equation Inputs

Variable	Value
D = Diameter of transmitting aperture (meters)	1
P = Power of laser (Watts)	50,000
λ = Wavelength (meters)	1.315×10^{-6}
ω = Wavefront error (root mean square as percent of λ)	.2 λ
j = Jitter (root mean square as a percent of λ / D)	0/2.205 λ
τ = Transmission of atmosphere (percent)	.9

Captain Azar's research offers some insight regarding what factors have the most impact on HEL effectiveness. He examined the influence of factors such as target priority, laser propagation, cruise missile launch time, azimuth, power, and jitter had on fraction of targets killed and total laser firing time (Azar, 2003:3-22, 4-1,4-5).

Research of Captain Michael Cook

Capt Cook's effort paralleled Capt Azar's but had two major differences. As opposed to using the brightness equation, power propagation tables were provided by HELEEOS, and in this effort ATL effectiveness against ground, as opposed to air, targets was assessed (Cook, 2004:17). Using power propagation input from HELEEOS is actually preferred over using brightness equations, as HELEEOS accounts for thermal blooming and jitter, where the brightness equation does not explicitly (Cook, 2004:19). 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 (Cook, 2004: 22).

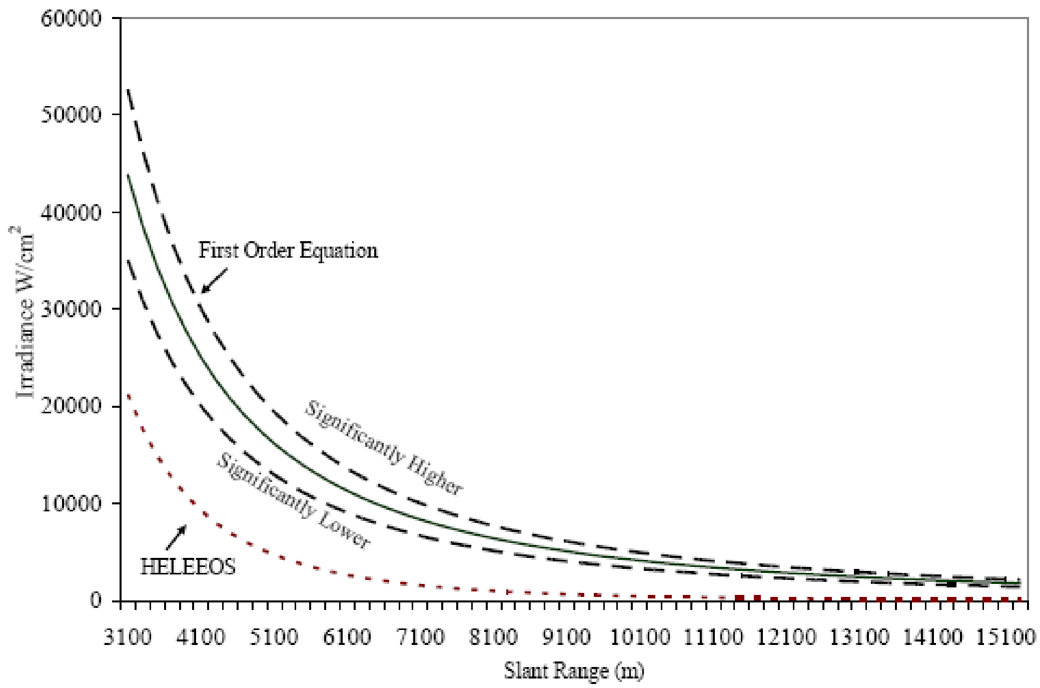

Figure 5. Power Comparison with Thermal Blooming (Cook, 2004:21)

Capt Cook also noted the brightness equation's inability to properly represent degradation of HEL effectiveness due to jitter (Cook, 2004: 24). Turbulence induced jitter and vibration induced jitter adversely effect HEL's ability to hit a target (Liu,Y.T. et, al, 2005). As Figure 6 shows, depending upon beam quality and wavefront error, jitter plays a significant role in hitting a target (Neal, 1994:5). This graph shows the allowable amount of jitter. If these thresholds are exceeded HELs ability to hit a target greatly decrease.

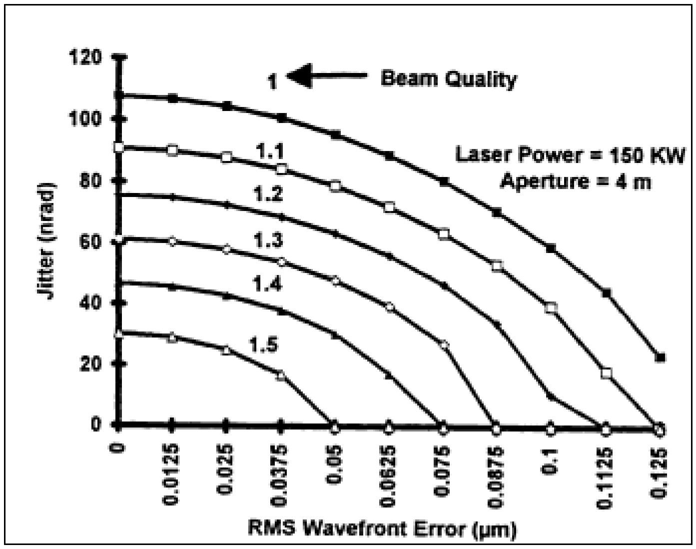

Figure 6. Allowable Jitter 150 kW System (Neal, 1994:5)

Perfect beam quality is 1 and higher numbers denote decreased beam quality. According to subject matter expert (SME), Mr. Rick Bartell, HELEEOS reflects the degradation on the ability to accurately hit a target when jitter values of greater than 5 are input into a model simulating a solid state laser, which is typically given a beam quality of 2 (Bartell, 2007). This is verified by the figure above and albeit COIL has a better beam quality at 1.3, as used in Capt Cook's study, they are still effected by jitter. As can be seen by the graph lower beam quality and greater wavefront 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 effecting HELs ability to destroy targets, but also on how they effect average dwell time. These factors included power level, vulnerability level, target selection priority, weapon altitude, propagation, and weapon velocity. Capt Cook used similar inputs to Capt Azar's to formulate power propagation values which were fed into EADSIM however, the other factors differed considerably and are shown in the table below.

Table 2. Cook's Factor Settings (Cook, 2004:47)

Factor	Low	Medium	High
Weapon Altitude (m)	1000	4500	8000
Weapon Velocity (m/s)	140	220	300
Target Priority	1 - Shortest time to kill 3 – Lowest Elevation Angle		2 – Longest time to kill 4 – Highest Elevation Angle
ATL Power Level (W/cm^2)	50000	100000	200000
Vulnerability Tables (J/cm^2)	10000	50000	90000

Capt Cook concluded that weapon altitude, power level, slant range (a direct result of weapon and target altitude and position), target vulnerability level, and weapon velocity all had significant effects on the measure of effectiveness. He also noted, albeit it was more robust in measuring propagation, his study did not model absorption. In order to more accurately predict target vulnerability future studies of this nature should attempt to account for energy loss from atmospheric absorption (Cook, 2004: 91-93).

Research of Captain James Markham

Capt Markham's study investigated the lethality of HEL weaponry and how to appropriately measure it, in order to produce data which could be entered into the Joint Munitions Effectiveness Manual (JMEM) (Markham, 2005: iv). His study, like Capt Cook's, focused on engaging ground targets however, his study more accurately evaluated target vulnerability by using empirical test data, instead of theoretical values, for required flux densities and also by evaluating multiple aimpoints. Capt Markham used the following parameters and settings (Markham, 2005:26, 36).

Table 3. Markham's Factor Settings (Markham, 2005:26)

Parameter	Scenario Settings
Slant Range (m)	2000 3000 4000 5000 6000 7000 8000 9000 10000 11000 12000
Platform Altitude (m)	2000
Dwell Time (sec)	1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
Platform Velocity Perpendicular to LOS (m/s)	77 90 103 116 126
Susceptible Target Length/Width (m)	.01 .02 .03 .04 .05 .06
Laser Power (W/cm^2)	100,000
Beam Quality	1.1
Magazine Depth (sec)	5

Bucket, or spot, size refers to the area in which laser energy can be deposited in order to cause damage and dwell time refers to the seconds of laze time, although 5 seconds is listed it is merely a minimum time for a single engagement in EADSIM and 100 seconds was actually used to account for multiple engagement scenarios (Markham, 2005:32). Aerosol and atmospheric types were also factors, not listed in the table, used in this study. Data for these factors were directly generated by HELEEOS and applicable values were used in the scenarios. In addition to influential factors on the effectiveness of HEL weapons found by Capt Azar and Capt Cook, Capt Markham concluded that limitations existed on the applicability of ATL capabilities based on range to target, atmospheric profile, and target vulnerability (Markham, 2005:65).

Applicable scenarios, settings, and findings from all three prior theses were considered and applied in the development of this study. Many settings were identical, or close to, settings used in the prior studies discussed however, one major difference is weapon platform velocity and laze time. HELLADS was employed from a fighter aircraft and given greater laze times.

Summary

9/11 quickly made Homeland Defense a top priority, and with no foreseeable end to the conflicts in the Middle East it is, and will continue to be such. Programs have been established by DoD to help protect our country from those who wish to do us harm. Skyguard is one such program proposed by Northrup Grumman. It is conceptually comparable to the Army's THEL system and could be used to protect airports, cities and industrial areas. One system could protect approximately a 10km radius against aerial attacks (Skyguard, 2006).

Raytheon's Laser Area Defense System (LADS) uses off the shelf solid state technology in conjunction with commercially available optics technology recently demonstrated its ability to strike small, stationary mortars at a distance of 550 yards away (Electric Lasers Shoot Mortars, 2007). The threshold of 100kW is conceivably not far out of reach and using an already existing tracking system for aerial strikes will be LADS next hurdle. If successful LADS potentially will provide another asset to Homeland Defense.

Over 30 years ago the Navy began The Mid Infrared Advanced Chemical Laser (MIRACL) program and has since been tested against tactical missiles and drone aircraft. It is the first megawatt-class, continuous wave, chemical laser built in the free world, and remains the highest average power laser in the US (Mid-Infrared Advanced Chemical Laser, 1998).

The Space Based Laser (SBL) is a program currently under development. The SBL has generated power levels, comparable to MIRACL's, in a low pressure, space operation environment. The next step is to prove the feasibility of space deployment through an integrated space vehicle ground test with a space demonstration (Space Based Laser, 2005). The SBL would provide Theater Missile Defense with its capability to shoot down ballistic missiles from space.

Directed Energy Weapons (DEW), including those implementing HEL, provide unique advantages, including operation at the speed of light, gravitational immunity, precise and adjustable targeting, affordability, minimal collateral damage, repetitive engagements, and platform diversity, which make them more suitable than traditional kinetic weapons for Homeland Defense (Spencer and Carafano: 2004).

Terrorists will use any means necessary to inflict damage and project fear into the American public. Asymmetric warfare is a low cost, high benefit way in which they can achieve these goals. Cruise missiles are easy to attain, easy to conceal, adaptable, cheap, and are able to deliver a variety of destructive warheads over a far reaching range (Keuter and Kleinberg, 2007:2).

HELLADS, along, with other HEL weaponry, will bring a distinctive advantage to Homeland Defense. Using an agile platform and sufficient, medium range HEL power, it will be an asset in thwarting threats, such as cruise missiles, that may otherwise go unchecked by other Homeland Defense systems.

III. Methodology

General Methodology

This chapter presents the scenarios, along with factor values and assumptions, which are employed in this study to assess HELLADS capability and effectiveness. The methodology stems from current, and proposed, HEL Concept of Operations (CONOPS), and the current capacities modeling and simulation offers for emulation, which were discussed in the previous two chapters. Factors, or inputs, into the models, such as beam characteristics and atmospheric conditions, for HELEEOS, and platform and target altitudes and velocities, as well as vulnerability data and weapon configuration, for EADSIM, were derived from subject matter experts and previous research done in HEL assessment via modeling.

HELEEOS Inputs for EADSIM

As mentioned earlier EADSIM offers four ways in which to specify Pk. Due to the nature of HELEEOS outputs being in the form of intensity, or irradiance, values, the intensity methodology for computing target lethality is used in this study. Modeling lethality in this manner requires irradiance values for computing Pk. 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 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. HELEEOS allows the user to go through a step-by-step process in setting up an engagement scenario. These steps are shown in the figure below and explained thereafter.

Figure 7. HELEEOS Setup

HEL weaponry exhibits unique operational advantages over kinetic weaponry. However, it does not come without a caveat that is often not fully accounted for, or rather made clear, when HEL assessments are conducted. In order to properly make this assessment the laser beam must be able to reach its target; therefore they must assume a clear line of sight, designated as Cloud Free Line Of Sight (CFLOS) in HELEEOS, to the target. 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 this assessment is only applicable when CFLOS exists. HELEEOS offers a worldwide probability of CFLOS. Figure 8 shows these probabilities for all default locations in HELEEOS.

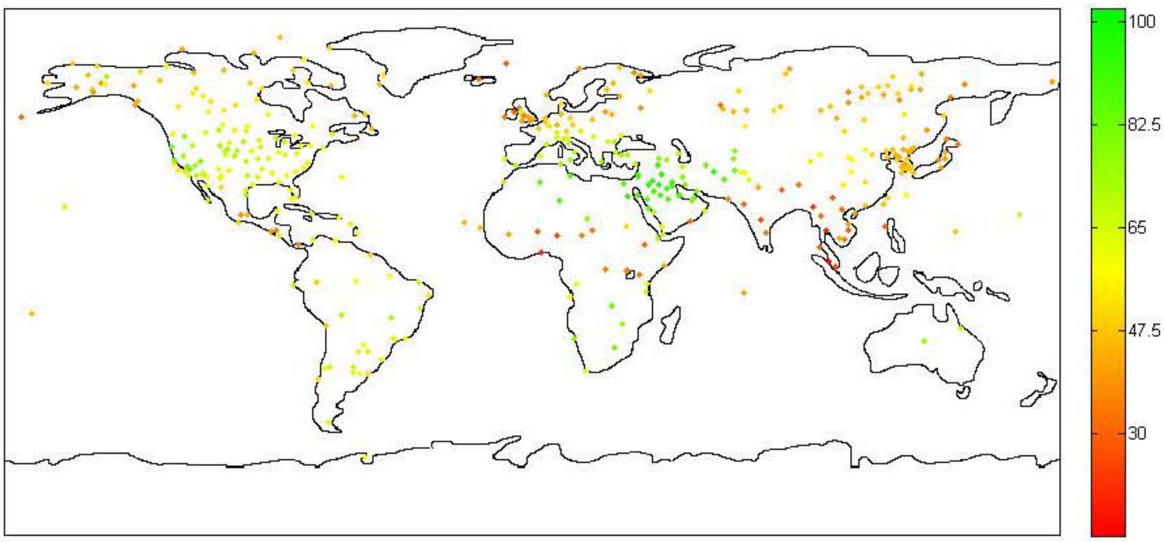

Figure 8. HELEEOS CFLOS Probabilities

HELEEOS also has a CFLOS feature which allows the user to choose more specific locations. Figure 9, below, shows CFLOS probability at the location of the scenarios ran in this study.

