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Improving the Estimation of Military Worth of the Advanced Tactical Laser through Simulation Aggregation

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IMPROVING THE ESTIMATION OF THE MILITARY WORTH OF THE ADVANCED TACTICAL LASER THROUGH SIMULATION AGGREGATION

THESIS

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Abstract

Fielding High Energy Laser (HEL) weapon systems presents technological challenges as well as employment and financial challenges. The risk associated with the challenges mandates the development process include computer simulation models capable of predicting weapon system performance from the engineering level to assessing the military worth of employing HEL systems in combat scenarios. This research effort focuses on developing laser performance data at a higher fidelity engagement model and integrating the performance data into a mission level model. The propagation of the laser from the transmitting aperture to the target is modeled at the engagement level through the employment of the High Energy Laser End-to-End Operational Simulation (HELEEOS), developed by the AFIT Center for Directed Energy (CDE). The output from HELEEOS directly transfers into data lookup tables for the Extended Air Defense Simulation Model (EADSIM). The EADSIM simulations asses the combat performance of a proposed new HEL weapon, the Advanced Tactical Laser (ATL), in a well-defined mission level scenario based on HEL Joint Technology Office (JTO) requirements for future HEL systems. EADSIM is a mission level simulation model included in the Air Force Analytical Tool Kit. Specifically the research explores the development of the necessary information requirements for HELEEOS and EADSIM to accurately model ATL effects and evaluates challenges related to modeling HEL engagements in EADSIM. Results include discussion on EADSIM HEL weapons modeling capabilities, recommendations on general mission level characteristics that should be modeled, and appropriate measures of performance for campaign-level modeling.

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Michael T. Cook

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IMPROVING THE ESTIMATION OF THE MILITARY WORTH OF THE ADVANCED TACTICAL LASER THROUGH SIMULATION AGGREGATION

I. Introduction

Background

A silent war always occupies our resources and threatens our future. The war is fought neither politically nor economically. The silent war involves neither forward lines nor tactical maneuvers. This war is fought through industrial development and the application of technology. Whether America is formally at war or not, the war of technological attrition faces us every day. Those who would see freedom destroyed and the innovative hard working American perish spend their time and resources attempting to gain the edge through technological superiority. If anywhere, we must remain vigilant; we must remain vigilant in watching the future of warfare.

Weapons of mass destruction (WMD) such as nuclear, biological, chemical (NBC) weapons have been labeled as one the greatest threats to the United States and this threat is expected to increase in the future. Such an increasing threat forces an "increasing requirement for nontraditional defense systems, such as high-power microwave and lasers" (Lester, 1996: 2). The Department of Defense Laser Master Plan created March 24, 2000 implies that High Energy Lasers (HEL) are ready to begin

meeting the challenges of todays threats (DoD Laser Master Plan, 2000). Meeting the challenge of National Missile Defense will by no means prove to be easy. In a public address regarding missile defense, Philip E. Coyle compares the difficulty of missile defense to attempting to defend a roomful of people against a handful of rocks being thrown at any number of people without warning (Coyle 2002). The threat awareness is not the only difficulty, laser weapon applications also face the problem of effective employment in a tactical combat environment. The properties of a laser weapon are fundamentally different from every weapon in the DoD arsenal today. In addition to technical difficulties and employment challenges, the demanding budget of laser weapon development threatens the continued exploration of laser technology. The master plan communicates the vital necessity to continue programs that investigate the potential of laser weapons to meet the challenge of tomorrow's warfare and implores developers to innovately manage the expensive nature of the technology (Lester, 1996: 2).

Simulation remains one of the most effective tools for low cost technology exploration, while significantly reducing hazards to personnel and equipment. The effects of a non-existent weapon system can be explored. However, the results derived from the exploration of non-existent systems through simulation are only as good as the assumptions made about the real system. If the assumptions about the weapon system effects do not resemble how the actual system operates, then obviously the results of the simulation cannot provide accurate information regarding its expected performance. This potential error highlights the need for developing simulations from the most technical level possible to accurately asses the military worth of new technology systems. An engagement level model of the laser provides critical input into combat simulations with

lower fidelity. Such development is supported in the Modeling and Simulation (M&S) Master Plan. The M&S Master Plan lists authoritative systems representation as third among the M&S objectives. Appendix A of the M&S Master Plan defines authoritative representation as "models, algorithms, and data that have been developed or approved by a source which has accurate technical knowledge of the entity or phenomenon to be modeled and its effects" (DoD M&S Master Plan). In addition, the M&S Master Plan highlights the need for adequate aggregation of systems into a single group of entities (DoD M&S Master Plan, 4-18).

HEL weapons possess unique capabilities harnessed from recent advances in the development and application of directed energy. The full capabilities of the HEL systems remain undiscovered due to the lack of opportunity to fully employ large numbers of new platforms in actual combat. The anticipated nature of future threats combined with the goals presented in the M&S and Laser Master Plan point to a simulation based solution to explore the military worth of laser weapon systems. The Advanced Tactical Laser (ATL) is of particular interest as an Air Force HEL weapon application. The ATL is one of the platforms the Air Force is currently working toward developing and employing in combat environments. The ATL has some commonalities with the Airborne Laser (ABL), however, the ATL platform will be mounted on a smaller, more maneuverable C-130 or CV-22 aircraft equipped with a low power laser. In comparison, the low power laser for the ATL would be approximately 50 kilowatts (kW) whereas the ABL carries a megawatt class laser. Proper utilization of the ATL could reduce or eliminate enemy forces ranging from ground troops to enemy ballistic missiles and WMD.

Problem Statement

The goal of this study is to explore the military worth of the ATL by adequately modeling the laser at the engagement level and providing input into a mission level model. The aggregation requires defining a scenario at the mission level, developing the required output from the engagement model for input to the mission level model, and then assessing the effects of the ATL. The exploration involves an understanding of the differences in modeling lasers as well as the assumptions and methodology used in the modeling software. Additionally, a moderate amount of coding is necessary for the development of scripts that interact with the simulations to obtain the desired information. Analyzing the effect at the high fidelity level and developing input to the next higher level is critical to proving the military worth of the ATL. Only from such careful attention to detail through this interactive process can decision makers have a solid foundation for their decisions.

Research Objectives

The study will begin with determining the effects of the laser using the High Energy Laser End-to-End Operational Simulation (HELEEOS). HELEEOS is a model "designed to provide reasonable fidelity in predictions of energy delivered to a target over a broad range of engagement scenarios" (Bartell, 2003:2). Currently, it is under the development of the Air Force Institute of Technology (AFIT) Center for Directed Energy (CDE) M&S Workgroup. HELEEOS was bench-marked against Science Applications International Corporation's (SAIC) Atmospheric Compensation Simulation (ACS). The simple graphical user interface of HELEEOS allows the user to perform the major

simulation functions: specify parameters, accept and run the scenario using those parameters, and view a variety of outputs including single output values, two-dimensional plots, and three-dimensional plots. The outputs display several irradiance (power in W/cm^2) values sorted by the factors included in the calculations of the effect. For example, one output value calculates irradiance based on the initial parameters that contribute to thermal blooming, while a different output calculates the maximum irradiance possible without regard to the effect of thermal blooming. A detailed propagation table from HELEEOS will be the input into EADSIM (Extended Air Defense Simulation). EADSIM, originally an army initiative, is now also a mission level model in the Air Force Standard Analysis Toolkit.

Scenarios will be examined in EADSIM to analyze the effectiveness of the ATL at the mission level using various statistical techniques. In addition, nontraditional measures of effectiveness will be explored. Effects from the mission level will be analyzed to determine appropriate input into a campaign level model, such as THUNDER.

Figure 1 – AF M&S Pyramid (AF M&S Master Plan)

As seen from Figure 1, each of the types of models listed fall into a different level in the pyramid. Choosing to conduct simulation studies at every level provides some practical insight at each level while allowing for an increased amount of accuracy in higher fidelity simulations that come from eliminating high level assumptions and estimations. The engagement level model, HEELEOS, determines the laser irradiance on a target considering thermal blooming and based on the geometry of the ATL and its target. At the mission level, EADSIM will allow simulations of multiple platforms engaging multiple targets using the propagation tables built from specified engagement level scenarios. The output from EADSIM will provide input to the campaign level. Necessary tables and factors levels should be identifiable from the mission level output and the campaign level requirements.

Scope

General Scenario

A briefing by the HEL Joint Technology Office (JTO) describes several scenarios that should be used to asses the performance of HEL platforms (Stadler, 2002). The scenarios are characterized by specification of weapon system platform, target, and environmental requirements. Altitude and velocity are the primary parameter specifications for the platform. The target has altitude, velocity, size, and route requirements. The environment specifies either a particular global location or

characteristics of the necessary operating environment. The briefing continues to apply those requirements to platforms aiming to address different roles in combat.

Table 1 – JTO HEL Scenario (Stadler, 2002)

	Air to Surface Scenario
Description	Airborne platform attacking fixed and moving surface targets
Goal	Maximize range of effectiveness
Environment	Desert, Littoral, Urban, Maritime
Platform Velocity	450-1000 ft/s (140-300 m/s)
Platform Altitude	0-40000 ft (12 km)
Platform Candidate Wavelengths	1.315, 1.064, 1.029 μm
Target Velocity	0-75 ft/s (0-23 ms)
Target Altitude	6 ft (2 m) AGL

Measures of Effectiveness

The ATLs performance in the scenario will be quantified using a set of Measures of Effectiveness (MOE). The laser is a revolutionary capability with respect to military applications, not merely a faster or stronger version of existing capabilities. Thus, comparing it to current systems using standard MOEs may not grant full insight into the advantages and disadvantages of the military worth of the ATL. Some considerations might include MOEs that specifically highlight the advantage of laser weapons. According to the HEL Technical Operational and Policy Issues Report, the following advantages might aid in developing MOEs that reflect the benefits of laser weapons:

- **Speed-of-light deliverance** – A laser travels at the speed of light which is obviously faster than any kinetic munitions.
- **Maneuvering and crossing targets** – The weapon system does not necessarily require the airframe to move into position.
- **Avoidance of collateral damage** – Because the laser is light, there is no risk of having expended munitions drop to the ground.
- **Lethal to non-lethal capability** – The laser allows for non-lethal target casualties.

- **Multiple Engagement** – With light speed deliverance, the laser will handle greater volumes of enemies completely differently than kinetic weapon systems. (Zimet, 2002)

A more encompassing range of MOEs would highlight, when possible, the advantages as well as the disadvantages of both conventional missiles and laser weapons. For example, harsh weather conditions are not advantageous to laser weapons. The laser may also be less effective against stationary targets due to the thermal blooming phenomenon.

The HEL JTO briefing also outlines several questions deemed important to evaluating the military worth of the laser. System reliability was among the first considerations (Stadler 2002). Because the ATL is a revolutionary unproven weapon system, the question of reliability is one of the most critical. Another significant MOE, which is also mentioned in the list above, addresses the ability of the laser to negate targets in a timely manner.

Unfortunately, not all of the MOEs can be addressed. The limitations arise from the simulation model selection and the specific focus on aggregation in assessing military worth. The simulation model selection limitations are based on the inability of the particular model to either input or output particular types of information. The first obstacles originate in the limitations of the HELEEOS model. For example, HELEEOS does not currently measure weapon system reliability. It operates under the assumption that the laser aperture fires perfectly. The non-lethal damage also becomes excluded considering that neither EADSIM nor HELEEOS are equipped to asses varying degrees of non-lethal damage. Additionally, the target vulnerability tables are not developed well

enough to asses varying degrees of non-lethal damage. The specific focus on aggregation suggests that the more important output parameters of the analysis relate to a comparison of a model built without aggregation instead of comparing the results of a laser to a conventional weapon.

Considering the valuable measures of effectiveness and the previously mentioned limitations, both the time to kill and number of targets destroyed meet the qualifications and may grant insight into other MOEs.

Summary

The laser may be a revolutionary key to national defense in the future. Laser weaponry is relatively new, not fully explored, and expensive to build. Thus, simulation should play a huge role in determining its military worth. This study examines directly feeding data from an engagement level model into a mission level model to evaluate effectiveness of the ATL in scenarios deemed important by the HEL JTO. Chapter Two offers information on hierarchical modeling, similar studies, and general modeling background relevant to the study. Chapter Three describes the establishment of the baseline scenario and the design of experiments. The next chapter contains an analysis of the results from the simulation. The fifth and final chapter provides a brief summary of the research project.

II. Literature Review

Transition Though the Hierarchy

As seen from the AF M&S Pyramid in Figure1, models developed for specific purposes have a corresponding level of fidelity and resolution associated with them. That level of fidelity and resolution places the model in a specific pyramid category. Furthermore, the Air Force has a specific set of models for each respective category compiled into the Air Force Standard Analysis Toolkit.

Lasers mandate multi-level modeling and simulation aggregation more than conventional weapons because the amount of energy delivered to the target changes significantly with respect to varying environments and engagement geometries. Because of the vast weapon output variance, passing information through levels of the Modeling and Simulation pyramid is required to perform adequate assessments of treating the ATL in simulation environments,. To aggregate the necessary information several concerns should be addressed.