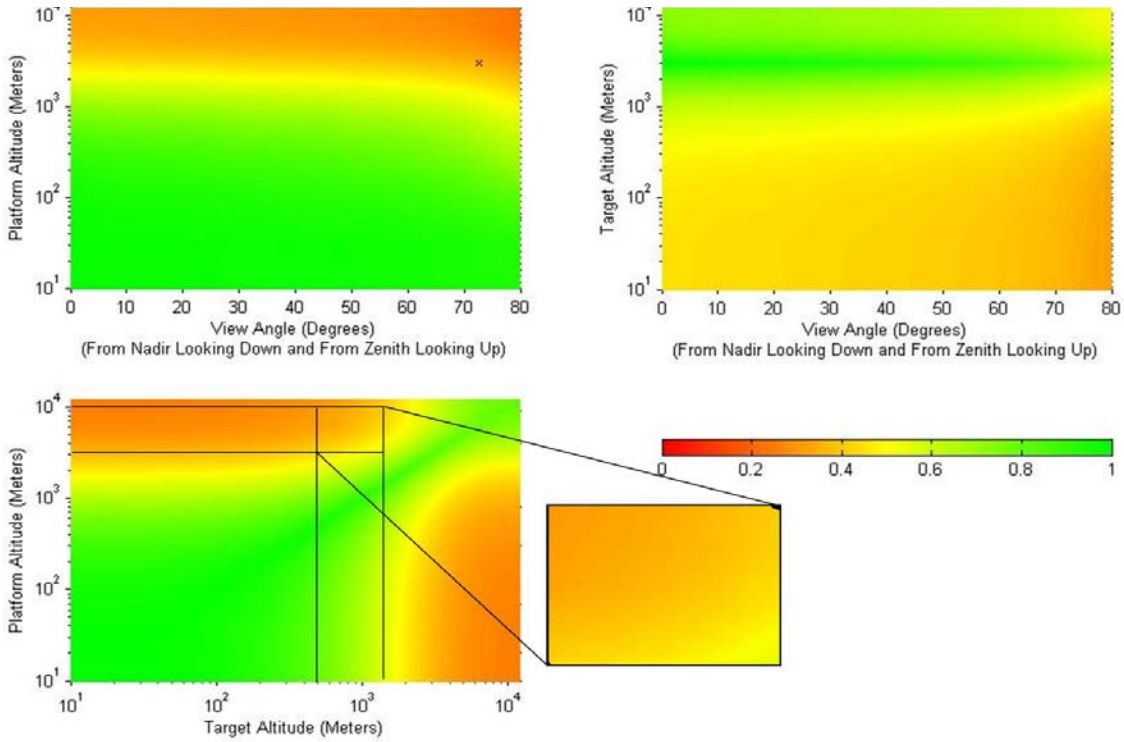

Figure 9. CFLOS Probabilities off US North Eastern Coast

It is apparent from the lower left graph that there is a relatively low probability, approximately 30-50%, of CFLOS for the settings of weapon and target altitudes used in this study. In general CFLOS probability is highest when the platform and target are the same altitude, highlighted by the diagonal space, having a slope of one traversing the graph in the lower left graph, corresponding to 100% CFLOS probability. As seen from the zoomed in scenario setting box, 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. This graph shows the highest probability, 50%, for the scenario settings occurs when the platform is at 3000 meters and the target altitude is 1500 meters. This probability decreases as the vertical distance of the platform to the target increases, thus is at it's lowest when the platform and target are 10,000 and 500 meters, 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 (Bartell, 2007).

The options tab allows the user to choose the desired scaling law, weapon configuration, and outputs. For this study the Share Scaling Law was chosen because it allows for adaptive optics to be used. It also uses the angle between the target velocity and beam for angle of incidence calculations. Weapon configuration allows the user to choose from no aero optical model, conformal aperture, or slow moving turret to represent the different effects each of these has on laser power delivery. A conformal aperture is what typically is found on a pod configuration, but can also be capable of slewing in this arrangement. According to A9 analyst, Tim Booher, HELLADS configuration will be equipped on such a pod; therefore conformal aperture is used for HELEEOS setup, along with a slewing ability employed in EADSIM. The Line of Sight of the HELLADS in this configuration plays an important role in engagement geometries and hence is considered a major factor in deciding Rules of Engagement (ROE) and CONOPS. This will be discussed in further detail later. Finally, output for EADSIM tables and the appropriate text and matlab file selection are chosen to create the appropriate propagation tables that will be used to populate EADSIM vulnerability tables.

The Setup Atmosphere tab allows the user to choose aerosol type and atmosphere type. Available HELEEOS atmospheric conditions are based on actual data from several reputable sources and reflect variability produced by worldwide seasonal, diurnal, and geographical spatial-temporal factors. Aerosol types are classified into groups consisting of urban, rural, continental, maritime, desert, and arctic. Each of these groups have different levels, average, clean, tropical and polluted to choose from. For this study the Advanced Navy Aerosol Model is used to represent the ocean's aerosol characteristics. Atmosphere type is segregated by location and can be general areas such as Mid-latitude North Atmosphere, or more specific, such as Ocean Regions. One can further specify location with latitude, longitude settings. In this case the model uses data from the closest one-by-one, latitude-longitude grid system in which it is partitioned. Furthermore the model gives the choice of seasonal atmospheric conditions in the selected region.

Earlier, the generalities of laser beam degradation from aerosols were discussed, but a more specific discussion of this relationship, as it pertains to maritime environments, is in order. Aerosol volume decreases as altitude increases; they are negatively correlated. In general, aerosols will have a negligible effect on laser engagements occurring above the 'boundary layer', or 500 meters, however, laser effectiveness degrades for engagements occurring below this threshold. The volume of aerosols which adversely effect 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. As mentioned above season also plays a role in the amount of aerosols in the air. In general summer will have more however for this particular study, because it occurs over the ocean, the differences between summer and winter are too subtle to have a significant impact on the peak irradiance (Bartell, 2008).

This study assesses HELLADS capabilities for Homeland Defense in a maritime environment and investigates HELLADS performance on the upper edge of, and above, this boundary layer. Regarding HEL effectiveness, this type of scenario is potentially very degrading. However, as eluded to earlier in the *HEL Modeling and Simulation Challenges* section, the distortion, caused by aerosols depends on beam wavelengths, with specific wavelengths mitigating these degrading effects. Figure 10 shows the extinction coefficient, i.e., sum of scattering and absorption, as a function of wavelength. (Sprangle and others, 2004).

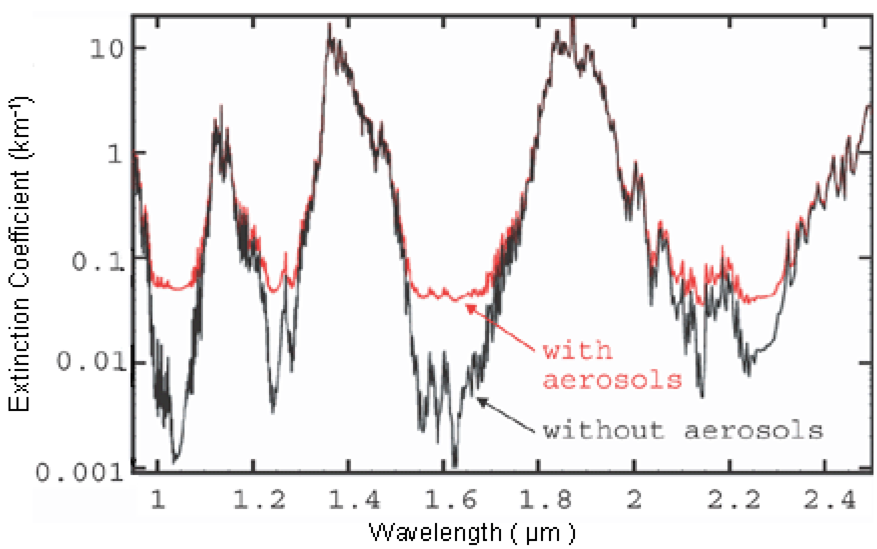

Figure 10. Extinction Coefficient vs Wavelength (Sprangle, 2004)

Figure 10 was generated by data representative of a mid-latitude 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, or more specifically water vapor for this case.

The turbulence profiler offers several choices, provided by the Master Database for Optical Turbulence Research in Support of the Airborne Laser, for the user to choose an applicable turbulence level. For this study the Hufnagel Valley 5/7 profile is chosen as it is seen as the default and is appropriate for this study (Bartell, 2007).

Next is the Engagement Geometry Setup which allows the user to input platform, target and wind settings. Wind settings can be chosen between the Bufton and Expert Wind Profile. If the Bufton Wind Profile is selected a speed is chosen however, when the Expert Wind Profile is selected a percentile is chosen. Wind direction is designated for both profiles. The Expert Wind Profile is chosen for this study because it contains seasonal average wind speeds over ocean areas. Platform and target settings consist of altitudes, vertical and horizontal velocity, vertical and horizontal acceleration, and velocity and acceleration headings. 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 used in this study, geometry will play little to no role in irradiance values This particular wavelength will have little absorption which means it will also have very little thermal blooming. Geometry effects thermal blooming but since there will be very little thermal blooming associated with this wavelength, geometry is essentially not a factor in calculating irradiance (Bartell, 2007).. Note this wavelength is very close to the first trough found in Figure 10 above. Engagement dwell time and number of steps can be specified here, but also are irrelevant to this study as they are solely used for HELEEOS Pk calculations and will not be used in EADSIM.

Target setup consists of choosing susceptible target length and width, and also allows the user to calculate target damage threshold by material and thickness inputs. Again, for this study these are irrelevant for the same reasons just explained.

The final setup step involves laser parameter inputs. Here wavelength, relative obscuration, beam quality, wavefront error, total system RMS jitter, laser type, laser propagation model, laser power, adaptive optic levels, laser system weight constraints, and magazine depth are specified. Typically a wavelength of 1.31525 µm was used in EADSIM for previous studies assessing similar HEL capabilities however, for this study the wavelength is 1.07 µm, representing the proposed HELLADS wavelength. With guidance from Rick Bartell a beam quality of 1.3 is used in this study and resembles that of previous studies of this type. Beam quality is a value which denotes the focusability of a laser beam. The diffraction limited signifies the optimal, or best, spot size which can be achieved by a laser beam, and is denoted by 1. A beam quality of 1.3, then, equates to a beam which is capable of achieving a spot size of 1.3 times that of the optimal. It is calculated via dividing wavelength by aperture diameter, thus beam quality goes down, gets better, as wavelength goes down and aperture diameter goes up. Here aperture diameter is set to .3 meters (1 foot) to simulate the typical aperture size used by a conformal aperture weapon configuration (Rick Bartell, 2007).

Relative obscuration is a measurement of how much the primary mirror is obscured by the secondary mirror and is set at .1, or 10%, which is typical for HEL. Wavefront error only becomes a factor at slant ranges greater than approximately 100 km. Given this study concentrates on closer ranges, wavefront error is set at zero. Total system RMS jitter is a measurement of uncompensated platform jitter and is compensated for by the medium Adaptive Optics (AO) system setting chosen in this study. The AO, and tracking system associated with this setting, will not be affected by jitter under 5 µm for ranges under 30 km, therefore jitter is also set at zero. Magazine depth is not relevant as it relates only to the HELEEOS Pk calculation and will not play a role in EADSIM, thus it is left at its default setting of one. Laser type is set at continuous wave and laser power is set at 150 kW to represent proposed operational values of HELLADS. The HELEEOS input parameters are summarized in the following table.

Table 4. HELEEOS Input Settings

Parameter	Initial Settings	Parameter	Initial Settings
Scaling Law	Share	Target Vertical Velocity m/s	0
Aero Optic Model	Conformal Aperture	Target Acceleration Heading	N/A
Aerosol Type	Advanced Navy Aerosol	Target Vertical Acceleration	N/A
Turbulence Profiler	HV 5/7	Target Horizontal Acceleration	N/A
Atmosphere Type	Ocean Summer: Lat 38, Lon -74	Engagement Dwell Time	N/A
Turbulence Multiplier	1 (default)	Number of Steps in	N/A
Wind Model	Expert	Susceptible Target Width	N/A
Wind Percentile	50% (average)	Susceptible Target Length	N/A
Wind Direction	90 (east)	Target Damage Threshold	N/A
Platform Altitude m	3000, 6500, 10000	Laser Wavelength µm	1.07
Platform Velocity Heading	0 (north)	Relative Obscuration	.1 (Default)
Platform Initial Distance from platform	--	Beam Quality	1.3
Platform Horizontal Velocity m/s	200, 250, 300	Wavefront Error	0
Platform Acceleration Heading	--	Total System RMS Jitter	0
Platform Initial Relative Azimuth to Next Object	315 (NW)	Laser Type	Continuous Wave
Target Altitude m	500, 1000, 1500	Laser Propagation Model	Top Hat
Target Velocity Heading	270 (west)	Adaptive Optics	Med (No AO, Average Tracking System)
Target distance from last object m	25,000	Exit Aperture Diameter m	.3
Target Horizontal Velocity m/s	200	Magazine Depth	N/A

EADSIM Overview

The primary EADSIM mission used in this study will be regarding attacks from the air. The employment of HELLADS to quell threats from the air, i.e. missiles and rockets, will be assessed by running operationally realistic potential scenarios. Air to ground attacks, in particular cruise missiles, will be the primary focus of this study. These are the threats that brought HEL into conception. Lasers travel at the speed of light and are capable of destroying enemy rockets before they even are out of their boost phase. For example if a SCUD missile is launched and a missile, with an average speed of mach 5, is fired to intercept the SCUD, it will take approximately 3 minutes for the missile to reach a distance of 200 miles. Considering ballistics missiles are most vulnerable in their boost phase, and given a SCUD's boost phase is 60 seconds, the missile will not arrive in time to ensure a high probability of kill (Zimet, 2002). Assuming it is in a position where it can engage, a HEL weapon, on the other hand, can deliver energy to the SCUD instantaneously, arriving during a ballistic missile's boost phase, hence greatly increasing the probability of kill.

Factor Levels

Simulation model output from inputs which do not represent HELLADS CONOPS, or are not practical, and would be invalid, thus to properly assess HELLADS capabilities great care must be taken in using appropriate inputs. The methodology used in this study uses a baseline scenario, in which inputs are set at basic levels to verify model output aptness. Once this is accomplished, factor levels are changed to explore HELLADS operational envelope. These scenarios 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 and the rationalization in making these choices follow.

Weapon Platform Factors

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 3000, 6500, and 10000 meters. 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. The target velocity settings remain unchanged at 200 m/s throughout this study. The question for this scenario becomes: Do higher platform altitudes, which result in slightly higher irradiance values but have relatively smaller CFLOS probabilities, give the HELLADS any advantage in this particular scenario? This question is answered in the next chapter.

The scenario setup resembles a situation in which cruise missiles are detected off the coast and a fighter is scrambled to intercept them before they reach the coastline. The scenario occurs when the first cruise missile is approximately 322 km off the coast line, with the fighter flying directly at the salvo. The engagement scenario begins when the fighter is approximately 90 km directly in front of the first cruise missile, in between the salvo and it's intended target. This scenario allows the fighter to begin lazing on the incoming cruise missiles while flying head on with them. When the fighter surpasses the salvo it turns 180 degrees and follows the cruise missiles, at which time the cruise missiles turn in an attempt to evade the chasing fighter. The fighter reacts to the evasion maneuver by mimicking the evasion pattern of the cruise missiles and continues to engage them.

The scenario time is 1000 seconds, or 16 minutes and 40 seconds, and the salvo of nine cruise missiles come in 3 groups of three, with each group starting at a different time, but at approximately in the same location, in the scenario. The first, second, and third group of cruise missiles' initiation times are 0, 100, and 180 seconds, respectively.

Weapon configuration also plays a role, albeit indirect, in peak irradiance. HEL delivered by a slewing turret, potentially, has the advantage of engaging targets in a 360° field of view. This configuration's shortcoming is the degrading effect airflow has on the laser beam when shooting with the wind, which arises anytime lazing occurs in a direction greater than ±90° from the trajectory of the platform (Bartell, 2007).

For this study a pod, or conformal aperture, is used to resemble the proposed HELLADS configuration specified by Capt Timothy Booher, an A9 HELLADS analyst (Booher, 2007). Although when lazing into the wind the laser beam degradation is negligible, employing a conformal aperture for laser beam delivery does limit HELLADS engagement, namely with regards to LOS. For this reason the target must be in the conformal apertures LOS before it can be engaged. However, the agility of the platform, a fighter, should compensate for this configuration's LOS restrictions.

Having a conformal aperture with no slewing capability is not a feasible configuration for this would put an enormous workload on the pilot. To compensate for this limitation it was suggested, by A9 analysts, to incorporate a slewing capability into the HELLADS. With advise from Rick Bartell and A9 analysts two different slewing settings were employed in this study; ±30° and ±60° (Bartell, 2007; Booher and others, 2007).

Target Factors

Targets in this study consist of **c**ruise missiles, which are typically low flying, and applicable altitudes and velocity were chosen to be 500, 1000, and 1500 meters and 200 m/s, respectively. A salvo of nine cruise missiles incoming from the sea towards the coast, where the fighter scrambles to, represents the engagement scenarios. The ability for a laser to burn through a material 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 (McGinnis and others, 2000:3).

According to some experts there are four main ways to kill a target via HEL (Souder and Langille, 2004:3). 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 aimpoints for a cruise missile; nose, fuselage, and wing. In this study it is assumed that burn through at any of these aimpoints will cause failure and result in a kill.

Vulnerability Table

EADSIM uses a vulnerability table to look up applicable data in making a Pk assessment. Peak irradiance values were generated in HELEEOS for specific platform and target altitudes, with specific slant ranges, and used to generate power propagation (pp) files in EADSIM. EADSIM uses these pp-tables to look up applicable peak irradiance values which it then uses to look up the dwell time needed to kill the target, given the value from the pp-table. The vulnerability table, or ll-file, contains the same peak irradiance values from the appropriate pp-table, along with chosen Pk values, which are calculated by a random draw in EADSIM. Using the peak irradiance values and the randomly drawn Pk, it looks up the applicable dwell times which populate appropriate vulnerability table, or ll-file. The platform altitudes are 3000, 6500, and 10,000 meters. Using each of these platform altitudes, scenarios were set up to engage the targets at their applicable settings. Examples of the power propagation and vulnerability tables in Appendices A and B. Employing these HELEEOS inputs, results in the desired Peak Irradiance values, at resulting slant ranges, used by EADSIM to assess Pk.

EADSIM has a built in cruise missile target designator and Pk values are calculated, by estimating the power necessary to defeat such a target. A material damage study conducted at the Naval Postgraduate School (NPS) in 2000 investigated this very issue. It used the following equation, along with physical characteristics of aluminum, to calculate laser intensity required to bring aluminum to vaporization temperature:

$$E_0 = \rho d(c[T_m - T_o] + \Delta H_m + C[T_v - T_m] + \Delta H_v) \tag{2}$$

Where E_0 is the required flux density, ρ is the density, d is material thickness, C is 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 (McGinnis and others, 2000:5, 6). Table 5 shows specific values for these variables used in the NPS study.

Table 5. Aluminum Properties

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

Using 3 cm for d, and an ambient temperature of 25ºC, equation (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 calculations, this flux density is converted to 226, 468 W·sec/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.

$$T_d = \frac{E_0}{Irradiance} \qquad (3)$$

Units cancel out leaving dwell time, T_d, required to destroy the target in terms of seconds. In this manner it is possible to estimate how long it will take, given certain inputs, to destroy a cruise missile in EADSIM.

For each target EADSIM makes a random draw, from a uniform distribution, to establish the amount of energy required to defeat it. The average, or minimum, energy required to defeat a specific target would be considered the 50th percentile and would correspond to a .5 being drawn in EADSIM. The methodology used in this study equates any draw less than or equal to .5 to the average irradiance, approximated from equation 2, needed to defeat a cruise missile; recall this values was estimated to be 226, 468 W·sec/cm^2. Table 6 shows energy required for percentiles above 50, which correspond to random draws in EADSIM above .5.

Table 6. Energy Required for specific random draws

EADSIM Random Draw (d)	Energy Required Percentile	Energy Required W/cm^2 (E_0)
$0 < d \leq .5$	50th	226, 468
$.5 < d \leq .6$	60th	249,115
$.6 < d \leq .7$	70th	271,762
$.7 < d \leq .8$	80th	294,408
$.8 < d \leq .9$	90th	317,055
$.9 < d \leq 1$	100th	339,702

Random draws in increments of ten represent 10% more energy to defeat the target. Therefore energy required for the 60th, 70th, 80th, 90th, and 100th percentiles are calculated by multiplying the minimum energy required at 0th to 50th percentiles, 226, 468 W/cm^2, by 1.1, 1.2, 1.3, 1.4, and 1.5, respectively. Once the energy requirement has been established equation (3) will determine the dwell time requirement by using the E_0 from Table 6 and the irradiance found in the propagation tables, provided by HELEEOS, for the specific engagement parameters. This methodology is used in populating the vulnerability tables, or ll-files in EADSIM.

EADSIM Scenario Setup

Taking into consideration the Homeland Defense nature of HELLADS CONOPS, scenarios for this study are located on coastal areas. A fighter is scrambled to intercept and destroy an incoming salvo of cruise missiles. The cruise missiles' target is an airbase located near the coastline and once the fighter intercepts the cruise missiles' path, and begins engagement, the cruise missiles start evasion tactics which the fighter reacts to with its own offensive maneuvers.

EADSIM scenarios are built in a hierarchical process with each level building on lower levels. The elements level is the lowest level and consists of airframes, sensors, rulesets, communication devices, jammers, weapons, navigations, protocols, radar cross sections, infra-red signatures, probability of kill (Pk), formations, fly out tables, maneuvers, and electromagnetic pulses (EADSIM User's Manual, 2006: 5-13, 5-14). Combinations of these individual components makeup the systems, which are the next level up in the hierarchical process. Systems are then deployed to form the next level, platforms, which are subsequently organized to form laydowns. These laydowns are interconnected with networks and combinations of all these lower levels can be built to form scenarios. This hierarchical construction process is summarized in Figure 11 (EADSIM User's Manual, 2006: 5-2, 5-3).

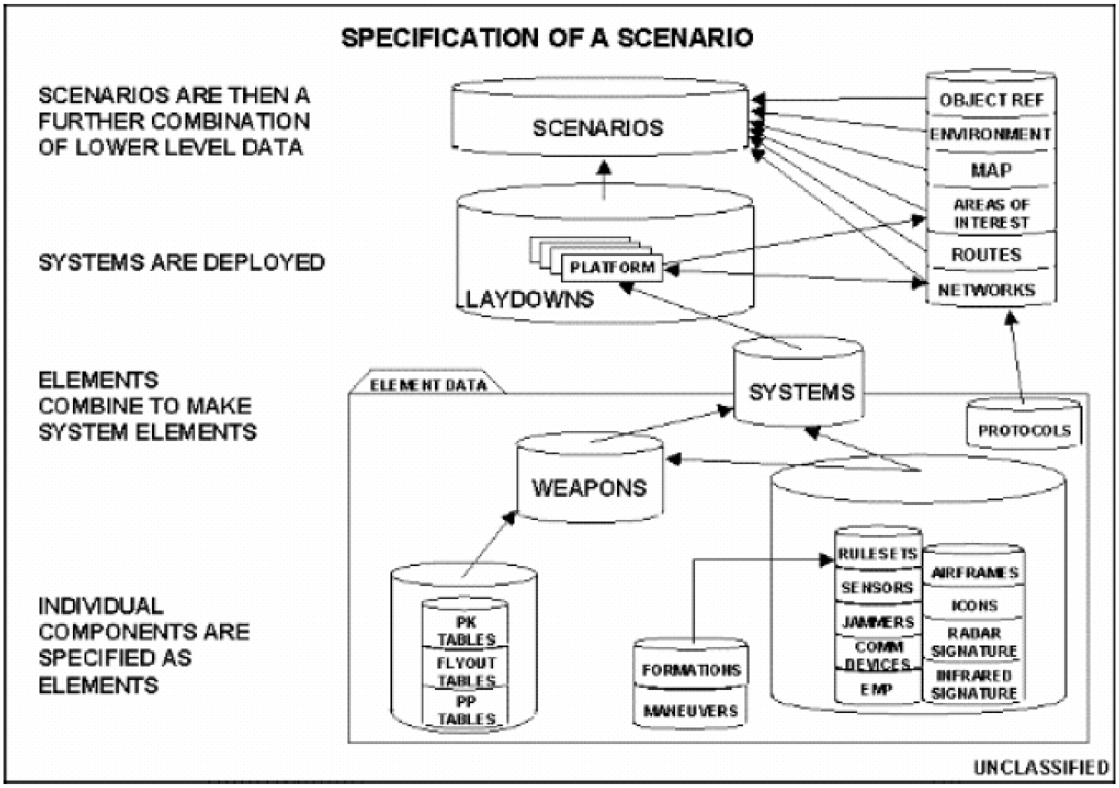

Figure 11. EADSIM Data Organization

The four main elements used in this study are airframe, sensor, weapon, and ruleset. A fighter aircraft is chosen as the airframe and given applicable settings for HELLAD type engagements versus cruise missiles. Sensors are set up to be able to perform the functions required by a HEL weapon. Here also, laser is the obvious weapon choice and ruleset features are discussed below.

A combination of defined elements makes up a system. A system can be one of three types, ground, airframe, or satellite. A system ruleset determines how the chosen system type will behave (EADSIM User's Manual, 2006:5-26, 5-27). Ruleset architecture consists of three main areas: the Battle Management/C3 (BM/C3) phases, Message Processing, and Track Processing. The first two areas are highly interdependent as BM/C3 decisions will be based on received messages (EADSIM Methodology Manual, 2006:4-24).

Tracks can be initiated, maintained, and updated via local and remote sensors (EADSIM Methodology Manual, 2006:4.6-1). The fighter in this study, for instance, relies solely on it's onboard tracking sensor. It is imperative for a HEL weapon to have a tracking system that is capable of performing at a level which allows the HEL weapon to operate as it is intended. A HEL weapon should be able to track and laze, simultaneously. Without an appropriate tracking system the advantages a HEL weapon possesses are negated (Bartell, 2007).

Both local and remote track data is processed the same with the local track thread being totally devoted to processing incoming track data in the form of locally generated track measurements. Figure 12 summarizes the track thread processing methodology (EADSIM Methodology Manual, 2006: 4.6-7, 4.6-8).