1. Identification of higher fidelity model output
2. Identification of lower fidelity model input
3. Identification of modeling processes, assumptions, and limitations
4. Formulation of direct correlation between higher fidelity model output and the lower fidelity model input

More specifically restating the concerns with respect to the ATL simulation study identifies issues needing understanding and further research. Regarding the first two questions, the output from higher fidelity HELEEOS model should be identified as well as the input into EADSIM. The modeling assumptions used for HELEEOS and EADSIM

must be identified. Such assumptions may include general types of engagement conditions and environments. Furthermore, model evaluation should reveal the valid data ranges. Finally, the output from HELEEOS and input to EADSIM should be correlated as closely as possible while documenting the assumptions made to account for connections not directly established. More accurate information programmed into the model leads to higher accuracy in the model output.

Unique Challenges of Laser Modeling

Before examining the entire input and output correlation methodology, some general laser weapon modeling information will provide insight into the difficulties and challenges of modeling laser weapons as opposed to conventional weapons.

Most of the weapons currently used by U.S combat forces are projectile weapons or rocket propelled weapons. Projectile weapons range from M-16's to artillery rounds to dumb bombs, but can be classified as initial force driven, gravity driven, or both. In other words, the effect the weapon is intended to have depends upon its initial force from the projecting unit such as an M-16, gravity to aid the weapon to the target such as a dumb bomb, or a combination of the two such as artillery rounds. Regardless of the physics on which the weapon depends, the key similarity between these projectile weapons is that the weapon has no ability to autonomously control itself after initial launch. The resulting modeling of the weapon may become a simple physics equation based on the initial firing conditions associated with probabilities that account for human errors and the unpredictability of the weapon systems.

Rocket propelled weapons are more difficult to model than projectile weapons. However, the forces that act on these weapons are very similar to the forces that act on aircraft: drag, thrust, pitch, and yaw. Thus, modeling rocket-propelled weapons closely matches the mechanical physics of modeling an aircraft entity.

Lasers operate neither as projectile weapons nor as rocket-propelled weapons. The laser travels in a straight line from the light source origin to the target area at the speed of light. The factors that effect traditional weapons such as gravity, wind speed, thrust or launch force do not affect the laser. However, some forces that may have little to no effect on traditional weapons affect the laser: light dissipation, clouds, rain. The presence of a cloud has negligible affect on the AIM-120. However, a laser will not fire while in the presence of a cloud. The amount of destructive energy in a missile will not differentiate between 10 meters and 100 kilometers. The explosives carried on the system to affect the target will have that explosive power upon successful arrival to the target. A laser, because it is directed light, will lose destructive energy at a rate directly proportional to distance due to the increasing effect of light dissipation.

Every weapon must have a controllable factor for the simple reason that if there were no controllable factors the weapon would be uncontrollable and thus, in general, unusable. The control factors of conventional weapons involve speed, rate of fire, time of explosion, trajectory, etc. The two primary control factors inherent in the laser, aside from the obvious factor of direction, are the power and duration. The laser power, usually specified in kilowatts (kW) for military applications, refers to the amount of energy leaving the laser aperture. The laser beam traverses the atmosphere to the intended target while gradually decreasing in magnitude proportionally with the distance

traveled. The impact energy of the light upon the target is measured in kW per square centimeter (cm^2). The change in units is necessitated because spreading the beam over the surface detracts from the effect of the light. The importance of surface area can clearly be illustrated in the age-old childhood fascination with using a magnifying glass on an ant. An undisturbed ant can walk around in a confined circular area under the sun without incident. However, when the intensity of the sunlight expanding to the entire circular area becomes focused by a magnifying glass on the ant, the ant begins to sustain serious injury. Damage to a target is caused by using power distributed over a surface for some required duration, usually quantified in seconds.

Table 2 – Units Reference

	Power	**Irradiance**	**Intensity**
Reference	Leaving Aperture	Traversing Atmosphere and Delivery to Target	Irradiance Distributed over Time
Units	W	W/cm^2	J/cm^2

The required duration for damage, commonly known as vulnerability, requires a comparison of the energy on target to the required energy to neutralize the target. For conventional weapons, various target vulnerabilities are explored to some capacity. The vulnerability of military targets to laser weapons, however, is a developing area of study.

Another unique aspect of the revolutionary technology lies in the vulnerability field. The conventional missile or bomb may give non-lethal damage to the intended target. The non-lethal damage, at the very least, arrives in a different form because the entire amount of damage whether lethal or non-lethal rests in the delivering munitions. Thus, upon accurate impact, assuming the right weapon selection, the target is destroyed. Upon near exact impact, the entire energy required to destroy the target is delivered to the

proximity of the target. As mentioned earlier, the laser requires a duration of power on a particular surface area for the target to incur damage.

One of the key components in assessing the military worth of the ATL rests in determining the ability of the laser to break the vulnerability threshold. The aggregation of laser propagation tables from HELEEOS to EADSIM does not directly affect the accurate assessment of target vulnerability. Such an assessment would require a separate engagement level model. The aggregation involved in this study directly contributes to assessing the ability of the ATL to break the threshold given that the threshold is accurate.

Energy Loss

Energy loss is another key modeling difference between conventional weapons and laser weapons. Conventional weapons contain within them the entire amount of explosive energy. At some point, by automated detonation or impact, the explosion occurs. The only concept of energy loss involved in the process revolves around the proximity of the actual point of detonation to the intended point of detonation. Regarding directed energy, two primary instruments of loss are propagation and absorption. These two losses address the loss occurring after the transmission of the laser beam and the loss of the energy upon arrival.

The losses associated with atmospheric propagation are energy spread and energy waste. Energy spread decreases the intensity of the beam on the target because the beam expands proportionately as it traverses the atmosphere. Thus, gradually increasing the surface area on which the laser beam will affect, effectively reducing the intensity of the

beam. Energy waste decreases the amount of light delivered to the target due to interactions with the physical medium (Neilson, 1994:20).

One particular type of energy waste having significant effect on the amount of energy delivered to the target is thermal blooming. The effect is similar to a negative lens. When light passes through a negative lens, the convex shape of the lens redirects the waves and disperses the beam into different directions. In thermal blooming, the negative lens is formed as the light heats an area of the atmosphere in passing. Essentially thermal blooming occurs when the atmosphere becomes heated, creating excited molecules closer to the target expanding the distance between the molecules in the atmosphere due to increased temperature. The further this phenomenon happens from the target the less energy gets to the target. The effect of thermal blooming diminishes relative to the changes in platform and target velocity vectors. In general, less change in position results in more heating of the area (Bartell, 2004).

After the beam propagates through the atmosphere, an amount of irradiance arrives on the target. The absorption, typically modeled as target vulnerability, is classified in three main categories: conduction, convection, and radiation. Conduction refers to the process of energy flow from warmer regions to cooler regions. The energy transfer occurs until a uniform temperature is reached. In convection, the heat is carried away through the motion of the molecules. As the molecules move, a motion-induced "wind" reduces the effect of the heat. Finally, heat is lost through the emission of electromagnetic radiation. As molecules rotate, vibrate, and move randomly though space, they give off energy residing in their internal structure (Neilson, 1994:32-37).

In Table 3 the key energy loss methods are accompanied by their respective means of being addressed. The losses due to atmospheric propagation are modeled in HELEEOS. The losses due to target absorption are not modeled in HELEEOS and are beyond the scope of this project. However, such losses could be incorporated with various additional engagement level models.

Table 3 – Energy Loss Table

Means of Energy Loss	**How to Model the Effect**
Propagation: Energy Spread	HELEEOS engagement model
Propagation: Energy Loss	HELEEOS engagement model
Absorption: Conduction	vulnerability equation
Absorption: Convection	vulnerability equation
Absorption: Radiation	vulnerability equation

In summary, HELEEOS specifically addresses energy loss due to propagation and the effects of thermal blooming. The system analysis requires that the vulnerability data contain the approximations for fluence thresholds to account for energy loss due to absorption.

Research of Captain Maurice C. Azar

General Description

A particular study of interest, Assessing the Treatment of Airborne Tactical High Energy Lasers in Combat Simulations by Maurice C. Azar (2003), examined the ATL at different simulation pyramid levels. Primarily Azar focused on mission level simulation using a first order brightness equation as an engagement/engineering level laser model. In addition, Azar included discussion on issues for campaign level aggregation. This study parallels his work in general, but two major changes differentiate the studies: detailed laser propagation tables aggregated from a lower level model instead of a first

order approximation equation and the assessment of the military worth of the ATL in air to ground scenarios.

The research of Azar had two primary objectives: record data on potential ATL treatment in a mission level simulation, EADSIM version 9.00b, and propose aggregate measures of effectiveness for a campaign level simulation, THUNDER (Azar, 2003:1-4). The primary measures of effectiveness were targets killed and total laser firing time. Other MOEs were eliminated due to the nature of EADSIM output (Azar, 2003:3-22).

Achieving the first objective began by constructing a scenario based on the Advanced Concept Technology Demonstration (ACTD) program's desired weapon capabilities. The scenario used in this effort employed a single ATL platform to defend a friendly airfield against nine cruise missiles. The analysis of the scenario utilized design of experiment techniques focused on varying several input factors and examining their impact on a few output factors. The analysis of variance (ANOVA) table developed from a linear regression was the primary tool used in the analysis. Both MOE's were calculated from the readily available lasing start time and lasing end time statistics (Azar, 2003). The design of experiment varied the following scenario parameters.

1. Scenario Number – (1-9) specification of scenario setup. The nine scenarios were developed from area runs that generated random numbers for the latitude and longitude of each cruise missile as well as a random position for the ATL. The number generated for the ATL placed the platform at a position on the circular path after having traveled a random amount of time between 0 and 420 seconds.

Table 4 – Missile Location Distribution

	Latitude	**Longitude**	**ATL Position**
Distribution	*Uniform*	*Uniform*	*Uniform*
Minimum	*29.8*	*47.35*	*0*
Maximum	*29.97*	*47.75*	*420*
Randomization	*Stream 1*	*Stream 2*	*Stream 3*

2. Threat prioritization – (Table 5) the ATL attacking order

Table 5 – Threat Prioritization

Threat Prioritization		
Highest Track Maturity	Shortest Time to Kill	Longest Time to Kill

3. Jitter – (0x and 5x spot size) a measure of beam spread resulting from vibration at source

4. Azimuth – (180, 270, 360) the degree of weapon coverage around the ATL

5. Power – (50 kW, 100 kW) the power capability of the laser

Demonstrating ATL potential required entities to be created or modified in EADSIM. The two primary entities, the ATL and cruise missile, were modeled with specific assumptions, guidelines, and random settings (Azar, 2003:3-1,2).

The ATL, a C-130 Hercules with a HEL weapon located under the center of the aircraft was assumed to have an unrestricted slew rate up to a 360-degree field of engagement (based on azimuth parameter setup). The ATL entity flew at 150 nautical miles per hour in a circular pattern with a 5 km radius. Because target detection was an unwanted source of variability the radar field of view was set to 360° and the detection range exceeded the effective engagement distance of the ATL's weapon (Azar, 2003).

The cruise missiles were launched in a salvo with a random launch position from a designated area. The missiles flew at 100 m above ground level (AGL) with a speed of 400 knots and headed due south to a predetermined waypoint before changing course to attack the target airfield (Azar, 2003).

Input from Brightness Equation

To create and deploy a HEL weapon system in EADSIM, Azar built a laser propagation table based on Tyson's first order brightness equation (Tyson, 1998):

$$(1) \qquad Brightness = \left(\frac{\pi D^2 P}{4\lambda^2}\right)\exp\left[-\left(2\pi\frac{\omega}{\lambda}\right)\right]\left[1+\frac{\pi^2}{2}\left(\frac{j}{\frac{\lambda}{D}}\right)^2\right]^{-1}\tau$$

Specific parameters used to generate brightness values are listed in Table 6. The equation does not specifically account for thermal blooming.

Table 6 – HELEEOS Setup: First Order Equation Parameters

Variable	Value	Units	Definition
D	1	Meters	Diameter of transmitting aperture
P	50000	Watts	Power of laser
λ	1.315×10^{-6}	Meters	Wavelength
ω	0.2λ	Meters	Wavefront error
J	0	-	Jitter
τ	0.9	-	Transmission of atmosphere

Assessment of Equation (1) adequacy may be shown through the comparison of HELEEOS output to Equation (1) results. The comparison is difficult because the inputs must be made to be as similar as possible. The jitter variable is broken down into two types of jitter in HELEEOS. In Equation (1), the single jitter parameter must account for both types of jitter as well as their interaction. Additionally, HELEEOS needs more information to simulation an engagement. The comparison of one Equation (1) calculation could be compared to various HELEEOS simulations. The goal of the comparison is to identify the differences between Equation (1) calculations and HELEEOS output for a particular scenario. To facilitate such comparison HELEEOS code produced irradiance values based on parameter setup matching the same Equation (1) parameters Azar used to generate the propagation table (Table 6), the geometry used for EADSIM scenarios (Table 7), and the target and platform velocities used in EADSIM scenarios (Table 8). The target and platform velocities only affect thermal blooming in HELEEOS. The resulting comparisons in Figure 2 and 3 show the difference between

the values generated for the general engagement geometry used for the simulation study. Of the two comparisons, the first shows Equation (1) values against HELEEOS output without thermal blooming and the second comparison shows Equation (1) values against HELEEOS output configured to show the thermal blooming represented in the EADSIM scenario based on the engagement geometry.