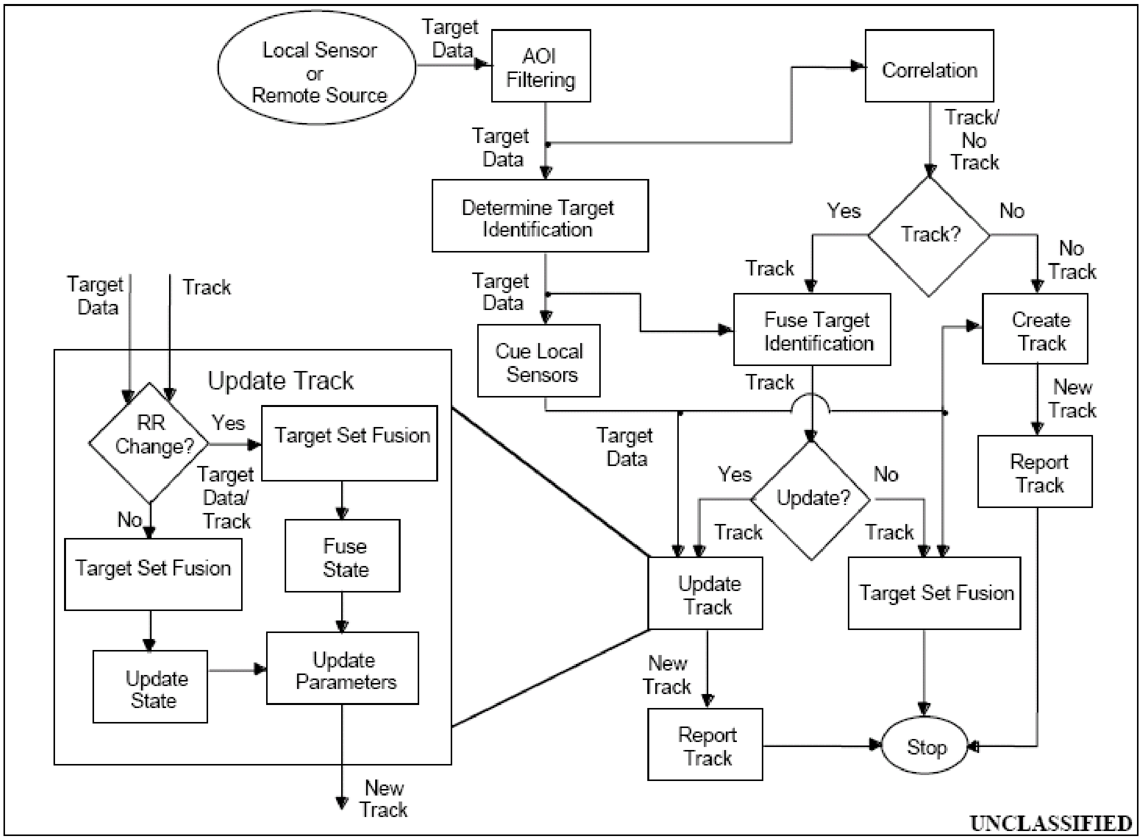

Figure 12. EADSIM Track Processing Flow Diagram

Tracked targets are added to a target list where they are prioritized on a user defined basis. Engagement prioritization can be assessed using the following options: shortest time to kill, longest time to kill, highest altitude, lowest altitude, highest elevation angle, lowest elevation angle, shortest time to burnout, track maturity, and shortest time from launch (EADSIM Methodology Manual, 2006:4.7.33-12). Once the engagement decision is reached the laser phase, consisting of slewing, warming, settling, and lazing, begins.

Table 7 shows the settings for the EADSIM scenarios with three factors at three levels and one factor at two levels. For a full factorial, in which all combinations of every setting is represented, this experiment result in $3^3 \cdot 2^1$, or 54 runs.

Table 7. EADSIM Scenario Factor Settings

Factor	Low	Med	High
Weapon Altitude (m)	3000	6500	10000
Weapon Velocity (m/s)	200	250	300
Target Altitude (m)	500	1000	1500
Target Velocity (m/s)	200	200	200
HELLADS LOS (deg)	±30	N/A	±60

Summary

This section explained the methodologies of this study as they pertain to models used, HELEEOS and EADSIM, and also discusses applicable parameter settings and the reasoning behind their designations. Subject matter expert input was used in all settings possible, such as weapon configuration, assumptions, limitations, and HELLADS CONPOS. The methodologies in this section are used in building scenarios that, as closely as possible, represent realistic operational HELLADS engagements. Output from these scenarios was analyzed to determine the significance of factors, such as weapon and target altitude and speed, and HELLADS LOS, and how they effect MOEs, primarily HELLADS Pk. The next chapter, *Results and Analysis*, delves into the analysis of the outputs provided by the methodologies discussed in this chapter.

IV. Analysis and Results

Overview

This chapter discusses the results determined by analyzing the data provided in Appendix C. The primary analysis tools used in this study are ANOVA and linear regression. ANOVA is applied in determining how each factor, and factor interactions, effects the MOEs. Once this determination is made, significant factors can be labeled and used, via linear regression, to build a prediction equation which provides a reasonable method for predicting MOEs given specific factor settings.

Data Table Generation

As explained in the previous chapter there is a total of 54 runs in this study. For half of these however, the pp-tables are identical since one of the settings, HELLADS LOS, set in EADSIM, does not affect peak irradiance values. HELEEOS is used to generate peak irradiance values for 27 runs, each consisting of 50 slant ranges, resulting in 1350 total irradiance values, which are subsequently used to populate the appropriate pp-tables used in EADSIM. Also discussed in chapter 3 was the methodology used to calculate the dwell times for peak irradiance at each slant range for the 0^{th}, 50^{th}, 60^{th}, 70^{th}, 80^{th}, 90^{th}, and 100^{th} Pk percentiles. This results in a total of $7 \cdot 50 \cdot 27$, or 9450, dwell times used to populate the vulnerability tables, or ll-files, in EADSIM. An example of the tables used for power propagation, pp-tables, and vulnerability, ll tables, are shown in the figure below.

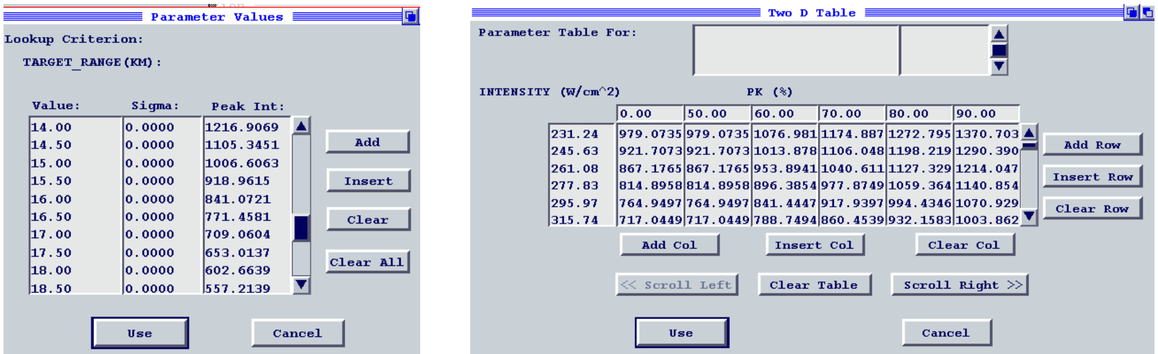

Figure 13. EADSIM Propagation and Vulnerability Tables

HELEEOS Results

Plotting peak irradiance values generated by HELEEOS allows investigation of their validity. In other words do HELEEOS peak irradiance values reflect the expected effects of different factor settings? We would expect the peak irradiance values to be lower for more oblique angles and larger slant ranges. The fifty slant ranges used range from 500 to 25,000 meters in increments of 500 meters. Note that certain slant ranges are not applicable at specific platform and target altitude settings. For instance, platform and target altitude settings of 3,000 and 500; 3,000 and 1,000; and 3,000 and 1,500 meters; will never have a slant range of less than 2,500; 2,000; and 1,500 meters respectively. Table 8 shows the slant ranges that are not applicable for certain platform and target altitudes.

Table 8. Non-applicable slant ranges

Platform Altitude (m)	Target Altitude (m)	Non-Applicable Slant Ranges (m)
3000	500	< 2500
	1000	< 2000
	1500	< 1500
6500	500	< 6000
	1000	< 5500
	1500	< 5000
10000	500	< 9500
	1000	< 9000
	1500	< 8500

From figure 14 it is evident that peak irradiance values calculated by HELLEOS do follow our expectation and decrease as slant range increases. Although there is a small increase in average peak irradiance at closer slant ranges for slower velocities, it has a negligible effect.

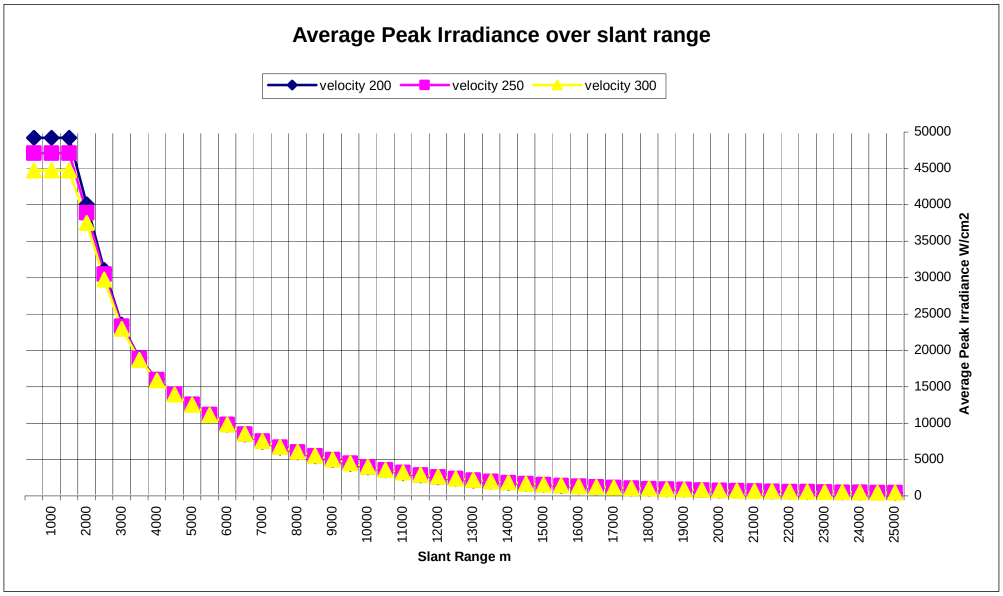

Figure 14. Average Peak Irradiance over slant range

The next validity check on HELEEOS output is to verify the expected effect angle, referred to earlier as obliqueness, has on peak irradiance. In this assumption, as the angle between the laser and the target decreases so will the peak irradiance. In other words the more similar the altitudes of the platform and target are, the lower the peak irradiance should be. Figure 15 below shows the average peak irradiance values, over all applicable slant ranges, across all altitudes and velocities used in this study.

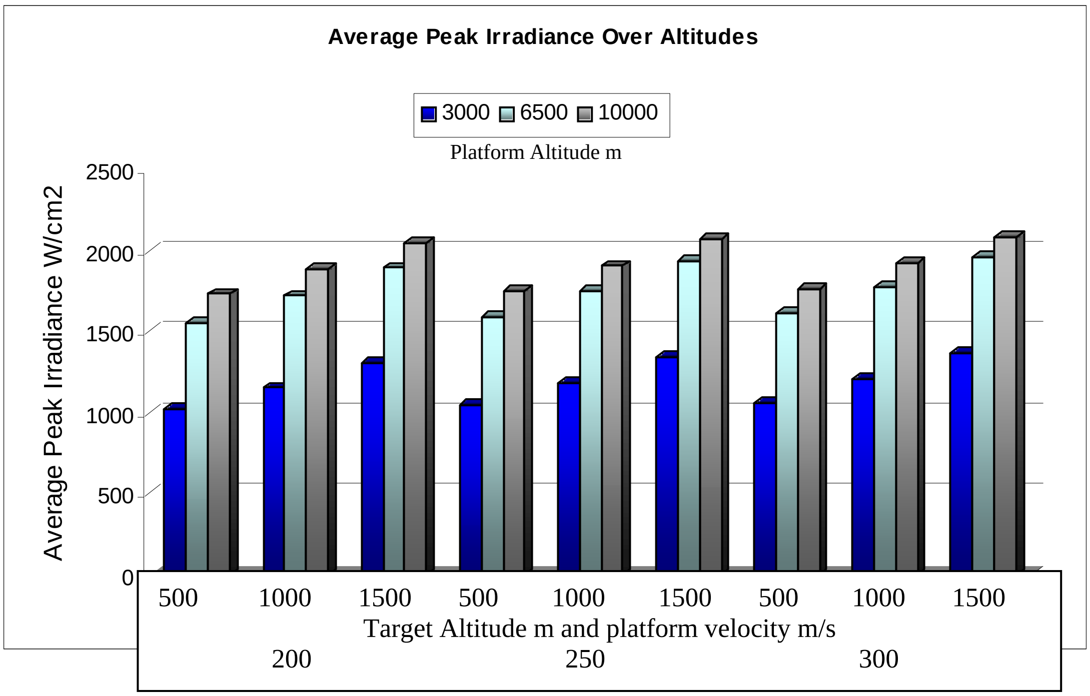

Figure 15. Average Peak Irradiance over all common slant ranges

It is apparent that the average peak irradiance increases as the platform altitude increases. This verifies that HELEEOS is reflecting the relationship between peak irradiance and angle of incidence correctly; as platform and target altitude differences grow, so does peak irradiance.

Figures 14 and 15, above, verify HELEEOS accuracy in calculating peak irradiance as it relates to specific parameters however, as seen in Table 8, higher altitudes negate more of the close slant range peak irradiance values. Figure 15 shows the average peak irradiance values applicable over all the platform altitudes for each target altitude, but the results for this table are calculated using only slant ranges applicable to all the platform altitudes at each target altitude. For example, for the case where target altitude is 500 meters the peak irradiance for each platform setting is averaged over slant ranges of 9500 to 25000 meters. In other words the average peak irradiance for higher altitudes is higher however; it does not take into account the peak irradiance values occurring in ranges that are applicable at lower platform altitudes. This is a vital insight in understanding EADSIM output.

By looking at Figure 15 it may be presumed that higher altitudes, resulting in higher average peak irradiance values, equates to a higher Pk however, this is not the case. Since peak irradiance values are more influenced by slant range, the increase of peak irradiance due to higher altitudes is completely negated by the larger slant ranges they apply to. A platform and target altitude of 10000 and 500 meters, respectively, will never have a slant range of less than 9500 however, if the platform and target altitudes are 3000 and 500 meters, respectively, the minimum slant range is 2500 meters. Peak irradiance values at smaller slant ranges, applicable only in lower platform altitudes, give the platform a much better advantage than peak irradiance increases due to higher platform altitudes, see Figure 14. It is also important to keep in mind CFLOS probability, not accounted for in this study, decreases as the platform and target altitude differences increase.

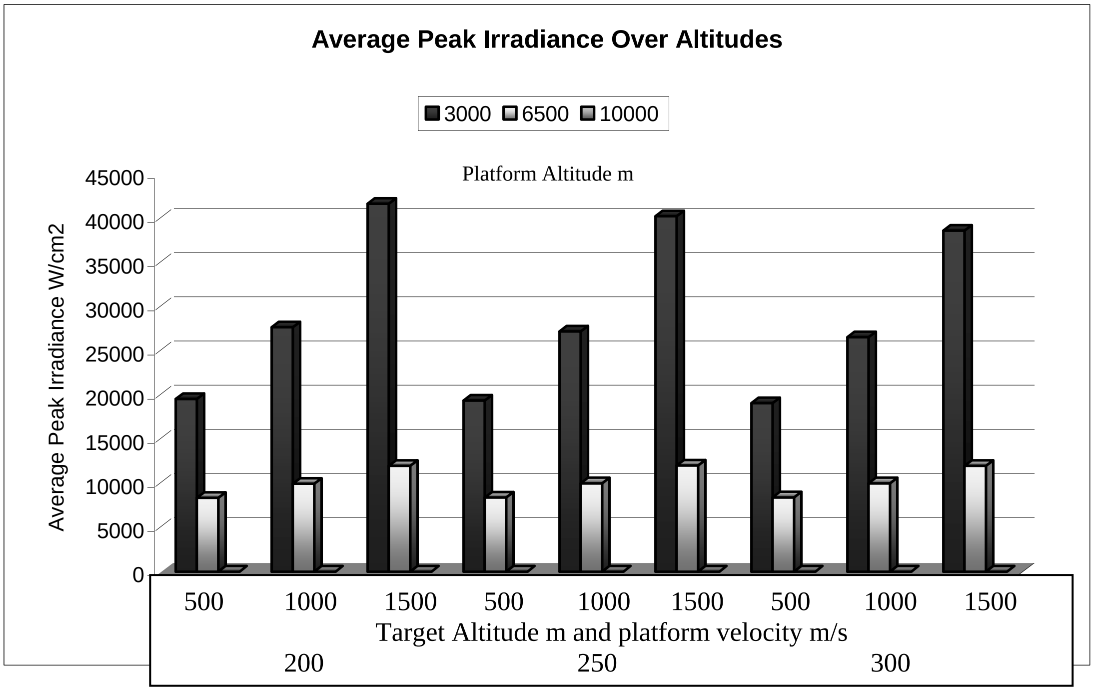

Figure 16. Average Peak Irradiance over low altitude slant ranges

It is very clear from this figure that the lower slant ranges, which only apply for lower platform altitudes, result in relatively large peak irradiance values. It is at slant ranges, not attainable at higher platform altitudes, where HELLADS should be most effective.

EADSIM Output

For this study each of the 54 design points was run 5 times using the monte carlo feature in EADSIM. This feature allows the user to run a determined number of runs for a specific scenario. Each run originates from a different set of random numbers generated using the built in linear congruential algorithm.

The factorial design for this study consists of three factors at 3 levels and one factor at two levels with 5 replications at each combination of each factor level combination, resulting in $3^3 \cdot 2^1 \cdot 5$, or 270, total observations. In order to model this design correctly each factor and every interaction must be incorporated in the regression model. There are $\binom{4}{1}$, or 4, main effects, $\binom{4}{2}$, or 6, two way interactions, $\binom{4}{3}$, or 4, three way interactions, and $\binom{4}{4}$, or 1, four way interaction to be considered, resulting in the model:

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

where $h = 1, 2, 3$

$i = 1, 2, 3$

$j = 1, 2, 3$

$k = 1, 2$

$l = 1, 2, 3, 4, 5$

Here μ represents the overall mean of the MOE, 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, this model is general in that it does not show possible quadratic effects.

To determine what factors significantly affect the MOE an ANOVA was conducted investigating all main effects and interactions. Using kills as the MOE the following ANOVA table was generated with A, B, C, and D representing platform altitude, target altitude, platform velocity, and HELLADS LOS respectively.

Table 9. ANOVA for all effects with kill count as MOE

Source	SS	DF	MS	F	P-value Prob > F	Significance
Block	12.57	4	3.14			
Model	1240.30	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	1441.50	269				

The p-value, for each factor, is the probability of getting an F Value equal to the size shown in the table if the term does not have an effect on the response variable. Terms with p-value of less than .05 are considered influential on the response, or significant. P-values greater than 0.10 are generally regarded as not significant. This ANOVA table shows A, B, C, D, AB, AC, BC, CD, ABC, ABD, and ACD to be significant to the MOE, kills. Since AD, BD, BCD, and ABCD were not found to have a significant effect on kills they can be rolled up into the error term. Doing so and reanalyzing the model results in the same terms A, B, C, D, AB, AC, BC, CD, ABC, ABD, and ACD being significant factors. All factors in this model are significant and the adjusted R squared value of .8350 means that this model is explaining 83.5% of the variation about the mean. The closer the adusted R squared is to 1 the more variation the model is explaining, and thus better fitting the data. Although this model fits the data nicely, it consists of eleven factors, which is considered a lot. In regression, parsimony is sought to attain a model which adequately 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. The goal in linear regression is to adequately fit the data with a minimum nuber of terms, or effects. Basically, the analyst should be willing trade a higher adjusted R squared value, for less terms, in determing the final model.

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

Since a model using only main effects can adequately explain our data the next step in analyzing the data is to ensure certain assumption hold. These being the assumptions of normality, independence (uncorrelated data), 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. The residual equation is presented below.

$$\varepsilon_i = y_i - \hat{y}_i \qquad (5)$$

where $i = 1, 2, 3, \ldots, 270$

Where y_i represents the actual observed values at the ith observation and $\hat{y}_i$ represents the fitted value, given by the current model, for the ith observation.

The normality assumption is checked by examining the Normal Probability Plot (NPP) of the residuals. The NPP plots the residuals in rank order against the cumulative probability given by

$$P_i = (i - \frac{1}{2}) / n \qquad (6)$$

where $i = 1, 2, 3, \ldots, 270$

If the NPP resembles a straight line, the normality assumption is satisfied. Checking for independence, or the absence of correlation, requires a check for time dependency in the residuals. For this assumption to hold there should be no obvious patterns related to time. In other words we should see no trends in the residuals over time, this plot should be structureless. Checking for error terms with mean zero and constant variance requires examining the plot of residuals versus fitted, or predicted, values. This plot should be stuctureless as well, with no noticeable patterns.

All these assumptions hold for the main effects model however, the software package used for this analysis, Design Expert, suggests using a Box-Cox, or power, transform to correct a slightly noticeable nonconstant variance term for the error. The purpose of the Box-Cox transform is to stabilize the variance of the response variable. When residual versus fitted values plot shows some recongnizable pattern it indicates the residuals are actually somehow related to, or dependent upon, the predicted response variable. The Box-Cox transformation modifies the response variable, by applying a power to it, which stabilizes the relationship between the residuals and the fitted response, equating to a more constant variance for the residuals. Design Expert suggests using $y^{1.29}$, in place of y, for the response variable. Power law transformations can only be performed on responses that are greater than zero, so in this case, since there do exist responses of 0, a constant of 1 is added to all responses to satisfy this limitation. Rerunning the aforementioned analysis using the transformed response data results in adequate adjusted R squared, justifying the use of using the main effects model for the response variable kills. The following figure shows the model assumptions are satisfied.

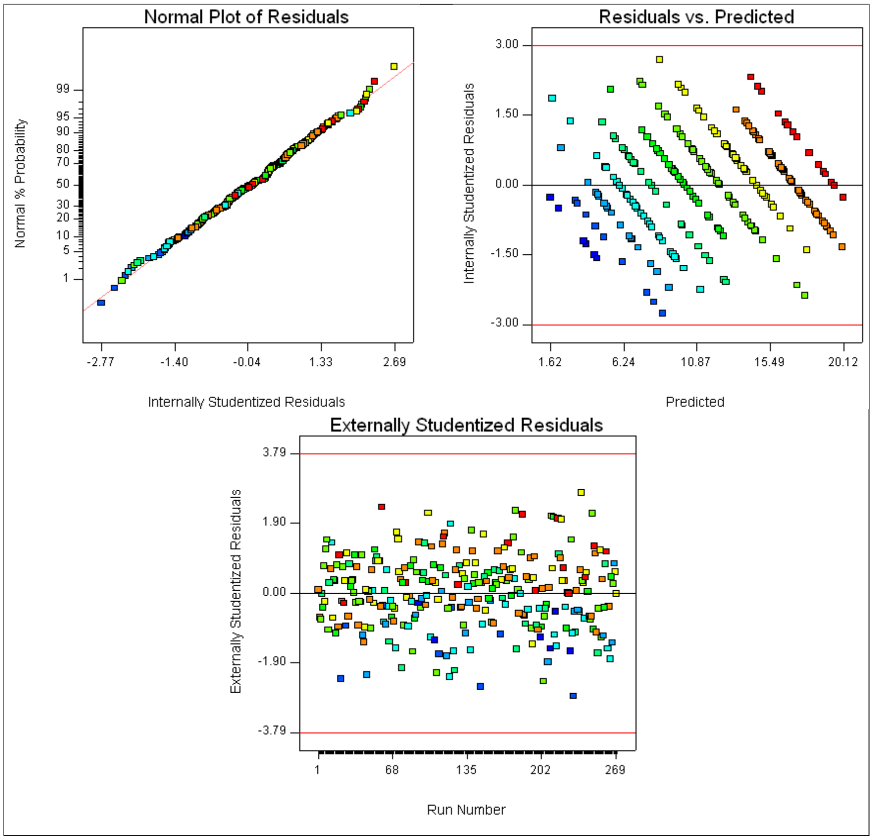

Figure 17. Model Adequacy Checks

At a glance the Residual vs Predicted plot in the upper right of Figure 17 causes some initial suspicion. The plot shows an obvious lines with negative slopes throughout. Patterns that would raise concern would be disproportionate amounts of points either above or below zero for any specific predicted values. For instance an outward opening funnel pattern would signify the variance is increasing as our response variable increases. This plot shows the residuals are scattered both above and below zero for all predicted kills, thus there is no reason to suggest a nonconstant variance.

This analysis on kills as the response results in a prediction equation:

$$(y + 1)^{1.29} = 11.46 + 4.67A + .071A^2 - 1.94B + 1.01B^2 - 1.85C + .42C^2 + .79D \qquad (7)$$

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 the next table. Recall A, B, C, and D represent platform altitude, target altitude, platform velocity, and HELLADS LOS, respectively.

Table 10. Factor Level Regression Settings

Factor	A	A^2	B	B^2	C	C^2	D
Level 1	1	0	1	0	1	0	-1
Level 2	0	1	0	1	0	1	1
Level 3	-1	-1	-1	-1	-1	-1	N/A

To solve equation (7) to predict how many kills are expected when the platform is flying at 3000 meters (A: level 1) and a speed of 300 m/s (C: level 3), the target is flying at 1000 m (B: level 2), and the HELLADS LOS is ±30 degrees (D: level 1) we put the linear and quadratic values given in the table above for the applicable levels given. Solving for y results in an expected number of kills of 8.3. The actual average number of kills given for these factor levels is 8. Using this methodology the following figure was created to show actual versus predicted values for the average number of kills for each of the 54 design points.

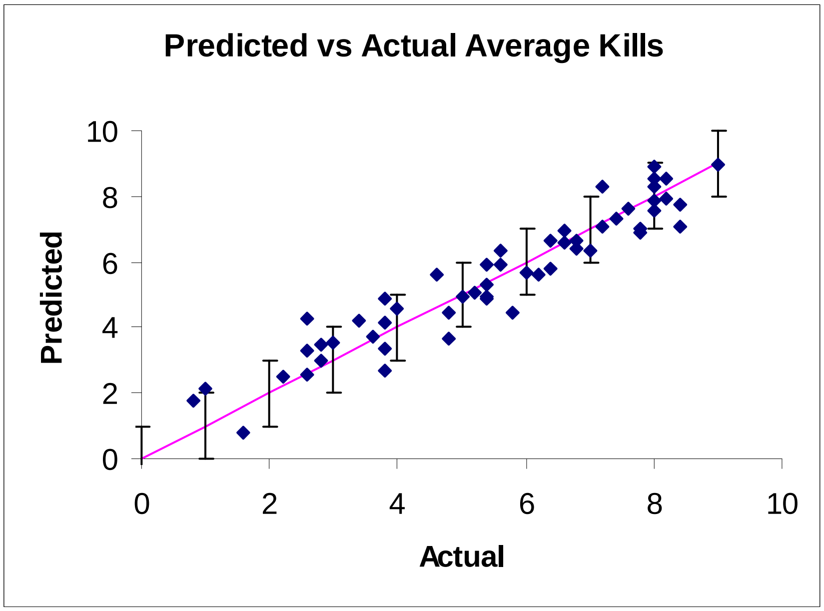

Figure 18. Predicted versus Actual Average Kills

The error bars show, in general, 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 equation (7) and the given the factor levels in table 10 above. 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 has also has a positive correlation with mean kills, the higher the LOS the higher the kills. From the equation 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. The figure below show the total kills for each factor level.

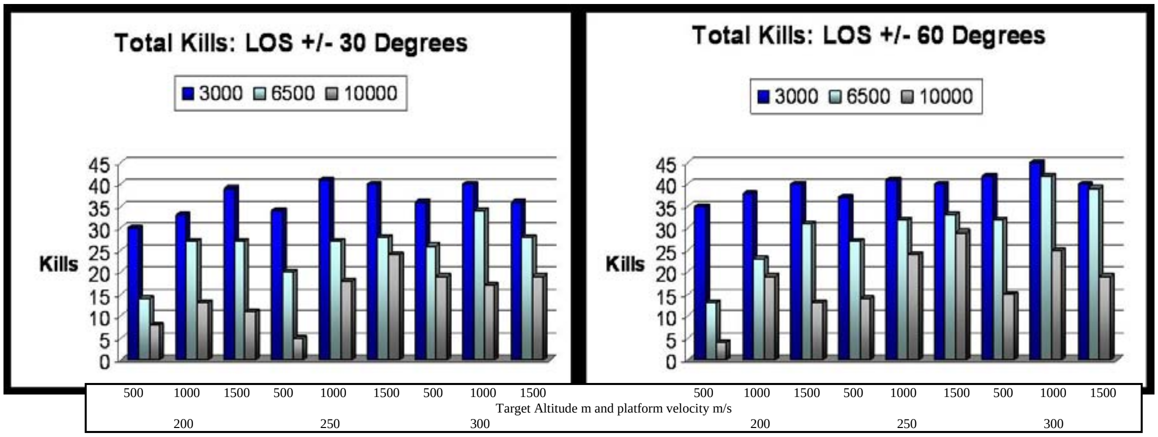

Figure 19. Total Kills over all Factor Settings

These results matchup with similar analysis conducted on HELEEOS peak irradiance values performed earlier. 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 practicl shot, the higher the kill count. The only caveat on this general observation is 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 2000 meters. This is apparent by the drop in kills, when the platform is flying 50 m/s faster than the target, when the altitude difference is 1500 meters, for both LOS settings. A positive correlation can also be seen between platform velocity and kill count, except for the case where the platform and target are at 10000 and 1500 meters, respectively,. This trend was observed in the EADSIM runs. A higher platform to target velocity ratio gives the platform an advantage because it can more easily get the target in range once it’s detected. Unfortuately, velocity change in EADSIM was a limitation in this study. In a realistic engagement the fighter could vary its speed to maximize time on target and consequently probability of kill.