Table 7 – HELEEOS Setup: EADSIM Scenario Parameters

Parameter	Value	Units
Platform Altitude	2010	m
Target Altitude	100	m
Wavefront Error	0.2λ	-

Table 8 – HELEEOS Setup: Thermal Blooming Parameters

Parameter	Value	Units
Wind Velocity	4	m/s
Platform Velocity Parallel	77	m/s
Platform Velocity Perpendicular	0	m/s
Target Velocity Parallel	205	m/s
Target Velocity Perpendicular	0	m/s

A Matlab script in Appendix A executed the HELEEOS code using the parameters described above increasing the slant range by 200 meters for each simulation execution. After the completion of the entire series of simulations another macro formatted the inputted values for comparison. A multiplicative factor to HELEEOS output values changing watts/meter^2 to watts/centimeter^2 effectively correlated HELEEOS output with Equation (1) output. Figure 2 and Figure 3 compare Equation (1) and HELEEOS irradiance values corresponding to specific slant ranges without and with thermal blooming respectively.

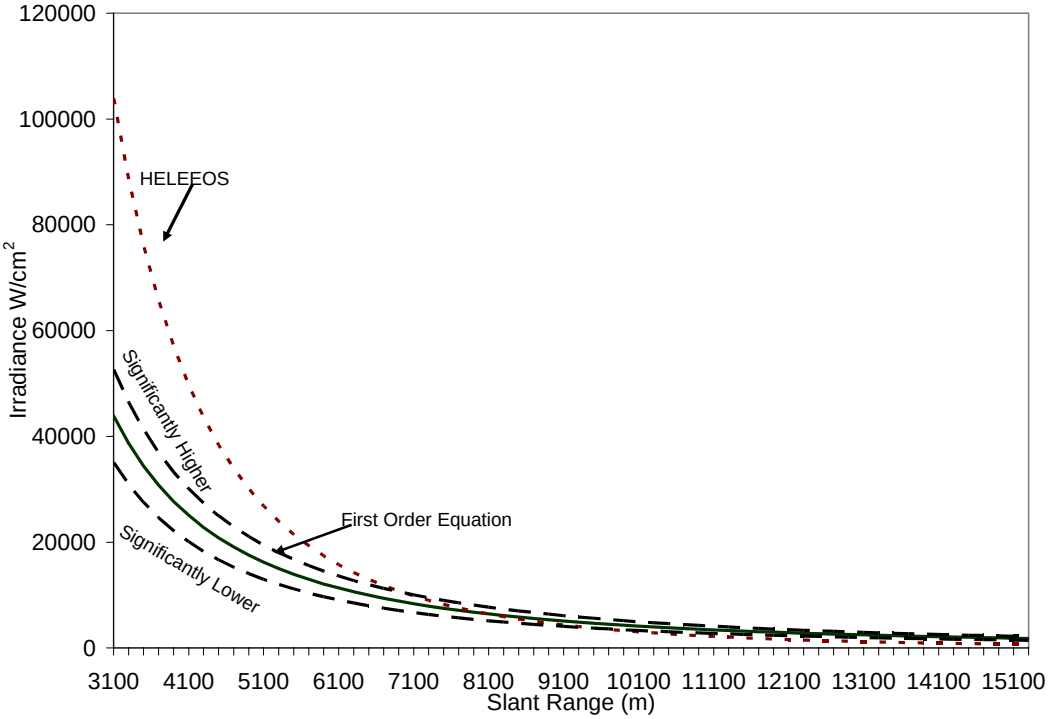

Figure 2 – Power Comparison without Thermal Blooming

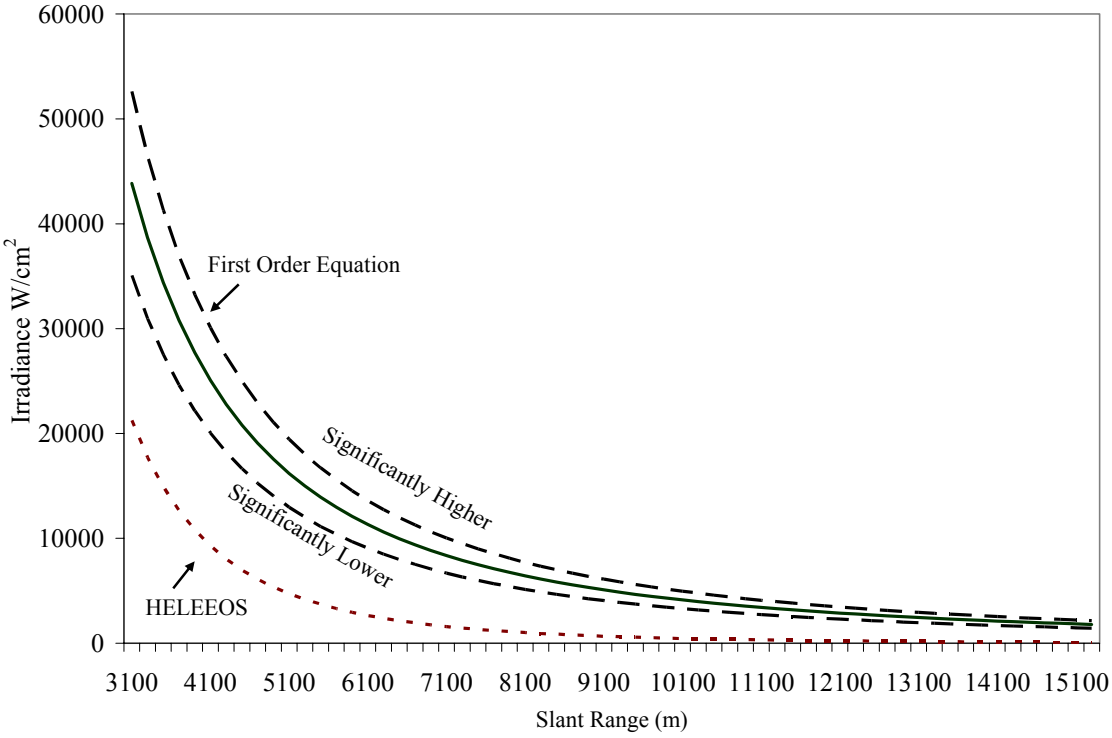

Figure 3 – Power Comparison with Thermal Blooming

According to subject matter expert (SME) Rick Bartell, a twenty percent change in general indicates a significant difference (Bartell 2003). This twenty percent difference is indicated on the graphs by the dotted lines. The first graph shows the Equation (1) result was significantly below HELEEOS when the slant range was less than 7000 meters, had no significant difference from approximately 7000 to 9000 meters, and was significantly above HELEEOS from 9000 meters to the end of the values used in the propagation table. The second graph indicates the Equation (1) result was always significantly higher than HELEEOS. The consistently significant lower yield developed because the HELEEOS platforms were not in motion. The lack of motion further contributes to the heating the atmosphere which would ultimately increase the negative effects of thermal blooming.

The first graph more accurately depicts the setup used for an ATL lasing a cruise missile. Both the missile and ATL will not be stationary. The second graph accentuated the effect of thermal blooming by leaving both platforms stationary. A similar propagation table would more accurately reflect the engagement of ground targets. One important realization derived from the difference between the two HELEEOS curves is that very different outputs occur based on engagement velocities. The illustration can be seen more clearly in Figure 4. Figure 4 depicts the differences in maximum irradiance values based on platform altitude. The ATL was setup similar to the previous setup, however, the target remained at 10 meters above the ground and the ATL altitude evaluated at 2000 meters, 4000 meters, 6000 meters, and 8000 meters. In Figure 4 the vertical line represents the beginning of valid engagement geometry for the scenario.

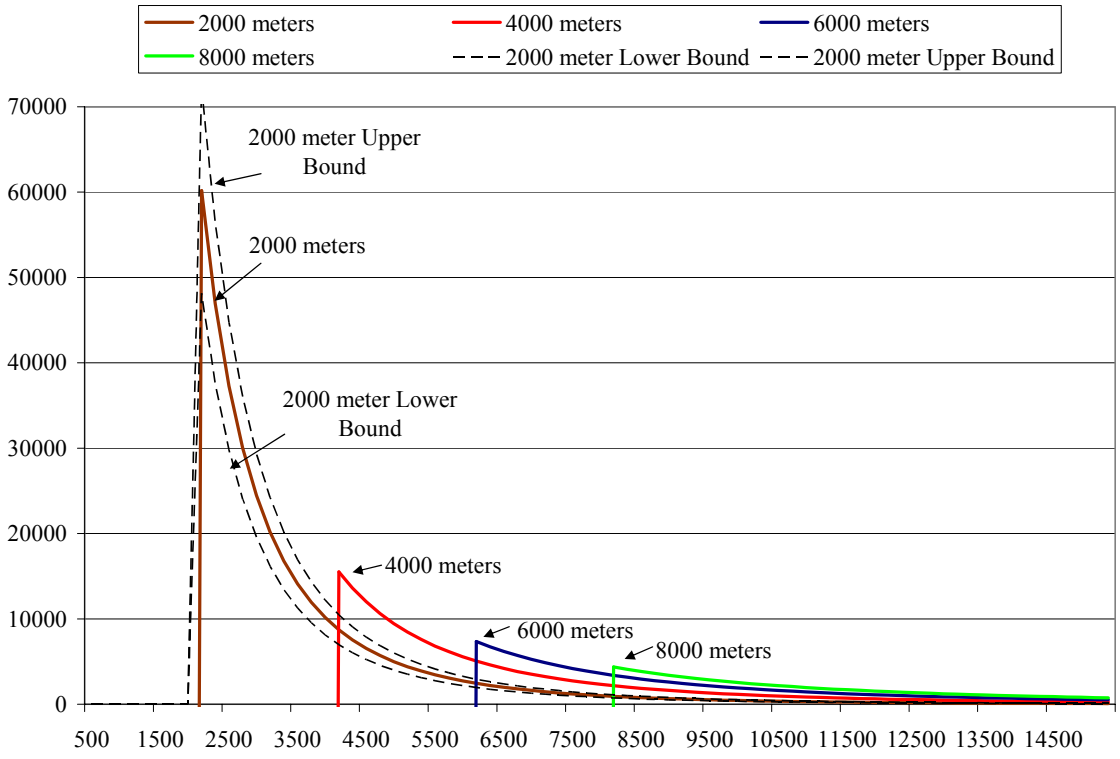

Figure 4 – HELEEOS Irradiance Comparison Based on Platform Altitude

The figure shows that the irradiance values generated for platform altitudes of 4000, 6000, and 8000 meters are significantly different than the irradiance values generated when the platform was at 2000 meters. Equation (1) would simply use the same value regardless of the engagement geometry. The comparisons made above suggest that HELEEOS varies to compensate for several critical laser performance factors. The engineering level model more accurately assesses the effects of engagement geometry and engagement velocity. Such flexibility establishes the model as an improvement over the simplistic Equation (1) model.

Unaddressed Issues

As demonstrated in the graphs above, using HELEEOS produces different outputs than Equation (1). Some other general complications arise for other reasons including model input limitations, modeling assumptions, and computing resource limitations.

The following paragraphs discuss the specific problems of thermal blooming, jitter representation, and replication numbers.

The effects of thermal blooming are not explicitly represented. Equation (1) has some commonalities with the output from HELEEOS regarding shape of the curve for the specified altitude. However, the effect of thermal blooming increases and decreases based on engagement geometry and velocities. Thus, at different altitudes and velocities the two curves may not be similar even in general shape.

The effect of high jitter does not necessarily bear equality to spreading the laser uniformly over a surface. Two primary types of jitter contribute to missing the target. One type of jitter occurs because of differing refractive indexes between the platform and the target. The second type, mechanical jitter, refers to the instability in the laser firing aperture. The undesirable movement of the device causes an angular shift having greater impact with increasing slant ranges. Although Equation (1) has no inherent capability to model the effects of both types properly, the HELEEOS code adjusts for both types of jitter (Bartell 2004).

In addition to the modeling difficulties, Azar was limited by computing facilities and software resources. Primarily this resulted in using only five replications for each design point. While five replications are better than only one, a small number of replication inhibits robust model variance. Effective utilization of computing resources

could offer greater understanding of model variance. The Major Shared Resource Center (MSRC) possesses a vast amount of computational potential. To increase the rate of simulations, facilities such as the MSRC could be utilized.

Through the introduction of the uniqueness of the laser some general differences were introduced. Other complications were presented through the study of Azar's thesis. Understanding relevant modeling difficulties helps focus the development of the necessary input, output, and correlation details necessary to aggregate the ATL from the engagement level to the mission level.

HELEEOS

Background

The most basic step in the Modeling and Simulation Pyramid begins modeling the laser at the engineering level. The output from the engineering level model, ACS, provides the validation data for HELEEOS. "ACS is a general purpose code intended primarily for time-domain, wave optics simulation of adaptive optics systems" (Link 2001). The ACS code has been used to model several systems including both space and ground high-energy laser weapons (Link 2001). A single input file containing detailed characteristics of "deformable mirrors, wavefront sensors, trackers, fast steering mirrors, beacons, and scoring beams" controls the code (Link 2001). The light provided to the system can originate from a number of source types. The performance is affected primarily by atmospheric turbulence, but also by other factors including jitter and thermal blooming (Link 2001).

The validation of the HELEEOS output is derived from its correlation to the ACS output as well as output from Wave Train, developed by MZA Associates Corp (Bartell 2003). Table 9 shows the initial points tying the two codes.