Analysis of 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. Since these two factors are directly under a pilot's control they can be adjusted to create an engagement, where target altitude and LOS are known variables, which should maximize HELLADS effectiveness.

Next data analysis using average laze time as an MOE is discussed. Performing a similar ANOVA to average laze time resulted in platform altitude, target altitude, and platform velocity being significant. All laze times were utilized for this analysis, even if the laze 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 reps for the reduced number of design points. In this case, for instance, since 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, which here is 3^3. 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 effected average laze time. From Figure 20 below it is apparent that the only main effect practically influential on average laze time was platform altitude.

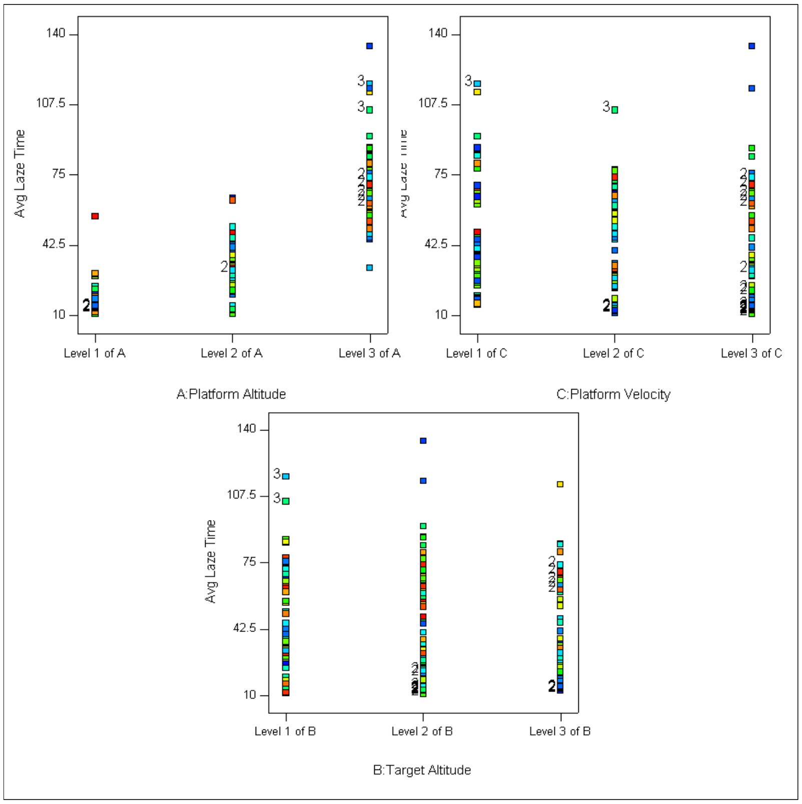

Figure 20. Average Laze Time versus Factors

Also indicative from examining this figure, and the previous figure concerning factor influence on kills, is the negative correlation between kills and average laze time. In other words this figure shows the average laze time increases as platform altitude increases, whereas in the kill analysis the opposite was evident, the response went down as platform atltitude went up. This suggest that higher average laze times do not equate to higher kill counts. This trend can be seen in the following figures.

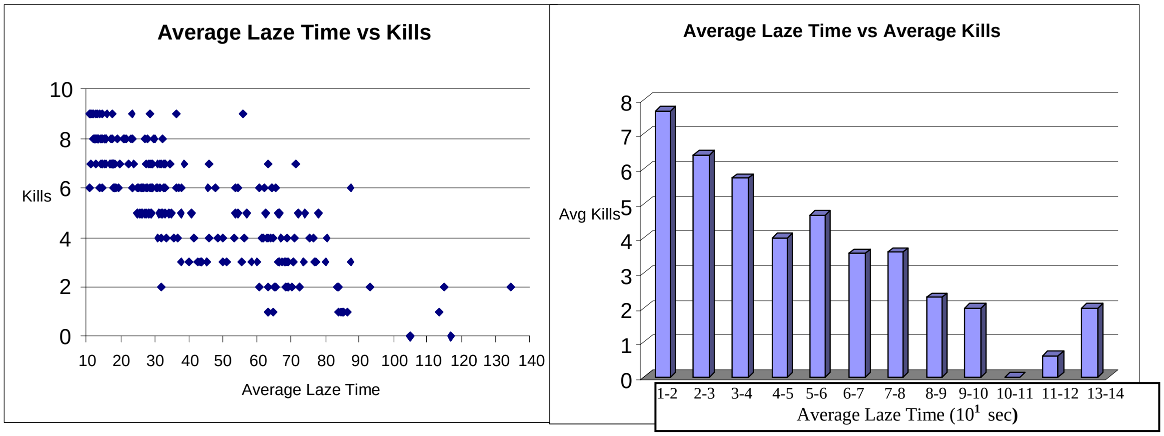

Figure 21. Average Laze Time versus Kills

Note the graphs in the figure above are essentially showing the same trend in the relationship between kills and average laze time. The graph on the left shows the relationship over all 270 runs and the graph on the right shows it for the average kills in each of the 10 second bins specified.

The tendency for higher laze times equating to less kills was also witnessed in the EADSIM playback files. The higher the platform altitude setting the more laze 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 Pk for these particular scenarios. Higher average laze times found in these scenarios can be attributed to the corresponding lower kill counts. Lower average laze times actually indicate 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.

Similar analysis was conducted using minimum and maximum laze times as MOEs. As expected, results were very much the same as using the average laze time as the MOE. Both max and min laze times were influenced most by platform altitude and, like the analysis on average laze time, increased as platform altitude did.

V. Conclusions and Recommendations

Chapter Overview

This chapter discusses the divergence from original or suggested research plan paths. Reasons for these departures will be provided, along with tying in how this study can be used as a baseline for future research. Conclusions, derived in Chapter 4, will be highlighted and recommendations will be formulated. Finally, future research suggestions will be offered.

Development of Research Plan

This research used simulations to investigate how different factors would affect a HELLADS system. Varying realistic and appropriate input parameters, resulted in varied model outputs, thus the analyst could form a relatively accurate estimation of how these factors may affect real world engagements in an operational HELLADS platform.

Originally, a lot of factors were under consideration, including jitter, aperture size, seasonal atmospheric conditions, dynamic engagement profiles, and target priority, none of which were actually tested. Some factors, such as seasonally atmospheric conditions, were not considered simply because they would have had no impact whatsoever on the HELLADS system. Others, such as jitter, aperture size, and target priority, were not included because their effect was already known, either from basic physics, previous research, or subject matter expertise. Finally, others, such as dynamic engagement profiles, or one in which the platform and target flight patterns would react to one another, were not examined due to time constraints and EADSIM knowledge. Time did not allow learning how to set up dynamic flight profiles in EADSIM.

Conclusions of Research

The factors actually tested, platform altitude, target altitude, platform velocity, and HELLADS LOS was accomplished and could be used in forming a baseline for future research regarding this type of laser platform. All the factors mentioned, but that were not included in this study, could be investigated to see how they affect HELLADS performance. Again the results from this study could be used as a starting point for the investigation of these factors.

This study revealed the most influential factors on HELLADS performance and also identified settings that increased HELLADS Pk. In most to least influential were platform altitude, target altitude, platform velocity, and LOS. Optimization showed that, regardless of target altitude and LOS, lower platform altitudes and higher platform velocities maximized HELLADS effectiveness. Keep in mind 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 1500 to 2500 feet above the target altitude. This ensures the HELLADS can be in a position to engage targets in a scenario which will have smaller slant ranges.

The results from the models revealed the most effective means to maximize HELLADS capability. Given target altitudes, velocities, and the LOS of the HELLADS a pilot could potentially increase the chances of defeating a target by flying at specific altitudes and velocities. Namely these would be 50 to 100 m/s faster than the target and, at the most, 3000 feet above the target. This assumption is based on a HELLADS with the same factor settings used in this study however, as mentioned earlier, most of these settings, if changed, would have a significant effect on HELLADS performance. For example, increasing the aperture size of the laser would equate to higher peak irradiance values, and thus increase HELLADS effectiveness. The conclusions of significance in terms of factor correlation and influence would most likely not change if factors such as these were varied, but would mirror what would be expected. However, varying such factors would, most likely, change the operational envelope of HELLADS. For instance if a higher laser power setting were used, i.e. 200 kW, the platform altitude and velocity, relative to the target, would probably still have the same effects on HELLADS performance only in this case they may even have a bigger impact. It may also increase the significance of factors which weren't found to be very significant in this study. For instance, more power would increase the lethal slant range and mask the degrading effect platform altitude had on HELLADS effectiveness, witnessed in this research. Given increased power would increase HELLADS lethal range, this degradation would still be apparent, only at larger slant ranges.

Significance of Research

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 laze 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 laze time, could actually be tested in future research more completely. This study revealed that longer average laze times was synonymous with less kills however, if certain input factors were varied, such as power, longer laze times may prove to have an enormous benefit.

This study explored initial capabilities of a developmental high energy laser weapon system using proposed input factors and realistic engagement scenarios. It presents a view of what HELLADS is initially capable of and a baseline for follow on research.

Appendix A: Power Propagation Tables

The following 3 tables show peak irradiance calculated by HELEEOS for derived slant ranges applicable to platform and target parameters. These tables directly contributed to EADSIM Power Propagation tables. Velocity refers to platforms velocity (target velocity is always 200 m/s), TA refers to target altitude, and PA refers to platform altitude.

Velocity 200	TA 500			TA 1000			TA 1500		
Slant Range	PA 3k	PA 6.5k	PA 10k	PA 3k	PA 6.5k	PA 10k	PA 3k	PA 6.5k	PA 10k
25000	231.239	437.6557	527.8839	234.8757	458.5544	543.4019	246.6658	476.0056	555.9006
24500	245.6311	461.3529	554.6302	249.8283	483.144	570.7371	262.3162	501.2859	583.6405
24000	261.0772	486.7382	583.2159	266.0607	509.7427	599.938	279.2223	528.3352	613.2646
23500	277.8269	514.0832	613.8888	283.6571	538.0895	631.6792	297.6274	557.4557	645.0329
23000	295.9672	543.4488	646.7543	302.7201	568.5071	665.2214	317.5635	588.6897	679.0436
22500	315.7404	575.1759	682.1221	323.5362	601.3568	701.3024	339.3472	622.4159	715.6221
22000	337.2128	609.3316	720.1158	346.14	636.689	740.0406	362.9971	658.7325	754.8833
21500	360.7057	646.3584	761.1329	370.9169	674.9705	781.8441	388.9318	698.0216	797.2431
21000	386.3166	686.3612	805.345	397.9331	716.2929	826.8792	417.196	740.4064	842.9602
20500	414.3882	729.803	853.1858	427.5852	761.1392	875.5884	448.6264	786.391	892.3035
20000	445.1474	776.965	904.9765	460.0953	809.7875	928.293	482.6093	836.2514	945.679
19500	478.9326	828.2693	961.1527	495.811	862.667	985.4328	519.9258	890.4242	1003.529
19000	516.1833	884.2726	1022.262	535.1994	920.3499	1047.562	561.0825	949.4964	1066.414
18500	557.2139	945.3567	1088.756	578.5667	983.2126	1115.132	606.3627	1013.838	1134.785
18000	602.6639	1012.325	1161.402	626.6191	1052.085	1188.92	656.5077	1084.302	1209.427
17500	653.0137	1085.767	1240.845	679.8297	1127.549	1269.576	711.9896	1161.47	1290.992
17000	709.0604	1166.435	1327.889	738.8174	1210.367	1357.906	773.4478	1246.106	1380.29
16500	771.4581	1255.542	1423.691	805.4112	1301.787	1455.085	842.032	1339.493	1478.503
16000	841.0721	1353.942	1529.217	878.777	1402.653	1562.08	918.4054	1442.471	1586.602
15500	918.9615	1462.907	1645.783	960.7403	1514.256	1680.22	1003.669	1556.345	1705.921
15000	1006.606	1584.2	1775.11	1052.864	1638.394	1811.242	1099.485	1682.947	1838.207
14500	1105.345	1719.409	1918.899	1156.457	1776.813	1956.858	1207.193	1823.885	1985.178
14000	1216.907	1871.549	2079.286	1273.293	1931.316	2119.218	1328.79	1981.254	2148.994
13500	1343.463	2041.315	2258.876	1405.603	2104.626	2300.949	1466.21	2157.677	2332.293
13000	1487.831	2232.894	2460.928	1556.305	2300.06	2505.333	1622.632	2356.51	2538.371
12500	1652.916	2449.679	2689.002	1728.293	2521.031	2735.953	1800.999	2581.177	2770.824
12000	1842.555	2696.115	2947.634	1925.499	2772.027	2997.373	2005.283	2836.203	3034.235
11500	2061.456	2977.655	3242.383	2152.766	3058.551	3295.187	2240.398	3127.126	3334.221
11000	2317.533	3301.052	3580.13	2416.123	3387.411	3636.319	2512.547	3460.803	3677.73
10500	2614.491	3675.017	3969.632	2723.904	3767.395	4029.564	2829.826	3846.081	4073.59
10000	2963.33	4109.852	4421.521	3084.421	4208.871	4485.563	3201.544	4293.368	4532.472
9500	3376.035	4619.04	4950.216	3510.299	4725.416	5018.166	3640.141	4816.331	5068.229
9000	3868.049	5219.948	4950.216	4017.391	5334.499	5646.012	4161.637	5432.521	5698.701
8500	4459.832	5935.238	4950.216	4626.435	6058.948	5646.012	4787.009	6164.835	6448.166
8000	5178.62	6794.891	4950.216	5365.13	6928.925	5646.012	5544.114	7043.548	6448.166
7500	6061.302	7839.31	4950.216	6270.915	7985.026	5646.012	6473.937	8109.365	6448.166
7000	7158.626	9123.827	4950.216	7395.347	9282.876	5646.012	7621.538	9418.003	6448.166
6500	8542.038	10726	4950.216	8810.675	10900.28	5646.012	9062.997	11047.31	6448.166
6000	10315.92	12756.44	4950.216	10620.9	12948.82	5646.012	10902.89	13108.66	6448.166