Table 9 – HELEEOS and Wave-Optics Codes Tie Points

Aperture Diameter	0.5 m
Operating Wavelength	1.315 μm
Platform Altitude	1000 m; 2000 m; 3000 m; 4000 m; 8000 m
Output Power	50000 W; 100000 W; 200000 W
Slant Range	3000 m; 6000 m; 9000 m; 12000 m; 15000 m; 25000 m
Beam Quality	1.3
Central Obscuration	0.3
Jitter	0.5 μrad
Turbulence Profile	Hufnagel-Valley 5/7; Clear1
Atmospheric Absorption and Scattering	Based on 1976 US Standard Atmosphere, 23 km vis, rural aerosols
Wind Profile	Bufton

(Bartell 2003)

Later HELEEOS editions will contain code based on an expanded version of the initial list. Table 9 contains enough information to suggest good design points for the analysis of ATL military worth. The last three rows are less intuitive than the first rows. The atmospheric absorption and scattering information is of particular importance to addressing the requests of the HEL JTO. The JTO requests analysis of the ATL performing in worldwide environments. The restriction of atmospheric absorption and scattering to rural aerosols only threatens fully exploring all the desired environments. HELEEOS only uses the 1976 US Standard Atmosphere having middle attitude water vapor content. The standard assumes rural aerosols. Thus, HELEEOS does not specifically model the requested Desert, Littoral, Urban, Maritime environments. According to SME Rick Bartell, only the maritime environment will have dramatically altered irradiance values.

Additionally Bartell suggested some other scenario guidelines based on the above information. The 50 to 100 kW power range from HELEEOS has the most accurate correlation with the output from ACS. Beyond 200 kW the data does not reasonably match. Of the three requested wavelengths, HELEEOS currently models the 1.315 micron wavelength. The 1.06 micron wavelength will be added by January 2004 and the 1.029 micron wavelength will not be included in the near future.

HELEEOS Assumptions

The HELEEOS document describes some key assumptions in the initial alpha version of HELEEOS (Bartell, 2003). Most of the assumptions will not directly affect the study. A more comprehensive list is displayed in Appendix B. Some of the assumptions beneficial to keep in mind are the following:

- The wind and beam are distributed uniformly. The assumption seems to bring matching output results with ACS points. However, the effects of that assumption proving false at other points is unknown.
- HELEEOS is assuming a perfect tracking solution. In other words, the beam is expected to be able to stay on the target because the weapon system continually retains the ability to know the location of the target.
- The speed input parameters in HELEEOS only contributes to beam slewing. The consequence of the assumption means that the speed only contributes to the reduction of the thermal blooming effect. Other effects due to speed are not represented. (Bartell 2003)

HELEEOS Output

As displayed in the Figure 5, HELEEOS presents several output options. Because the primary output, irradiance, is measured in Watts per meter squared all output values will be divided by 10,000 to match kW/m^2 used in EADSIM.

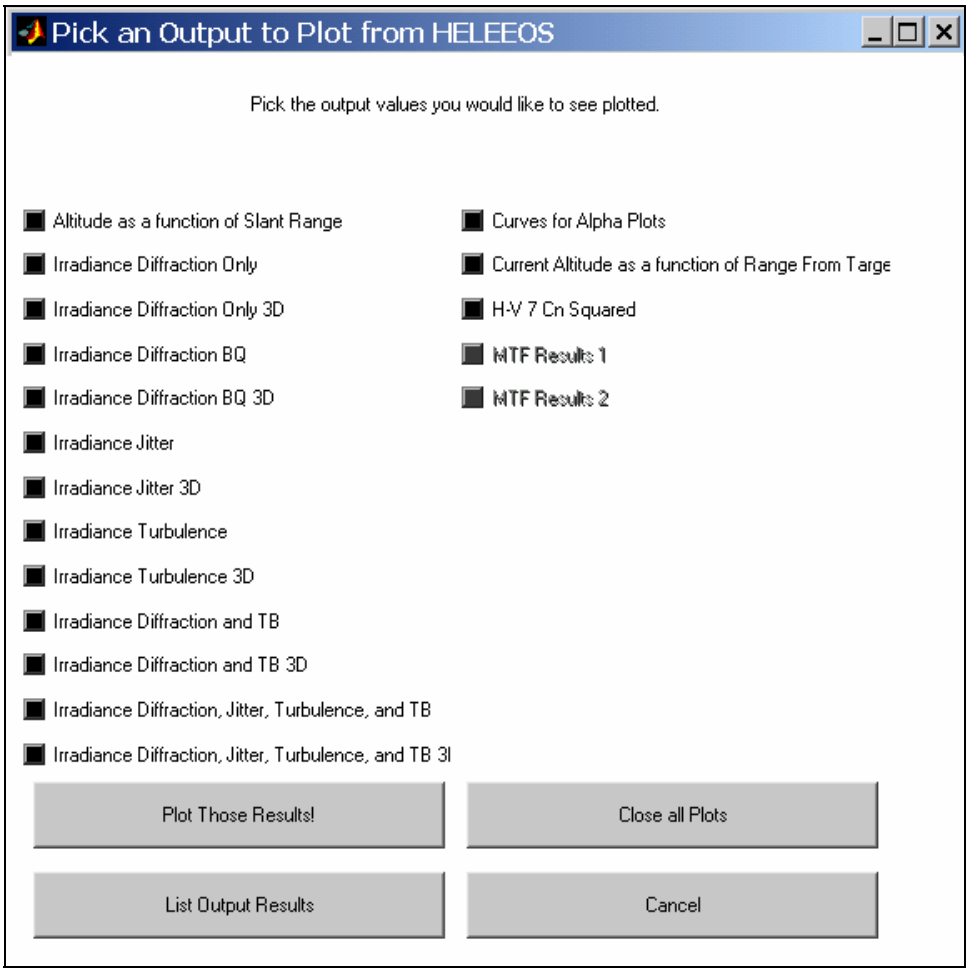

Figure 5 – HELEEOS Output GUI

The irradiance can be displayed in several different ways using combinations of the effects of jitter, turbulence, and thermal blooming. The data can be formatted in either two or three dimensions and can be displayed graphically using HELEEOS or obtained from specific areas in the data.Out array. In Figure 6 the graph on the left

shows irradiance values affecting a two dimensional surface while the graph on the right shows the one dimensional affect. Additionally the output data array offers a single peak irradiance value based on the combinations of the factors previously mentioned.

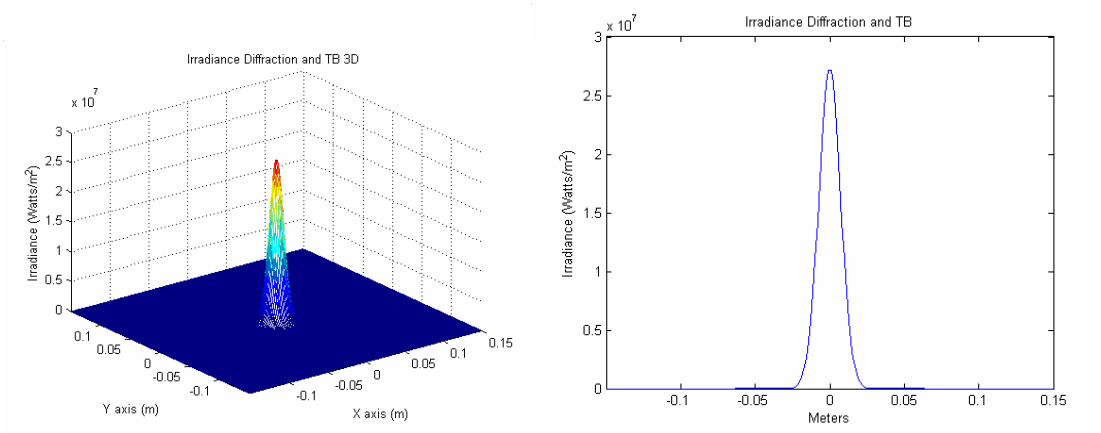

Figure 6 – Irradiance Graphs

The HELEEOS code provides irradiance in a form that bridges the gap between engineering detail and tactical employment of military platforms equipped with laser systems. The engagement model focuses the technological simulation model of the laser to military applications and provides a single type of value in several formats.

EADSIM Input

Overview

The EADSIM graphical user interface structures the simulation input based on system hierarchy. Most units are created from a bottom-up perspective or altering a previously made weapon system template. The core components, called elements, allow the user to build airframes, sensors, rulesets, communication devices, jammers, weapons, protocols as well as specify radar cross signatures (RCS), infrared (IR) signature,

probability of kill (pk) tables, formations, fiber optic topology (FOT), and maneuvers. The elements can then be assigned to a system which represents a generic type of assembled elements. For example, a laser weapon system may be formed by assigning a C-130 airframe, medium range sensors, laser ruleset, and a laser weapon. For the system to become anything more than a generic type specification the user must specify a scenario. A generic system becomes a unique platform when it is deployed to a particular location in the scenario and given a unique identity. A laydown refers to a specific collection of platforms. In addition to specifying the terrain type the scenario also specifies particular laydowns.

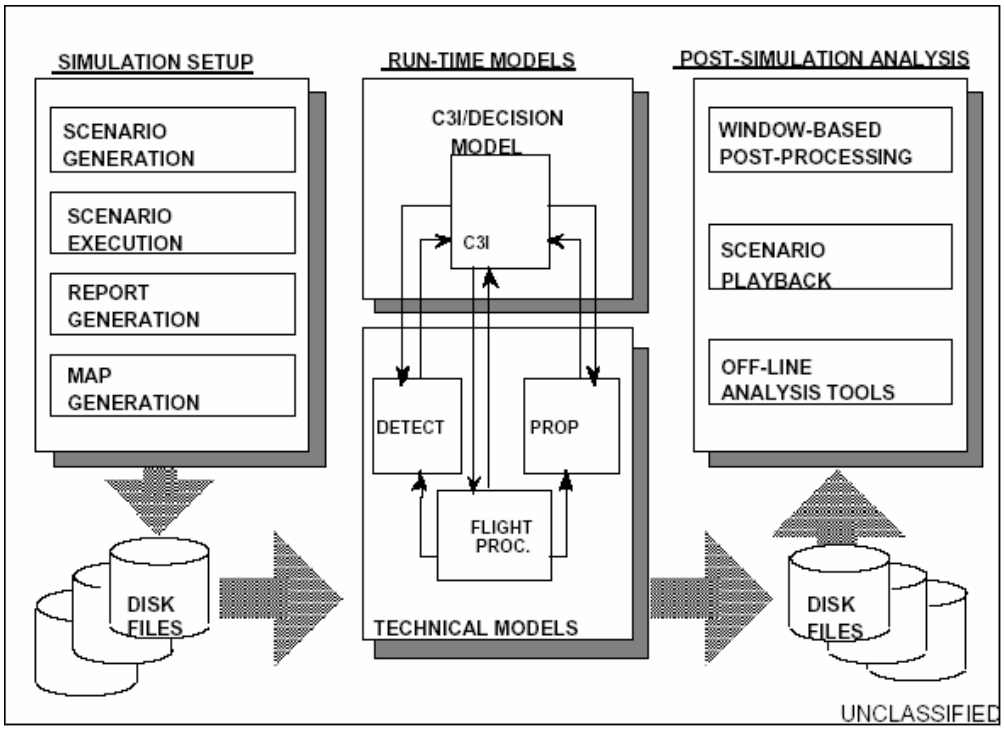

Figure 7 – EADSIM Architecture

Figure 7 offers insight into the general simulation functionally of EADSIM (EADSIM Methodology Manual, 2000). The user interface allows the user to generate

and execute a scenario while making several modeling decision regarding the nature of the events. The run-time models operate stochastically and deterministically based on the specifications given by the user, however the user has no real control while the run-time processes are operating. The simulation execution produces output files that can be viewed in EADSIM and easily exported to other analysis tools.

An investigation of the EADSIM directories reveals data structure and the specific files accessed by the run-time models and the GUI. The primary folder contains a data input folder, an executable folder, and a statistics folder. The data input folder contains sub-folders: area of interest (AOI), colors, elements, environment, high-level architecture (HLA), maps, networks, preferences (prefs), routes, scenarios, and statistics query (statquery). The elements file contains all the information about the specific system elements. The information can be viewed and edited in generic text editors, however, non-GUI data manipulation is neither recommended nor supported by EADSIM. Data accessible by very generic text applications often allows for a language accustomed to text file modification to easily change the data. The process of using an outside language to routinely manipulate files, referred to as scripting, circumvents the burdensome and tedious manual alterations to scenario data files using the GUI. Understanding of the data structure for EADSIM is essential to manipulating the files with a script.

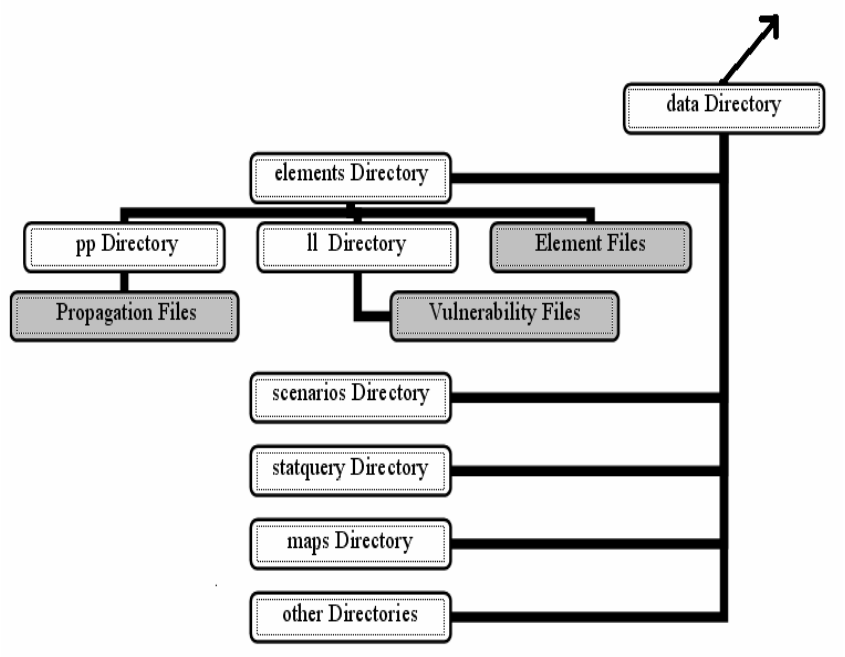

Figure 8 – EADSIM Data Structure 1

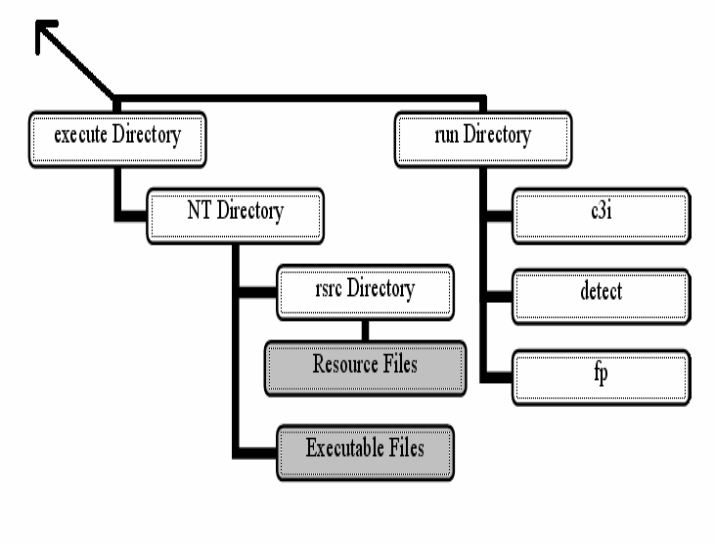

Figure 9 – EADSIM Data Structure 2

Figure 8 and Figure 9 show the data structure for the basic operations in EADSIM. The specific locations of the directories may vary depending on the computing system. The executable folder in the main EADSIM directory contains a list of executable files aiding the run-time execution or post-processing. The EASDIM non-

graphical executable file, named eadsim, and the non-graphical post-processing executable, named ngpp, enables the user to utilize the capabilities of the EADSIM GUI without using the GUI. The non-GUI executables allow the user to run the primary EADSIM components with command lines. The combination of a script and command line executables allow the opportunity for automating large quantities of design points.

EADSIM Laser Basics

EADSIM's laser ruleset provides versatile Directed Energy Weapons combat modeling options. Ground, air, and space platforms can utilize the laser capabilities. The ruleset enables modeling of laser slewing, laser warming, power propagation losses, and target destruction. The threat prioritization logic allows for targeting various types of platforms including both air and ground targets.

The laser engagement methodology is separated into basic events. The events are sequentially organized into two primary phases: target selection phase and launch/lase phase. As Figure 10 shows, the engagement process begins upon detection of a target. The platform assigns a track to the detected target and attempts to classify the target. If the target has been classified as a threat, the laser platform performs a turn-to-target maneuver classified as either target centriod or angle maintenance. When the slewing, or laser aperture turning, completes and the device is evaluated as stable enough to fire, the laser enters the launch/lase phase. The laser warming occurs simultaneously with the other process leading to the settling on the target which initiates when the laser is warmed and slewed to the target. The lase phase continuously cycles through slewing, settling, lasing, and warming until the target is either assessed as dead or engagement is no longer

feasible. The completion of the lase phase signals the preparation for the next target. A more extensive review of EADSIM laser modeling methodology can be found in the EADSIM methodology manual (EADSIM Methodology Manual 2000:4-307-360).

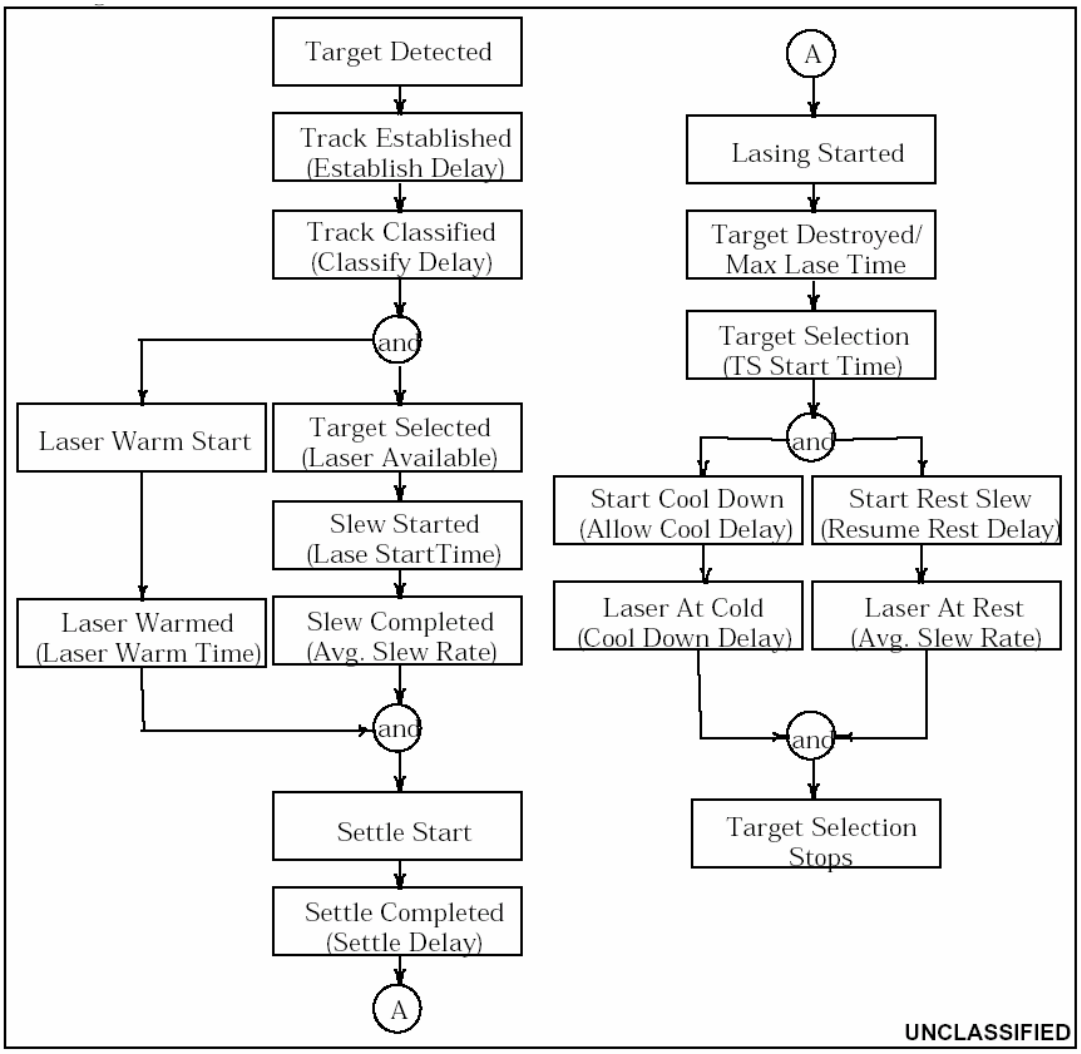

Figure 10 – Laser Engagement Timeline (EADSIM Methodology Manual, 2000)

Lethality Determination

As mentioned before, target destruction from a laser weapon engagement occurs when the energy deposited at the targeted location exceeds the material integrity threshold. Lethality with respect to laser weapons refers to the ability of the weapon to

breach the threshold. In EADSIM, the target lethality can be modeled four different ways: shared object model, Integrated Strategic Architecture Analysis Code (ISSAC), intensity based method, or fluence based method. The four methods are described in more detail below.

1. **Shared object model** – A user developed algorithm is called to determine target destruction.

2. **ISSAC** – The ISSAC lethality model, developed by the Schafer Corporation, performs primary laser operations including slewing, warming, settling, lasing, as well as final kill assessment. Theater ballistic missile (TBM) engagement is the only valid use of the model (EADSIM Methodology Manual, 2000).

3. **Intensity Based** – The intensity based methodology cross-references laser intensity delivered to target with the target vulnerability data to determine required dwell time. The vulnerability data contains information regarding target type, aimpoint, laser intensity, and pk. The data, stored in two dimensional tables, allows a time to kill look-up based on the desired probability of kill determined from a random draw (EADSIM Methodology Manual, 2000).

4. **Fluence Based** – A randomly generated pk determines the required amount of fluence for target destruction. With the input beam intensity, calculations including the length of time and intensity determine whether the target is destroyed (EADSIM Methodology Manual, 2000).

Considering the EADSIM lethality input options and the nature of the HELEEOS input to be used for the propagation tables, the intensity based method will be more efficient. The shared object model requires the development and validation of algorithms. The work of model development and validation has already been done with the HELEEOS code. The ISSAC model applies only to TBMs and cannot be used to model air-to-surface engagements. The fluence based model makes the assumption of constant intensity. While the constant intensity assumption may be suited for stationary laser platforms, as demonstrated earlier, a platform in motion firing the laser dramatically affects intensity.

EADSIM will report 'target destroyed' if the intensity delivered has exceeded the damage threshold. The threshold is a computation based on the properties of all the materials from the impact surface to the specific target. EADSIM needs a populated table of dwell times to evaluate target destruction. The dwell time (seconds) is obtained by dividing the threshold value (joules/cm^2) by an irradiance value (watts/cm^2).

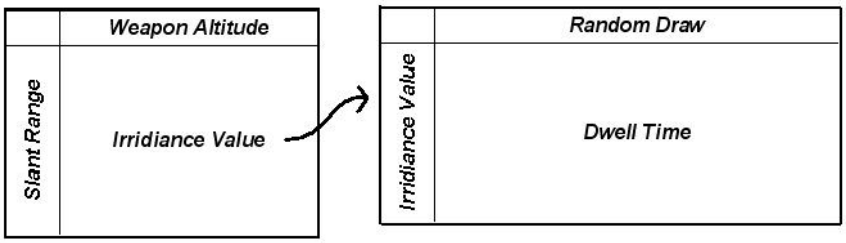

Figure 11 – Vulnerability Table Lookup

To determine target destruction, a random draw, made before the laser begins firing, selects the column from which the dwell time will be taken. The separate columns enable modeling a vulnerability threshold distribution often resulting from the absorption factors mentioned in the energy loss section. With the random draw, EADSIM also does an irradiance value lookup from the propagation table. The irradiance lookup and random draw return a dwell time value in the vulnerability table. For the laser to achieve target destruction, it must be able to remain on the target for the dwell time selected from the vulnerability table.

It is important to note that the report of 'target destruction' is an inaccurate depiction of the actual effect on the target. Because the laser has no explosive energy it cannot destroy the target in an explosive manner. Therefore, in order to affect the target the laser weapon will affect critical subcomponents delivering damage ranging from

mission delay to target destruction from internal explosion. Varying component vulnerabilities and effects require the establishment of different vulnerability tables, aimpoints and effect reports. For example, the following are a few of the vulnerable components associated with a vehicle.

1. Vehicle fabric or dash – Setting the fabric on fire would force the occupants of the vehicle to either exit the burning vehicle or put out the fire. In either case the vehicle would stop temporarily, but could be functional after some duration based on the ability of the vehicle inhabitants ability to extinguish fires. The advantage to targeting the fabric is the small energy requirements. Considering effects based operations, if the effect is to delay vehicle arrival time or arouse fear without regard to vehicle condition, then vehicle interior fabric should be a candidate for aimpoint.

2. Vehicle tires – The laser cutting through the tires would cause a small explosion similar to blowing a tire. The rubber would not need large amounts of energy to cause the explosion. The result of the destruction would affect the enemy mission completion time.

3. Vehicle engine components – The engine components are the most critical to vehicle operation because the operators have the least capability to compensate or adjust to damage done to the engine. Burning through the vehicle hood presents a significant challenge to accomplishing the goal. Truck hoods are typically made from fiberglass or some type of metal alloy. Both materials have higher heat capacities than the previous two aimpoints. Additionally some engine components are built specifically to endure extremely high temperatures. The effect of successfully damaging engine components could range from vehicle inoperability or target destruction.

Required Input: Propagation Table, Vulnerability Table

In EADSIM, the input fields drive several of the modeling decisions. To model the laser weapons system in EADSIM the user must work with the input fields allowed in the graphical user interface. The primary specifications in EADSIM regarding lasers are established in the weapon definitions window. More detail about that window, the specifications, and subcategories can be found in Appendix C. The important laser

modeling decisions are made in the laser parameters window. Figure 12 shows the necessary modeling decisions made specific to lasers.