5500	12629.94	12756.44	4950.216	12979.57	15597.05	5646.012	13296.66	15765.92	6448.166
5000	15717.45	12756.44	4950.216	16120.69	15597.05	5646.012	16477.1	19272.78	6448.166
4500	19946.34	12756.44	4950.216	20424.31	15597.05	5646.012	20816.2	19272.78	6448.166
4000	25928.47	12756.44	4950.216	26486.78	15597.05	5646.012	26931.17	19272.78	6448.166
3500	34730.45	12756.44	4950.216	35388.13	15597.05	5646.012	35895.91	19272.78	6448.166
3000	48335.51	12756.44	4950.216	49115.87	15597.05	5646.012	49702.46	19272.78	6448.166
2500	70797.31	12756.44	4950.216	71662.93	15597.05	5646.012	72382.5	19272.78	6448.166
2000	70797.31	12756.44	4950.216	112162.8	15597.05	5646.012	113012.6	19272.78	6448.166
1500	70797.31	12756.44	4950.216	112162.8	15597.05	5646.012	195151.7	19272.78	6448.166
1000	70797.31	12756.44	4950.216	112162.8	15597.05	5646.012	195151.7	19272.78	6448.166
500	70797.31	12756.44	4950.216	112162.8	15597.05	5646.012	195151.7	19272.78	6448.166

Velocity 250	TA 500			TA 1000			TA 1500		
Slant Range	PA 3k	PA 6.5k	PA 10k	PA 3k	PA 6.5k	PA 10k	PA 3k	PA 6.5k	PA 10k
25000	239.865	455.1792	540.9717	249.6868	477.5844	556.3569	264.0813	496.7287	569.0972
24500	254.8182	479.5392	568.1476	265.3594	502.8033	584.0498	280.4588	522.7344	597.2707
24000	270.8696	505.6209	597.1826	282.2735	529.7902	613.6285	298.1303	550.5513	627.3567
23500	288.2623	533.6765	628.309	300.6371	558.8128	645.332	317.3308	580.4599	659.5981
23000	307.1035	563.7898	661.6501	320.4991	589.9486	679.2813	338.1044	612.5283	694.1137
22500	327.6224	596.2762	697.4958	342.1356	623.5334	715.774	360.7502	647.1072	731.2062
22000	349.9065	631.2312	735.9913	365.6036	659.6512	754.9529	385.31	684.2693	771.0153
21500	374.2582	669.069	777.5118	391.2622	698.7378	797.2009	412.1829	724.4731	813.9316
21000	400.7956	709.9218	822.2514	419.1959	740.9176	842.7089	441.567	767.8261	860.1415
20500	429.8543	754.2334	870.6296	449.7882	786.6551	891.9035	473.629	814.8086	910.0776
20000	461.6739	802.2969	922.9768	483.2646	836.2428	945.1153	508.7181	866.1616	964.0717
19500	496.5934	854.5396	979.7322	519.9753	890.1171	1002.788	547.2089	921.4203	1022.569
19000	535.7138	911.501	1041.43	560.3922	948.8323	1065.462	589.6001	981.6012	1086.114
18500	578.0057	973.5946	1108.544	604.8395	1012.799	1133.611	636.2049	1047.109	1155.181
18000	624.7674	1041.596	1181.82	654.0015	1082.82	1207.991	687.7575	1118.768	1230.531
17500	676.4896	1116.105	1261.918	708.3671	1159.499	1289.263	744.7597	1197.175	1312.83
17000	733.7906	1197.892	1349.651	768.5658	1243.608	1378.244	807.8721	1283.112	1402.897
16500	797.631	1288.13	1446.145	835.9281	1336.357	1476.072	878.2171	1377.811	1501.88
16000	868.7454	1387.914	1552.393	910.6786	1438.63	1583.743	956.4885	1482.155	1610.775
15500	948.1928	1498.136	1669.715	994.1411	1551.723	1702.583	1043.822	1597.455	1731.84
15000	1037.417	1620.702	1799.806	1087.875	1677.397	1834.299	1141.836	1725.499	1864.956
14500	1137.77	1757.224	1944.38	1193.237	1817.271	1980.609	1251.887	1867.911	2012.766
14000	1250.996	1909.781	2105.583	1312.051	1973.445	2143.665	1375.793	2026.807	2177.433
13500	1379.268	2080.935	2286.484	1446.586	2148.507	2326.086	1515.843	2204.799	2361.59
13000	1525.367	2273.884	2489.42	1599.725	2345.698	2531.092	1676.342	2405.394	2568.476
12500	1692.249	2492.072	2718.404	1774.451	2568.484	2762.286	1857.488	2631.636	2801.712
12000	1883.755	2739.933	2977.965	1974.696	2822.564	3024.208	2064.641	2888.231	3065.859
11500	2105.237	3022.893	3273.651	2205.306	3110.97	3322.418	2302.686	3180.695	3366.501
11000	2361.509	3347.703	3612.336	2472.315	3441.726	3663.802	2577.806	3515.883	3710.551
10500	2660.653	3722.913	4002.681	2783.438	3823.462	4057.037	2897.949	3902.491	4106.704
10000	3011.874	4158.828	4455.323	3150.439	4266.556	4512.744	3272.473	4350.941	4565.589
9500	3427.174	4668.821	4983.651	3580.32	4784.482	5044.692	3714.31	4874.804	5099.066
9000	3922.114	5270.103	4983.651	4091.364	5394.564	5671.503	4238.233	5491.496	5728.185
8500	4517.112	5985.119	4983.651	4704.142	6119.412	5671.503	4865.452	6223.722	6475.177
8000	5239.237	6843.535	4983.651	5446.032	6988.854	5671.503	5623.65	7101.469	6475.177

7500	6125.087	7885.284	4983.651	6354.041	8042.954	5671.503	6550.113	8164.995	6475.177
7000	7224.839	9165.003	4983.651	7478.946	9336.477	5671.503	7696.18	9469.312	6475.177
6500	8608.85	10759.2	4983.651	8893.409	10945.84	5671.503	9133.991	11091.13	6475.177
6000	10378.19	12781.15	4983.651	10696.62	12976.87	5671.503	10966.91	13139.9	6475.177
5500	12681.75	12781.15	4983.651	13039.91	15599.01	5671.503	13346.37	15776.1	6475.177
5000	15756.55	12781.15	4983.651	16151.39	15599.01	5671.503	16501.64	19247.5	6475.177
4500	19938.26	12781.15	4983.651	20389.74	15599.01	5671.503	20792.7	19247.5	6475.177
4000	25822.81	12781.15	4983.651	26344.52	15599.01	5671.503	26810.88	19247.5	6475.177
3500	34406.03	12781.15	4983.651	35036.69	15599.01	5671.503	35592.59	19247.5	6475.177
3000	47567.61	12781.15	4983.651	48328.73	15599.01	5671.503	48979	19247.5	6475.177
2500	68977.43	12781.15	4983.651	69909.26	15599.01	5671.503	70670.57	19247.5	6475.177
2000	68977.43	12781.15	4983.651	107819.2	15599.01	5671.503	108644.2	19247.5	6475.177
1500	68977.43	12781.15	4983.651	107819.2	15599.01	5671.503	182157.1	19247.5	6475.177
1000	68977.43	12781.15	4983.651	107819.2	15599.01	5671.503	182157.1	19247.5	6475.177
500	68977.43	12781.15	4983.651	107819.2	15599.01	5671.503	182157.1	19247.5	6475.177

Velocity 300	TA 500			TA 1000			TA 1500		
Slant Range	PA 3k	PA 6.5k	PA 10k	PA 3k	PA 6.5k	PA 10k	PA 3k	PA 6.5k	PA 10k
25000	246.7657	466.1855	548.2455	258.9867	491.4457	565.9037	276.5428	511.5605	578.6569
24500	262.0401	490.9752	575.7121	275.1197	517.1357	593.8903	293.5573	538.094	607.2261
24000	278.4154	517.5199	605.0596	292.5361	544.6158	623.7758	311.9031	566.3518	637.5525
23500	296.126	546.0576	636.5091	311.4378	574.137	655.7871	332.2139	596.7002	670.0283
23000	315.2938	576.6908	670.1973	331.8905	605.7946	690.0581	353.7068	629.2278	704.7862
22500	336.1383	609.7174	706.4001	354.154	639.9028	726.8712	377.089	664.2645	742.113
22000	358.7649	645.2539	745.2798	378.3048	676.5675	766.3856	402.4193	701.9087	782.1667
21500	383.4672	683.6945	787.1941	404.6855	716.205	808.9692	430.0776	742.5948	825.3205
21000	410.3797	725.1915	832.351	433.3978	758.9578	854.8285	460.1396	786.4553	871.7783
20500	439.8296	770.1756	881.1577	464.8173	805.2767	904.3791	493.0143	833.9567	921.9609
20000	472.0683	818.9472	933.9492	499.1799	855.4581	957.9587	528.9368	885.397	976.2045
19500	507.4412	871.9362	991.1652	536.8367	909.9415	1016.013	568.2832	941.2233	1034.957
19000	546.6897	929.666	1053.328	578.2391	969.2647	1079.07	611.5286	1001.987	1098.751
18500	589.5754	992.5716	1120.926	624.4404	1033.86	1147.62	659.0065	1068.122	1168.077
18000	636.9993	1061.411	1194.688	674.6464	1104.505	1222.402	711.425	1140.431	1243.681
17500	689.4792	1137.533	1275.281	730.0892	1182.027	1304.086	769.2916	1219.53	1326.233
17000	747.6655	1220.22	1363.524	791.4213	1266.807	1393.497	833.2821	1306.22	1416.564
16500	812.4942	1311.355	1460.512	859.6386	1360.197	1491.74	904.4661	1401.685	1515.787
16000	884.7288	1411.861	1567.259	935.4925	1463.118	1599.835	983.5804	1506.844	1624.923
15500	965.4434	1523.015	1685.082	1020.082	1576.868	1719.109	1072.137	1623.003	1745.305
15000	1056.064	1646.515	1815.65	1114.928	1703.176	1851.716	1170.994	1751.92	1878.626
14500	1157.957	1783.98	1960.68	1221.391	1843.672	1998.487	1281.855	1895.224	2026.618
14000	1272.892	1937.494	2122.314	1341.286	2000.461	2162.006	1406.589	2055.04	2191.444
13500	1403.045	2109.614	2303.149	1476.88	2176.134	2344.888	1547.527	2233.975	2375.728
13000	1552.934	2303.479	2506.34	1630.983	2373.867	2550.312	1707.566	2435.238	2582.655
12500	1721.792	2522.558	2735.486	1806.606	2597.154	2781.899	1889.81	2662.336	2815.855
12000	1915.318	2771.267	2995.083	2008.401	2850.447	3044.172	2098.289	2919.751	3079.863
11500	2138.203	3055.008	3290.63	2239.79	3139.19	3342.663	2337.992	3212.965	3380.226
11000	2396.35	3380.51	3628.952	2507.435	3470.168	3684.232	2615.099	3550.149	3723.826
10500	2697.215	3756.188	4018.57	2819.036	3851.861	4077.439	2937.332	3937.133	4119.251
10000	3049.914	4192.324	4470.031	3183.952	4294.613	4532.842	3314.013	4385.667	4577.097

9500	3466.238	4702.177	4997.468	3614.391	4811.76	5064.043	3757.328	4909.194	5110.988
9000	3961.654	5302.789	4997.468	4126.093	5420.417	5689.355	4286.225	5524.944	5738.459
8500	4556.253	6016.336	4997.468	4739.613	6142.89	5689.355	4914.609	6255.333	6483.489
8000	5276.674	6872.075	4997.468	5482.048	7008.573	5689.355	5673.148	7129.919	6483.489
7500	6160.836	7909.285	4997.468	6389.718	8056.893	5689.355	6598.745	8188.295	6483.489
7000	7254.382	9181.548	4997.468	7512.482	9341.674	5689.355	7741.889	9484.435	6483.489
6500	8628.002	10763.65	4997.468	8920.053	10937.92	5689.355	9174.787	11093.38	6483.489
6000	10380.59	12765.84	4997.468	10718.97	12952.71	5689.355	10994.09	13121.84	6483.489
5500	12657.16	12765.84	4997.468	13041.41	15547.57	5689.355	13348.02	15722.06	6483.489
5000	15676.77	12765.84	4997.468	16115.26	15547.57	5689.355	16458.26	19138.73	6483.489
4500	19781.76	12765.84	4997.468	20285.76	15547.57	5689.355	20670.82	19138.73	6483.489
4000	25529.06	12765.84	4997.468	26113.58	15547.57	5689.355	26548.25	19138.73	6483.489
3500	33874.14	12765.84	4997.468	34558.89	15547.57	5689.355	35054.46	19138.73	6483.489
3000	46535.34	12765.84	4997.468	47340.9	15547.57	5689.355	47912.3	19138.73	6483.489
2500	66858.48	12765.84	4997.468	67764.51	15547.57	5689.355	68434.49	19138.73	6483.489
2000	66858.48	12765.84	4997.468	102675.4	15547.57	5689.355	103483.8	19138.73	6483.489
1500	66858.48	12765.84	4997.468	102675.4	15547.57	5689.355	168429.6	19138.73	6483.489
1000	66858.48	12765.84	4997.468	102675.4	15547.57	5689.355	168429.6	19138.73	6483.489
500	66858.48	12765.84	4997.468	102675.4	15547.57	5689.355	168429.6	19138.73	6483.489

Appendix B: Vulnerability Tables

The following table is one example of the 27 vulnerability tables used in EADSIM and shows the calculated dwell times needed to destroy a target given the Pk derived from the EADSIM random draw. Platform altitude is 3000 m, platform velocity is 200 m/s, and target altitude is 500 m.