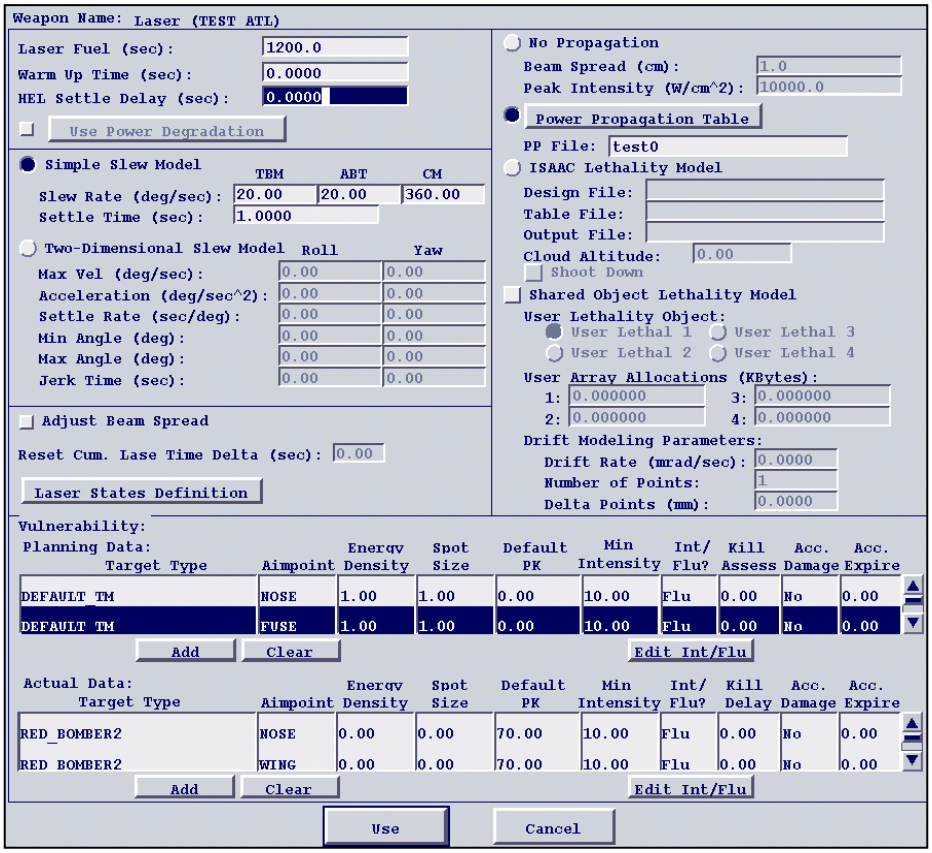

Figure 12 – EADSIM Laser Parameters

Several of the fields in the laser parameters window can be determined by gathering specific pieces of system data. The section in the upper left requires three specific values that can be established though system data or assumptions about the system. No methodology choices are required. The modeling methodology decisions are made by selecting the lethality model located in the upper right of the window. Choosing either the intensity or fluence based methodology requires additional input into the

vulnerability tables at the bottom of the window. Specifically choosing the intensity based methodology also requires a laser propagation table creation.

Correlating the Input and Output

The laser propagation table button opens a power propagation table development window. The peak irradiance values are placed into a power propagation table based on 10 optional lookup criterion: scenario time, target AGL, target altitude, target azimuth, target inclination angle, target NADIR, target perpendicular velocity, target range, total lase time, and weapon altitude. The necessary factors can be added to a lookup criterion list as seen in Figure 13.

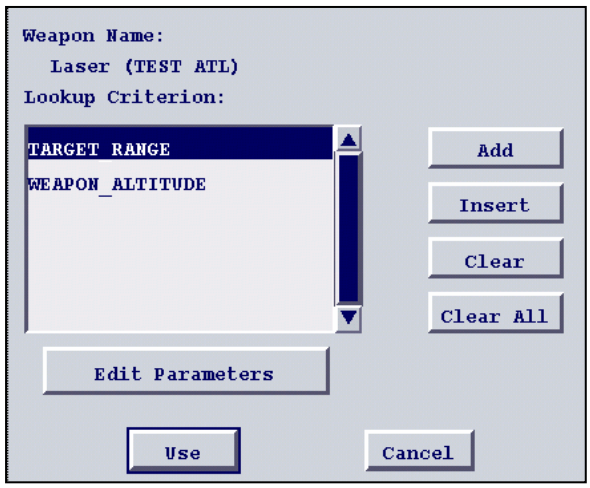

Figure 13 – EADSIM Power Propagation Table

The specific example shown in the figure above with the target range and weapon altitude selected as the key lookup criteria creates the need for a two dimensional data table to contain irradiance values for specific range altitude pairs of data. The lookup

table can be seen in the figure below. Both the target range and the weapon altitude are specified in kilometers.

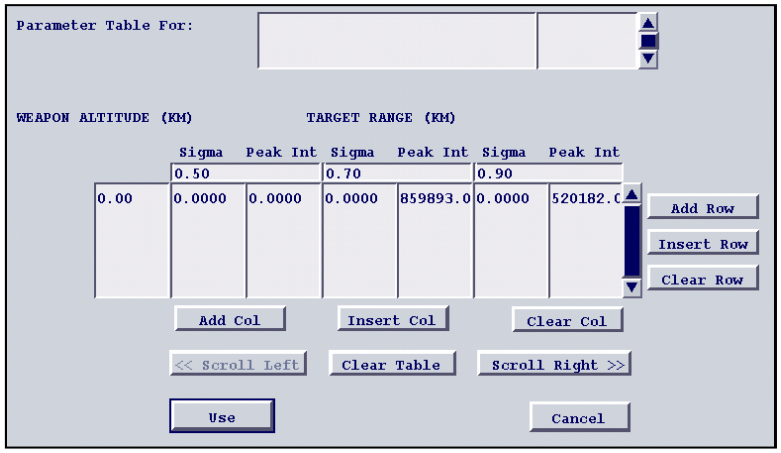

Figure 14 – EADSIM Two Dimensional Table

Adding more lookup criteria increases table complexity and adds considerable difficulty to the data entry process. Additional dimensions incorporate the use of the input box labeled 'Parameter Table For:' to clarify the very specific information to use in the data lookup. Because of the complications involved in multi-dimensional tables the propagation tables would be most efficiently filled out using the fewest criteria while accounting for the greatest changes in irradiance. To determine the laser parameters with the greatest effect, a basic experiment examined factor levels of parameters allowed to vary based on the JTO HEL requirements and HELEEOS limitations.

The parameter estimates give insight to the factors to be used for the propagation table. However, some restrictions disqualify the suggested parameters. Beam quality can not be interpolated because the value is derived from a specific type of component. Additionally, HELEEOS currently remains valid for only one specific beam quality. The

laser power, similarly, has both a limited range in HELEEOS and a maximum amount due to the size of the anticipated platform.

Analysis Techniques

Building a statistical regression model attempts to relate variables in a way that one variable can be predicted from a combination of other variables (Neter and others 1996). The variables used to predict are called predictors and the predicted variable is referred to as the response. The JMP software version 5.1.02 produced by the SAS Institute performs regression analysis. After inserting the predictors and responses into the JMP data tables and specifying a combination, the fit model option develops regression coefficients, labeled as parameter estimates, used in the equation that predicts the response. To be a good predictive model, the model must fit the data well and have reasonable justification that an assumption of normal error holds true.

To assess model aptness the coefficient of multiple determination, often called R-squared, measures the reduction of total variation specific to the set of predictors. Improving the R-squared value often requires adding more predictors or adding interactions terms from a previously linear model. The R-squared value alone does not imply the model is adequate. If the data seems relatively distant from the prediction line, the model may be inadequate. A visual inspection of the regression line with the data points often provides a good indication of model fit (Neter and others 1996).

One key assumption in the model development is that the error is distributed normally with a constant variance. A visual inspection of the residuals resulting from the fitted model versus the predicted values plot often gives enough evidence of constant

model variance. If the plot does not offer enough evidence, the error can often be standardized through employing a Box-Cox Transformation. The Box-Cox Transformation uses the method to maximum likelihood to minimize the error of sum of squares to correct unequal error variance in regression models. Selecting the transformation option in JMP produces a curve showing particular values of λ that would minimize the error and increase the standardization of error. Often a range of values is appropriate. After the selection of λ, JMP uses the geometric mean to compute a new set of response variables (JMP 5.1.0.2).

Summary

This research effort focuses on passing data from a higher fidelity engagement model to a mission level model to evaluate the military worth of the ATL. The necessary information requirements to perform the aggregation has been established in this section. HELEEOS was validated at several points with ACS. HELEEOS inputs several parameters specifying the general scenario, laser qualities, target setup, and atmospheric conditions. The output produces a single scalar maximum value or a graph of irradiance spread over an area. A series of these values are needed as input to EADSIM in the form of an intensity lookup table. Additionally EADSIM needs a corresponding vulnerability table. The two tables are utilized in producing a specific dwell time required to destroy a target. EADSIM simulations at different levels will assess the combat performance of the ATL in a mission level scenario. The output of the mission level runs could grant insight into campaign level input used for assessing the ATL impact on the war.

III. Methodology

General Methodology

Considering the issues mentioned in the previous chapter regarding input, output, data correlation and lethality offers structural guidance to an experiment methodology. The basic steps to be accomplished are the establishment of factor levels, development of vulnerability tables, setup and execution of HELEEOS to build appropriate propagation tables, construction of EADSIM baseline scenario, and script development for EADSIM scenario executions for the established factor level settings.

Factor Levels

Factor level settings should allow exploration of the proposed systems capabilities and offer some direction for improvement. The exploration could imply varying every possible modeled characteristic. Due to limited time, resources, model capabilities, and project scope, the factors chosen are suspected to have an impact when altered in the intended operational environment. The factor levels are limited by the requested scenario parameters, model capabilities, and validated HELEEOS design points. The factors are weapon altitude, weapon velocity, target approach, target area, random target setups, ATL power levels, and vulnerability tables. The justification for selection and levels are described below.

Weapon Altitude

In conducting experiments with HELEEOS and as seen in Figure 4, weapon altitude significantly affects laser performance. In general, as the weapon's altitude increases, the intensity on the target decreases. The HEL JTO scenario requirements set

the altitude range between 0 and 12,000 meters. The HELEEOS valid points in that range are 1000 meters, 2000 meters, 4000 meters, and 8000 meters. The validated HELEEOS points span the requested interval. Thus the altitude settings considered are 1000 meters, 2000 meters, 4000 meters, and 8000 meters.

Weapon Velocity

The evidence for the effect of velocity is derived from the difference in values for the HELEEOS output seen in Figure 2 and Figure 3 where the only changed parameters relate to velocity. However, it is to be noted that HELEEOS only uses velocities to calculate thermal blooming effects. The weapon velocity factor levels span the entire range of the JTO HEL scenario with a low value of 140 m/s, a midpoint of 220 m/s, and a high value of 300 m/s.

Target Area

Due to the unpredictability in target arrangement, several random target locations were selected for a given area. The target area establishment began by arbitrarily selecting latitude and longitude coordinates for a center point. The levels for target area were arbitrarily selected to be 1 km, 3 km, and 5 km from the center point. The specific latitude and longitude degrees were computed based on the following conversions.

Table 10 – Latitude and Longitude to Kilometers Conversion

	Latitude (km)	Longitude (km)
1 degree	111.6993	111.321
.1 degree	11.16993	11.1321
.01 degree	1.116993	1.11321

The conversions are assuming a location near the equator. Microsoft Excel® enables the generation of ten random values for each the three specified ranges. The exact values are shown in Appendix D.

Target Approach

Adding a target approach variable accommodates the changes in target location and weapon location at the time of attack. Additionally, target approach investigation can potentially contribute to the requested task of weapon effect maximization. Multiple runs on only one target location setup may bias the analysis to tailor to that specific setup. The approach will be treated as a qualitative variable that has two variants: target area approach from east to west and target area approach from north to south.

Target Velocity

The JTO HEL requirements indicate a scenario where the target will be moving between 0 and 23 m/s. Additionally, in the combat environment a target that can move will probably use that capability when necessary. The levels used for the target velocity factor will be 0 m/s, 11.5 m/s, and 23 m/s.

Target Priority

The target priority variable allows a differentiation in the target selection criteria. The choices are limited to the EADSIM settings. Further limitations are incurred because some of available options apply only in air-to-air engagements. The applicable options are shortest dwell, longest dwell time, highest elevation angle, and lowest elevation angle.

ATL Power Levels

The ATL concept based on current laser technology considers the power range of 50-100 kW. HELEEOS has been validated for 50 kW, 100 kW, and 200 kW. Considering the rate of technological development, a 200 kW laser is not out of the question. The rapidly declining intensity delivered to the target based on slant range suggests certain minimal power levels are required to affect the target. Thus exploring these levels as much as possible will provide valuable ATL military worth information. All three settings will be included as factor levels.

Vulnerability Levels

The trucks, or any other target, have multiple potential vulnerable components. The actual data on known target vulnerability remains classified. Calculations based on material heat capacity can produce a radiant flux capacity specified in kilowatt seconds per square centimeter. The radiant flux capacity of the target is modeled using three levels of vulnerability. The advantage of modeling using generic levels allows the analysis to appeal to a broad range of applications while avoiding investigation of sensitive information.

Factor Level Reduction and Design of Experiments

A combination of quantitative and qualitative factors, along with the multiple qualitative factors with more than two levels, complicates the design of experiments choices. With those factor types, basic response surface methodology techniques cannot be used. Specialized designs must be used to facilitate quantitative and qualitative factors with the multiple qualitative factors with more than two levels. Additionally, running a

very small number of points may become a bad choice if a particular design point fails to run. A greater amount of critical information is lost in smaller designs. The design of experiments consists of combinations of every factor at every level. A quick computation of the combinations of factor levels shows that 58,320 simulation runs would be required without consideration of replications. While that number of simulations is possible given the capabilities of the MSRC, the detailed debugging and analysis requirements are beyond the scope of the methodology development. Before developing a design of experiments, the factors will be reduced based primarily on engagement level results and ensuring a manageable number of outputs, but other considerations will arise. At this point the current factors and levels are shown in Table 11.

Table 11 – Appropriate Factor Level Settings

Factor	Low	Medium	High
Weapon Altitude	1000 meters	4500 meters	8000 meters
Weapon Velocity	140 m/s	220 m/s	300 m/s
Target Velocity	0 m/s	11.5	23 m/s
Target Approach	South-North	N/A	East-West
Target Setup	1 km radius 10 variations	3 km radius 10 variations	5 km radius 10 variations
Target Priority	1 - Shortest Time to Kill, 2 - Longest Time to Kill, 3 - Lowest Elevation Angle, 4 - Highest Elevation Angle		
ATL Power Level	50000 Watts/cm^2	100000 Watts/cm^2	200000 Watts/cm^2
Vulnerability Tables	10000 J/ cm^2	50000 J/ cm^2	90000 J/ cm^2

The first set of eliminations results from engagement level analysis in HEELEOS. The quantitative factors were evaluated at their high, medium, and low levels. Examining the output revealed the factors seeming to produce a significant effect and the factors with no apparent effect in engagements. The results of the engagement level simulations are shown in Table 15 in Chapter 4. The results show that the levels that have significant effects are laser power, weapon altitude, and slant range. The weapon and target velocities did not have a noticeable effect. Potentially the effect for weapon

and target velocities only occurs at much greater values. The target velocity will be discarded. The weapon velocity factor, however, will not be discarded. While the thermal blooming may not be significantly changed for the weapon-target velocities represented in this scenario, the time the weapon has over the target area is a factor. Preliminary simulation runs show results as high as 30 seconds for successful engagements. At 300 m/s the ATL can almost completely pass over the entire target area over this time.

Elimination of a 3 level factor reduces the number of combinations to 19,440. The manageable number will be considered around 2,500 simulation runs. Thus, the remaining factors and levels must be scrutinized more carefully.

As mentioned before the computation for run number does not involve replications. The target setup adds randomization to the experiment. Thus, the individualized setups will be considered as replications. Additionally, approaching the target area in a straight line is expected to only add to the randomness of the scenario setup and not contribute to anything other than variance. This expectation can be seen by interpreting the approaches from the east as approaches from the south with a different target setup. In addition to the elimination of target approach, the highest ATL power level will be removed from the experiment. Establishing factor levels with center points is an advantage that enables the regression model to be assessed for model curvature. The 200 kW level, outside of the requested HEL JTO parameters, does not facilitate curvature analysis. The weapon altitude has changes partly resulting from retaining center points.

Table 12 – Actual Factor Level Settings

Factor	Low	Medium	High
Weapon Altitude	1000 meters	4500 meters	8000 meters
Weapon Velocity	140 m/s	220 m/s	300 m/s
Target Priority	1 - Shortest Time to Kill, 2 - Longest Time to Kill, 3 - Lowest Elevation Angle, 4 - Highest Elevation Angle		
ATL Power Level	50000 Watts/cm^2		100000 Watts/cm^2
Vulnerability Tables	10000 J/ cm^2	50000 J/ cm^2	90000 J/ cm^2

The remaining factors included in the design of experiments are shown in Table 12. The design of experiments consists of an experiment for every combination of every factor level. After the reduction 216 design points remain with 10 different target setups each for a total of 2160 simulation executions.

Vulnerability Tables

In general the vulnerability values are established with consideration of the properties of the materials from the target surface to the vulnerable component and the necessary energy to damage the intended target. Due to the sensitive nature of specific component vulnerabilities and the irrelevance of the specific values to the analysis, the focus for the estimation is target penetration. Specific component vulnerabilities are ignored for the calculation. The resulting assumption specific to the calculation is that the beam, after penetrating the surface, will require a negligible amount of energy to critically damage the targeted component.

An estimation of the vulnerability of aluminum, performed by Azar, revealed a radiant flux density of 113234 joules/m^2 (Azar, 2003). The only variables in the equation relative to the specific environment are ambient temperature and material thickness. Of those two values material thickness is more likely to change from platform to platform as well as have a greater effect for typical operational values. Azar was evaluating a cruise missile. The calculations below examine an armored personal carrier

(APC). The equation, also referenced by Azar, utilizes the specific heat capacity, melting point, vaporization point, ambient temperature, material density, latent heat of fusion, and latent heat of vaporization of a particular material to produce radiant flux density. Aluminum-5803, a typical APC material because of the light-weight, material strength combination, will be used for comparison to Azar's values. The following formula computes the material radiant flux density.

$$(2) \qquad E_0 = \rho d[C(T_m - T_0) + H_m + C(T_v - T_m) + H_v]$$

Using Equation (2) and the values established in Table 13 below, the flux densities at the top of the tables were derived.

Table 13 – Radiant Flux Density Calculation

Variable	Symbol	Aluminum 5083 - APC	Aluminum - Cruise Missile	Units
Flux Density	E_0	*373383269*	*1132339500*	*Joules/m²*
Material Density	ρ	*2660*	*2700*	*kg/m²*
Specific Heat Capacity	C	*900*	*900*	*Joules/(kg*C)*
Melting Temperature	T_m	*591*	*660*	*Celsius*
Vaporization Temperature	T_v	*2518.85*	*2450*	*Celsius*
Latent Heat of Vaporization	ΔH_v	*11400000*	*11400000*	*Joules/kg*
Latent Heat of Fusion	ΔH_m	*397000*	*397000*	*Joules/kg*
Ambient Temperature	T_0	*30*	*25*	*Celsius*
Material Thickness	d	*0.01*	*0.03*	*m*

$$(3) \qquad V = \frac{E_0}{10000}$$

Equation (3) produces a radiant flux density in jules/cm^2 making the values consistent with the values being used for HELEEOS and EADSIM. Instead of using the specific values in the table, as mentioned before generic evenly distributed levels will facilitate development of contribution of the vulnerability factor to the overall ATL effectiveness

assessment. The generic levels to be used for V instead of values computed by Equation (3) are 10000, 50000, and 90000.

The EADSIM vulnerability table produces a required dwell time based on the irradiance value from the propagation table and a random draw. Thus, similar to the method used by Azar, the dwell times calculated for each irradiance value are multiplied by 1.0, 1.1, 1.2, 1.3, 1.4 and 1.5 to represent the 50^{th}, 60^{th}, 70^{th}, 80^{th}, 90^{th}, and 100^{th} quartiles respectively (Azar 2003). Equation (4) computed the specific dwell times.

$$T_i = \frac{(c_i)(V)}{Irradiance} \tag{4}$$

where c_i = 1.0, 1.1, 1.2, 1.3, 1.4, 1.5

With the selection of vulnerability levels the calculation methodology established for varying degrees of damage, the specific irradiance values included in the chart need to be chosen. Typically in input modeling a specific set of values or pairs of values is matched with a distribution. In this case, the pairs of data are dependent on each other and neither are given. A general equation has been formulated and pairs of data can be created through the equation. The curve formulated by the equation is shown in Figure 15.

Modeling the information from the equation could be accomplished by dividing the curve into segments that can be modeled as lines and segments that require more detailed modeling. A notional judgment of significant dwell times produces the range modeled in more detail. The times greater than and less than the significant region were modeled as lines. The significant region was assessed as 1 to 20 seconds of engagement.

Times less than 1 second and times greater than 20 seconds possessed much more sparse pairs of data for the vulnerability lookup table.

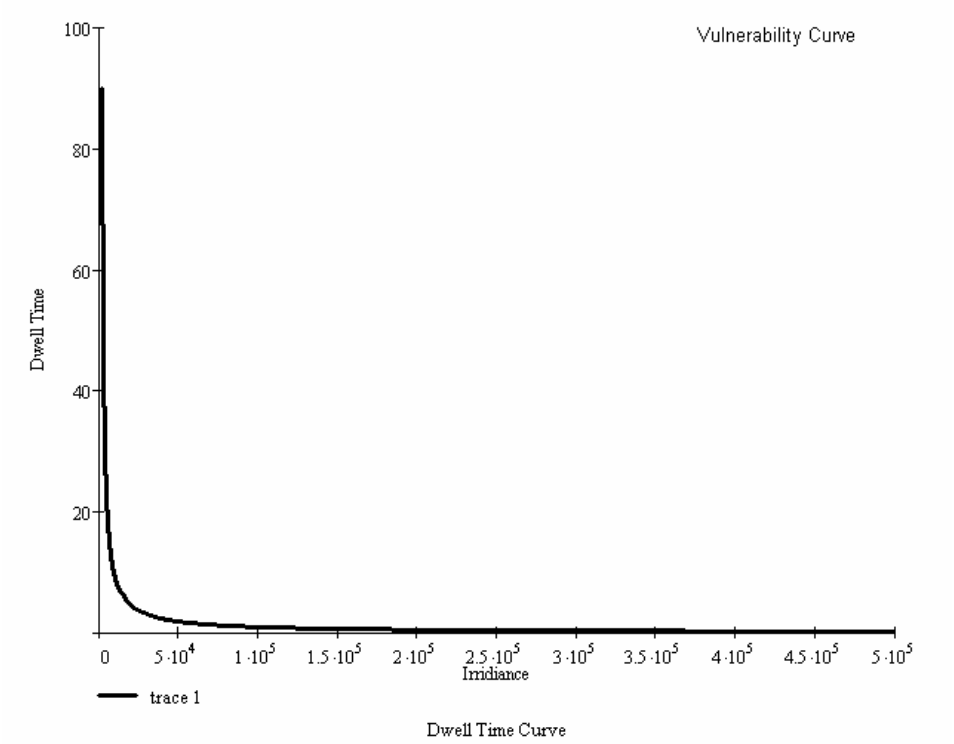

Figure 15 – Vulnerability Curve

The vulnerability tables used in EADSIM executions and curve fits from the values selected for the table can be found in Appendix E. Placing the vulnerability table into EADSIM requires transporting the values into a generic text file in the specific format read by EADSIM, saving the file as a *.ll file, and placing the file in the EADSIM ll Directory. Specifically the vulnerability files were saved as vul1.ll, vul2.ll and vul3.ll representing the low, medium, and high levels of vulnerability.

Although EADSIM can handle three aimpoints, the outcome in the laser summary report produced by the ngpp post-processing tool shows only the time and a statement classifying the laser engagement as successful or failed without indication of which aimpoint was targeted. If required an in-depth report can be generated, but assessment of the aimpoint requires a significant amount of data parsing. Instead, the ATL effectiveness at different vulnerability levels can be derived from varying the vulnerability of all targets in the scenario.

Propagation Tables: HELEEOS output to EADSIM input

The output for HELEEOS executions are derived from the input requirements from EADSIM execution. The preliminary HELEEOS runs at the high and low values for the quantitatives factors show the most significant factors to be power level, weapon altitude, and slant range. Since EADSIM does not have the capability to vary the power level, a new propagation table must be built for each of the power factor levels. Each propagation table is a matrix of irradiance values for corresponding pairs of weapon altitude and slant ranges. Because EADSIM linearly interpolates between the values in the table, no more values than the slant ranges used as tie points to ACS need to be used.

The Matlab code written to generate the values for the propagation table returned some values marked as invalid. The invalid results occurred when the slant range was less than the altitude. Since these engagements can never occur, EADSIM code will never attempt to lookup those values.

The output from HELEEOS was transformed in a similar fashion as the vulnerability tables. The values were placed in the required format and then into a

generic text editor. Each propagation table was saved as a *.pp file and placed in the pp Directory. The propagation tables are shown in Appendix F.

An EADSIM Baseline Scenario

Knowing that the parameters would be changed from outside the GUI led to the requirement to establish one and only one working baseline scenario. Changing from one design point to the next design point can be accomplished using a script. Based on information structure the baseline scenario required the following tasks to support the factor levels:

1) Create and deploy an ATL entity

    a. Set a weapon altitude
    b. Set the weapon velocity
    c. Set a start and end point for the ATL route
    d. Develop and integrate propagation tables
    e. Develop and integrate vulnerability tables

2) Create and deploy target entities

3) Debug the scenario until the engagement is successful

Creation of the entities and setting an arbitrary placeholder value for the factors, other than the tables, was not problematic and could be easily accomplished by personnel familiar with EADSIM GUI. The tables do not consist of a single value and table modification requires moderate understanding of the laser engagement methodology. The first major obstacle was discovered from analyzing the initial baseline scenario laser summary. The ATL platform failed to engage in every ground engagement regardless of target type. Although EADSIM methodology begins to describe ground engagement along with air to air engagements, at some point later in the methodology the manual

states that EADSIM laser target selection does not consider ground targets as threats. To escape the software flaw, a target the laser would engage had to be altered to represent a ground vehicle. The thought of using an airplane or missile to represent a ground vehicle may initially seem like a complete misrepresentation. However, visualizing the entities in EADSIM as real world objects is a false perception. Thinking of the entities as real world objects happens because of the EADSIM design. The GUI allows a series of check boxes, text boxes, and data tables to guide, enable, and disable the actual run-time code. For example, in a set of data associated with a building, the velocity must be ignored or disabled. Using the GUI, while saving time in learning a programming language, presents a considerable amount of modeling inflexibility. Because the entities in the EADSIM GUI are specific data values with labels grouped into a data classification, an aircraft or missile can represent a vehicle when the data fields are properly configured. Thus, when the particular vehicle data classification does not use a specific data value normally modeled in an aircraft or missile, then the data field was unused or set to an acceptable level.