	Pk	Required Dwell Times					
Intensity	0	50	60	70	80	90	100
231.239	979.0736	979.0736	1076.981	1174.888	1272.796	1370.703	1468.61
245.6311	921.7074	921.7074	1013.878	1106.049	1198.22	1290.39	1382.561
261.0772	867.1765	867.1765	953.8941	1040.612	1127.329	1214.047	1300.765
277.8269	814.8958	814.8958	896.3854	977.875	1059.365	1140.854	1222.344
295.9672	764.9497	764.9497	841.4447	917.9397	994.4347	1070.93	1147.425
315.7404	717.0449	717.0449	788.7494	860.4539	932.1583	1003.863	1075.567
337.2128	671.3861	671.3861	738.5248	805.6634	872.802	939.9406	1007.079
360.7057	627.6586	627.6586	690.4244	753.1903	815.9561	878.722	941.4878
386.3166	586.0479	586.0479	644.6526	703.2574	761.8622	820.467	879.0718
414.3882	546.3476	546.3476	600.9823	655.6171	710.2519	764.8866	819.5214
445.1474	508.5956	508.5956	559.4551	610.3147	661.1742	712.0338	762.8934
478.9326	472.7178	472.7178	519.9896	567.2614	614.5332	661.805	709.0768
516.1833	438.6039	438.6039	482.4642	526.3246	570.185	614.0454	657.9058
557.2139	406.3071	406.3071	446.9379	487.5686	528.1993	568.83	609.4607
602.6639	375.6654	375.6654	413.232	450.7985	488.3651	525.9316	563.4982
653.0137	346.7002	346.7002	381.3702	416.0403	450.7103	485.3803	520.0503
709.0604	319.2958	319.2958	351.2254	383.155	415.0845	447.0141	478.9437
771.4581	293.4702	293.4702	322.8173	352.1643	381.5113	410.8583	440.2054
841.0721	269.1802	269.1802	296.0983	323.0163	349.9343	376.8523	403.7704
918.9615	246.365	246.365	271.0015	295.6381	320.2746	344.9111	369.5476
1006.606	224.9142	224.9142	247.4056	269.897	292.3884	314.8798	337.3712
1105.345	204.8229	204.8229	225.3052	245.7875	266.2698	286.7521	307.2344
1216.907	186.0455	186.0455	204.65	223.2545	241.8591	260.4636	279.0682
1343.463	168.5197	168.5197	185.3717	202.2236	219.0756	235.9276	252.7796
1487.831	152.1678	152.1678	167.3846	182.6013	197.8181	213.0349	228.2517
1652.916	136.9701	136.9701	150.6671	164.3641	178.0611	191.7581	205.4551
1842.555	122.8729	122.8729	135.1602	147.4474	159.7347	172.022	184.3093
2061.456	109.8253	109.8253	120.8078	131.7904	142.7729	153.7554	164.7379
2317.533	97.69011	97.69011	107.4591	117.2281	126.9971	136.7661	146.5352
2614.491	86.59429	86.59429	95.25372	103.9132	112.5726	121.232	129.8914
2963.33	76.40054	76.40054	84.04059	91.68064	99.3207	106.9608	114.6008
3376.035	67.06092	67.06092	73.76702	80.47311	87.1792	93.88529	100.5914
3868.049	58.5308	58.5308	64.38388	70.23696	76.09004	81.94312	87.7962
4459.832	50.76425	50.76425	55.84067	60.9171	65.99352	71.06995	76.14637
5178.62	43.71821	43.71821	48.09004	52.46186	56.83368	61.2055	65.57732
6061.302	37.35171	37.35171	41.08688	44.82205	48.55722	52.29239	56.02756
7158.626	31.62618	31.62618	34.7888	37.95142	41.11403	44.27665	47.43927
8542.038	26.50421	26.50421	29.15464	31.80506	34.45548	37.1059	39.75632
10315.92	21.94666	21.94666	24.14132	26.33599	28.53065	30.72532	32.91999
12629.94	17.92566	17.92566	19.71823	21.51079	23.30336	25.09593	26.88849
15717.45	14.40437	14.40437	15.84481	17.28524	18.72568	20.16612	21.60655
19946.34	11.35045	11.35045	12.4855	13.62054	14.75559	15.89063	17.02568

25928.47	8.731714	8.731714	9.604885	10.47806	11.35123	12.2244	13.09757
34730.45	6.518775	6.518775	7.170652	7.82253	8.474407	9.126285	9.778162
48335.51	4.683927	4.683927	5.152319	5.620712	6.089105	6.557497	7.02589
70797.31	3.197862	3.197862	3.517648	3.837434	4.15722	4.477007	4.796793
70797.31	3.197862	3.197862	3.517648	3.837434	4.15722	4.477007	4.796793
70797.31	3.197862	3.197862	3.517648	3.837434	4.15722	4.477007	4.796793
70797.31	3.197862	3.197862	3.517648	3.837434	4.15722	4.477007	4.796793
70797.31	3.197862	3.197862	3.517648	3.837434	4.15722	4.477007	4.796793

	Pk	Required Dwell Times					
Peak Irradiance	0	50	60	70	80	90	100
231.239	979.0736	979.0736	1076.981	1174.888	1272.796	1370.703	1468.61
245.6311	921.7074	921.7074	1013.878	1106.049	1198.22	1290.39	1382.561
261.0772	867.1765	867.1765	953.8941	1040.612	1127.329	1214.047	1300.765
277.8269	814.8958	814.8958	896.3854	977.875	1059.365	1140.854	1222.344
295.9672	764.9497	764.9497	841.4447	917.9397	994.4347	1070.93	1147.425
315.7404	717.0449	717.0449	788.7494	860.4539	932.1583	1003.863	1075.567
337.2128	671.3861	671.3861	738.5248	805.6634	872.802	939.9406	1007.079
360.7057	627.6586	627.6586	690.4244	753.1903	815.9561	878.722	941.4878
386.3166	586.0479	586.0479	644.6526	703.2574	761.8622	820.467	879.0718
414.3882	546.3476	546.3476	600.9823	655.6171	710.2519	764.8866	819.5214
445.1474	508.5956	508.5956	559.4551	610.3147	661.1742	712.0338	762.8934
478.9326	472.7178	472.7178	519.9896	567.2614	614.5332	661.805	709.0768
516.1833	438.6039	438.6039	482.4642	526.3246	570.185	614.0454	657.9058
557.2139	406.3071	406.3071	446.9379	487.5686	528.1993	568.83	609.4607
602.6639	375.6654	375.6654	413.232	450.7985	488.3651	525.9316	563.4982
653.0137	346.7002	346.7002	381.3702	416.0403	450.7103	485.3803	520.0503
709.0604	319.2958	319.2958	351.2254	383.155	415.0845	447.0141	478.9437
771.4581	293.4702	293.4702	322.8173	352.1643	381.5113	410.8583	440.2054
841.0721	269.1802	269.1802	296.0983	323.0163	349.9343	376.8523	403.7704
918.9615	246.365	246.365	271.0015	295.6381	320.2746	344.9111	369.5476
1006.606	224.9142	224.9142	247.4056	269.897	292.3884	314.8798	337.3712
1105.345	204.8229	204.8229	225.3052	245.7875	266.2698	286.7521	307.2344
1216.907	186.0455	186.0455	204.65	223.2545	241.8591	260.4636	279.0682
1343.463	168.5197	168.5197	185.3717	202.2236	219.0756	235.9276	252.7796
1487.831	152.1678	152.1678	167.3846	182.6013	197.8181	213.0349	228.2517
1652.916	136.9701	136.9701	150.6671	164.3641	178.0611	191.7581	205.4551
1842.555	122.8729	122.8729	135.1602	147.4474	159.7347	172.022	184.3093
2061.456	109.8253	109.8253	120.8078	131.7904	142.7729	153.7554	164.7379
2317.533	97.69011	97.69011	107.4591	117.2281	126.9971	136.7661	146.5352
2614.491	86.59429	86.59429	95.25372	103.9132	112.5726	121.232	129.8914
2963.33	76.40054	76.40054	84.04059	91.68064	99.3207	106.9608	114.6008
3376.035	67.06092	67.06092	73.76702	80.47311	87.1792	93.88529	100.5914
3868.049	58.5308	58.5308	64.38388	70.23696	76.09004	81.94312	87.7962
4459.832	50.76425	50.76425	55.84067	60.9171	65.99352	71.06995	76.14637
5178.62	43.71821	43.71821	48.09004	52.46186	56.83368	61.2055	65.57732
6061.302	37.35171	37.35171	41.08688	44.82205	48.55722	52.29239	56.02756
7158.626	31.62618	31.62618	34.7888	37.95142	41.11403	44.27665	47.43927
8542.038	26.50421	26.50421	29.15464	31.80506	34.45548	37.1059	39.75632
10315.92	21.94666	21.94666	24.14132	26.33599	28.53065	30.72532	32.91999
12629.94	17.92566	17.92566	19.71823	21.51079	23.30336	25.09593	26.88849

15717.45	14.40437	14.40437	15.84481	17.28524	18.72568	20.16612	21.60655
19946.34	11.35045	11.35045	12.4855	13.62054	14.75559	15.89063	17.02568
25928.47	8.731714	8.731714	9.604885	10.47806	11.35123	12.2244	13.09757
34730.45	6.518775	6.518775	7.170652	7.82253	8.474407	9.126285	9.778162
48335.51	4.683927	4.683927	5.152319	5.620712	6.089105	6.557497	7.02589
70797.31	3.197862	3.197862	3.517648	3.837434	4.15722	4.477007	4.796793
70797.31	3.197862	3.197862	3.517648	3.837434	4.15722	4.477007	4.796793
70797.31	3.197862	3.197862	3.517648	3.837434	4.15722	4.477007	4.796793
70797.31	3.197862	3.197862	3.517648	3.837434	4.15722	4.477007	4.796793
70797.31	3.197862	3.197862	3.517648	3.837434	4.15722	4.477007	4.796793

Appendix C: EADSIM Output

The following table shows EADSIM output where
LOS: HELLADS Line Of Sight
PA: Platform Altitude
TA: Target Altitude
PV: Platform Velocity

LOS	PA	TA	PV	Average Kills	Average Laze Time	Average Max Laze Time	Average Min Laze Time
30	3000	500	388	6	18.56833	56.07	5.268
30	3000	500	485	6.8	12.95004	49.224	4.594
30	3000	500	582	7.2	18.91017	45.296	4.494
30	3000	1000	388	6.6	18.07167	54.998	4.396
30	3000	1000	485	8.2	16.09717	52.548	3.304
30	3000	1000	582	8	16.52332	46.624	4.078
30	3000	1500	388	7.8	15.86707	53.796	3.908
30	3000	1500	485	8	12.925	47.252	3.114
30	3000	1500	582	7.2	14.88633	44.994	3.582
30	6500	500	388	2.8	45.25533	66.418	31.246
30	6500	500	485	4	39.32986	59.23	27.184
30	6500	500	582	5.2	33.72314	57.512	14.528
30	6500	1000	388	5.4	35.77412	64.816	20.052
30	6500	1000	485	5.4	27.76235	53.2	16.928
30	6500	1000	582	6.8	32.11824	56.884	15.744
30	6500	1500	388	5.4	28.2962	65.5	14.59
30	6500	1500	485	5.6	25.4534	52.39	14.662
30	6500	1500	582	5.6	33.4127	69.318	12.702
30	10000	500	388	1.6	87.99233	97.594	79.706
30	10000	500	485	1	90.54233	100.008	81.606
30	10000	500	582	3.8	57.2048	80.974	33.246
30	10000	1000	388	2.6	72.30817	90.556	62.48
30	10000	1000	485	3.6	67.73303	91.264	45.112
30	10000	1000	582	3.4	95.07134	129.904	69.206
30	10000	1500	388	2.2	74.38853	110.512	46.144
30	10000	1500	485	4.8	56.36182	81.886	42.08
30	10000	1500	582	3.8	67.3405	95.918	48.286
60	3000	500	388	7	17.95029	55.686	4.438
60	3000	500	485	7.4	15.24179	49.086	3.986
60	3000	500	582	8.4	16.38722	44.974	4.174
60	3000	1000	388	7.6	16.182	54.438	4.756
60	3000	1000	485	8.2	21.66175	106.91	3.02
60	3000	1000	582	9	12.15578	43.012	2.88
60	3000	1500	388	8	15.607	54.704	3.934
60	3000	1500	485	8	12.925	47.252	3.114
60	3000	1500	582	8	18.045	51.87	2.75
60	6500	500	388	2.6	50.68547	64.406	41.048
60	6500	500	485	5.4	32.31953	56.34	19.758
60	6500	500	582	6.4	32.6641	54.454	16.64
60	6500	1000	388	4.6	36.33117	64.328	17.408
60	6500	1000	485	6.4	30.28119	58.058	15.306

60	6500	1000	582	8.4	29.93614	66.062	14.936
60	6500	1500	388	6.2	29.9573	57.262	14.21
60	6500	1500	485	6.6	28.43343	62.008	12.394
60	6500	1500	582	7.8	25.61127	51.118	12.654
60	10000	500	388	0.8	91.626	91.626	91.626
60	10000	500	485	2.8	70.16317	94.702	51.798
60	10000	500	582	3	59.55483	75.558	48.552
60	10000	1000	388	3.8	71.1046	105.19	46.726
60	10000	1000	485	4.8	61.87659	93.02	40.33
60	10000	1000	582	5	67.66345	118.628	43.754
60	10000	1500	388	2.6	78.5954	102.676	59.068
60	10000	1500	485	5.8	58.58071	98.44	29.188
60	10000	1500	582	3.8	67.3405	95.918	48.286

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14. ABSTRACT

High Energy Laser (HEL) technology continues to improve and its place in the battlefield is ever evolving. By combining the high energy delivery of solid state laser technology with the efficient thermal management of liquid laser technology, HELLADS has two main advantages over any HEL predecessors. 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 fire power 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 through a cost effective manner. Modeling and simulation supports this assessment as it yields itself easily to relatively low cost and robust testing methodologies. The challenge comes with building credible models through validation and verification of test parameters and scenarios. An Air Force Standard Analysis Toolkit model, the Extended Air Defense Simulation Model (EADSIM), is used in this study to meet these challenges. This research effort focuses on the assessment of the HELLADS operational capabilities through EADSIM. Of particular interest is the investigation of the envisioned HELLADS operational envelope and the potential advantages it offers over other HEL systems. Scenarios are applied to represent the Homeland Defense arena in which HELLADS is proposed to operate. Specifically this study explores what factors impact HELLADS effectiveness and suitability in the Homeland Defense scenarios examined.

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