The next step was to model a cruise missile to behave as similar to a truck as possible. Three aspects need to be addressed: velocity, shape which affects vulnerability, and vehicle interactions.

Since the velocity of the vehicle had been eliminated as a factor, leaving the vehicle velocity presented no problems to the scenario. Had velocity needed to be part of the scenario, the target movement could be restricted to flat surfaces.

The surface area and shape are different. The surface area and shape may affect the ability of the vulnerable component to be targeted as well as the targetable area. The

targeting issue is somewhat resolved by using only one aimpoint. However, this situation also requires the assumption that the aimpoint can always be reached. Thus a target such as a gas tank on the left side of the truck might not be represented in the results of these simulations. Regarding the targetable area, the spot size of the aimpoint can be determined in EADSIM. So with proper restrictions and cautions the cruise missile can perform the same function in the scenario as a vehicle would have performed.

This particular difficulty further reinforced the decision to use the intensity based modeling method. The use of the intensity based modeling allows the vulnerability information to be established in vulnerability tables. The vulnerability for a ground target could be established completely by the user within the vulnerability table. In other words, the target does really not matter in most respects.

The platform operation, or data interaction, was the other caution in modeling an aircraft or a missile as a ground target. The primary differences between vehicle operation and airframe operation are fairly obvious. First, a ground vehicle's vertical motion conforms to every rising on the surface of the earth whereas a cruise missile typically does not compensate for every rising on the surface of the earth. This difference imposes a certain velocity restriction and additionally suggests that movement in general might not be appropriate.

With some minor modifications the cruise missile scenario used in Capt. Azar's study could be used as a baseline scenario. The basic ATL system was copied and modified. It contained the following elements: laser ruleset, a laser airframe based on a C-130's capabilities, and a laser weapon. The initial attempts also utilized the propagation table built from Equation (1) as well as the vulnerability tables from the

values developed for aluminum from Equation (2). The cruise missile system was copied and labeled as 'fake truck'. Two separate laydown files contained all of the deployed systems: RED_FORCE and BLUE_FORCE. The red laydown contained all of the vehicles and the blue force contained the ATL. The initial development and executions occurred on a laptop with Windows NT. The successful execution of a baseline scenario on the laptop completed the baseline development and the script development stage was initiated.

EADSIM Execution Script Development

Recall that a laydown file consists of deployed systems. In general, changing details about the platforms required changing the laydown file for either the RED_FORCE or the BLUE_FORCE. If the propagation or vulnerability files were to be changed, a new elements file had to be generated. The experiment design points shown in Appendix G required the development of unique laydown files containing the start location, end location, altitude, and velocity for every platform. Unique laydown files forced the need for unique scenario files because the scenario files contained the laydown specification information. Changing the propagation and vulnerability tables required the elements file to be changed. Instead of changing a numeric value, a file name is changed to one of the previously built files.

Table 14 – Script File Change Requirements

Factor Level	Scenario File	Red Laydown File	Blue Laydown File	ATL Weapon Element File
ATL Weapon Altitude	x		x	
Target Approach	x		x	
Target Area	x	x		
ATL Power Levels				x
ATL Vulnerability Levels				x

For example, design point perhaps 56 would have files generated by the script:

Scenario File: BASELINE_56.scn

Red Laydown: RED_LAYDOWN_56.lay

Blue Laydown: BLUE_LAYDOWN_56.lay

Laser Report Query: BASELINE_56.statquery

Executing the design point, requires a command line entry specifying the scenario file. Changing from a design point with a different propagation table requires not only executing the scenario file but also changing the weapons element file. The weapons element file is a system file in a particular directory. If the scenarios are executed in sequence, the weapons element file can be changed before every simulation run.

When the simulations are run in parallel and the code attempts to change the weapons element file that has already been changed by another scenario already in progress, the results of the simulation will not be representative of the intended design points. The script developed to execute EADSIM at the MSRC utilizes the dynamic processing capabilities of the facility and obeying the requested continuous processor usage limitation of twenty-five processors. To fix the parallel processing dilemma, nine weapon systems were created. The nine changes originate from the combination of three

propagation tables and three vulnerability tables. Now only the laydown file will need to be changed for every design point.

Originally, the PERL script was written by Dr. Phil Amburn and used to submit simulation jobs to be processed in parallel. The script periodically assessed the number of simulations in execution on the server. Based on that number the script either submitted more scenarios for execution or reinitiated the wait period for server queue assessment. To accomplish that parallel scripting, the following steps were taken:

1. EADSIM File Location – The factor levels established for the scenario above were located in various directories and files.

2. Template File Construction – The specific files needing changes between each simulation execution had to be translated into template files. The files marked as template files were the basic scenario file (*.scn), the red force laydown file and blue force laydown (*.lay) file, and the laser report engagement query file (*.engquery). Each of the specific values to be changed were changed to variable names in the template files.

3. DOE File Construction – A design of experiment file contained every variation of factors and factor levels for the simulations. The file was labeled "jobcontrol" and consisted of a unique run number followed by the specific fields and values associated with the factors.

4. Master Script Construction– The master script combined the specific jobcontrol values with the variables in the template files to create unique scenario and laydown files for each design point. The script then issued a command line execution and the ngpp for each scenario.

The parallel processing effort brought about complications. As the simulations were being submitted to the server some of them never completed. Those simulations remained in process. Eventually many of the simulations would encounter the same problem and cause all of the available processors to become occupied. One particular cause for the problem could have been a limitation in the capabilities of the server which assigned simulations to be processed. Typically, the MSRC handles long,

computationally intensive simulations from several different customers. The EADSIM simulations were relatively short. For comparison, one simulation could run on the local Unix workstation and produce results in less than two seconds. Because of the speed on the local workstation and problems with parallel submission, the master script was modified to execute the simulations on the Unix workstation. The script modified to execute the simulations can be found in Appendix H.

Post-Processing

The output from the entire process was a series of laser report files with filenames corresponding to each scenario name associated with a design point. The output file (*.engrpt) contained a list of targets engaged, the duration the targets were engaged, and the status of the target at the end of the engagement period. EADSIM has no statistical analysis tool for assessing results of different factor level settings and obviously no statistical analysis executable file to facilitate summarizing this experiment. An Excel macro facilitated the analysis of over 2000 laser engagement reports in an Excel file. The macro opened each report file, formatted the data, calculated requested statistics, and closed the report file. The macro can be found in Appendix H.

Batch Run Verification

In theory, a thorough understanding of EADSIM methodology and flawless scenario modeling produces a seamless transition to the analysis phase of a project. However, in practice, the simulation does not always execute as intended. A simulation scenario execution with a particular variable set may provide a complete simulation while

changing just one variable may cause the simulation to abort. Additionally, EADSIM, when executed as in this project, offers few indications that the scenario being executed actually completed. The only real signs of a proper simulation execution are the absence of the signs of the simulation not completing. As the simulations were being processed, the screen displayed the phrase 'Abort (core dumped)'. The display of that phrase suggested that the simulation runs should be examined for errors.

Examining one EADSIM simulation scenario involves a visual inspection of the scenario playback and examination of the statistics files to determine whether the desired events occurred. Examination of more than two thousand simulation runs becomes much more complicated. Additionally because of the rate at which the information passed on the display, no record of scenarios and core dump associations could be created. Considering the possible outcomes of each simulation after the entire batch of runs finished, criteria had to be developed to accept the simulation run or reject the simulation run. The possible outcomes were: scenario complete, scenario sufficiently complete, and scenario incomplete. The scenario completion refers to the simulations that began and continued operating without flaw to the very end of the simulation. A sufficiently complete signifies a scenario where the ATL passed over the target area and engaged the majority of the targets possible given the engagement conditions. In the incomplete scenario, the ATL did not reach a position where it could have engaged a majority of the targets possible given the engagement conditions.

Next evaluation measures were developed based on available output information to assess with which outcome the simulations should be associated. The output from the each run displayed a list of an engagement times, the targets engaged, and the specific

dwell time for each target. Below the list the number of targets killed and the cumulative dwell time were displayed. The last engagement time recorded and the total number of kills were used to asses the scenario outcome classification.

The last engagement time recorded measures the last time the ATL engaged a target. If the time is excessively low, the conclusion is that the scenario is incomplete. If the time is not too low, the simulation may be complete or sufficiently complete. The specific values are calculated in the analysis section of Chapter 4.

The total number of targets destroyed assesses whether the engagements occurred. Additionally, this measure is necessary because simulations without engagements obviously do not have a last engagement time to be assessed. The cases where the number of targets destroyed is zero will be examined further. Some caution must be exercised when classifying the simulation based on the number of targets destroyed because some engagements could legitimately have such results in a complete scenario.

Summary

The methodology in this section focused on developing factors and factor levels to facilitate the aggregation of information from HELEEOS to EADSIM. The inputs were identified and the outputs were built. Some attention throughout the process was given to overcoming the challenges associated with the specific code or the aggregation process. The factors and factor levels were developed with respect to JTO HEL parameters, HELEEOS and EADSIM limitations, and notional values when necessary. From the factor levels, HELEEOS was able to produce the necessary information for the propagation tables. The vulnerability tables were developed from making notional

assumptions based on a generic assessment of vehicle vulnerability. The PERL script tied together the DOE, the HELEEOS work, and EADSIM execution and produced a single output for each design point. Finally, a macro placed all of the files in a usable format in preparation for the military worth assessment using various statistical techniques.

IV. Analysis

Overview

This chapter explains the results gained from 2160 simulations of the described scenario at the specified levels. The tools used to asses the results vary depending on the nature of the output. The analysis section covers the HELEEOS factor exploration runs, EADSIM batch run verification, and an analysis of the successful EADSIM simulations.

HEELOS Factor Exploration

The aggregation process began with exploring the effects of the laser at the engagement level. The engagement level aided the initial assessment of factors to include in the experiment. The top of Table 15 shows the levels for the first experiment in HELEEOS. Recall that the levels for this initial experiment were derived from JTO requirements and model restrictions. Iterations of HELEEOS code produced the results in matrix form. One consequence of the quick coding was the calculation of invalid engagements. The invalid engagements are signified by their gray background. An invalid engagement occurs when the slant range is shorter than the altitude. They have no real significance as far as input into the next model, but do have some significance as far as seeing patterns. HELEEOS does not yet have randomness in the model, thus results that are not significant are easily identifiable. The experiment investigates the factor effects on the maximum irradiance outputs through basic comparisons of output differences.

Table 15 – HELEEOS Factor Exploration

Low	*3000*	*130*	*0*	*50000*	*3000*			
High	*8000*	*300*	*23*	*200000*	*15000*			
Run	**Platform Altitude**	**Platform Velocity**	**Target Velocity**	**Laser Power**	**Slant Range**	**OUTPUT**	**Patterns**	
1	*3000*	*130*	*0*	*50000*	*3000*	6561	1	1
2	*3000*	*300*	*0*	*50000*	*3000*	6561	1	
3	*8000*	*130*	*0*	*50000*	*3000*	10976	2	
4	*8000*	*300*	*0*	*50000*	*3000*	10976	2	
5	*3000*	*130*	*23*	*50000*	*3000*	6561	3	1
6	*3000*	*300*	*23*	*50000*	*3000*	6561	3	
7	*8000*	*130*	*23*	*50000*	*3000*	10976	4	
8	*8000*	*300*	*23*	*50000*	*3000*	10976	4	
9	*3000*	*130*	*0*	*200000*	*3000*	13364	5	2
10	*3000*	*300*	*0*	*200000*	*3000*	13364	5	
11	*8000*	*130*	*0*	*200000*	*3000*	23909	6	
12	*8000*	*300*	*0*	*200000*	*3000*	23909	6	
13	*3000*	*130*	*23*	*200000*	*3000*	13364	7	2
14	*3000*	*300*	*23*	*200000*	*3000*	13364	7	
15	*8000*	*130*	*23*	*200000*	*3000*	23909	8	
16	*8000*	*300*	*23*	*200000*	*3000*	23909	8	
17	*3000*	*130*	*0*	*50000*	*15000*	61.2	9	3
18	*3000*	*300*	*0*	*50000*	*15000*	61.2	9	
19	*8000*	*130*	*0*	*50000*	*15000*	190.96	10	
20	*8000*	*300*	*0*	*50000*	*15000*	190.96	10	
21	*3000*	*130*	*23*	*50000*	*15000*	61.2	11	3
22	*3000*	*300*	*23*	*50000*	*15000*	61.2	11	
23	*8000*	*130*	*23*	*50000*	*15000*	190.96	12	
24	*8000*	*300*	*23*	*50000*	*15000*	190.96	12	
25	*3000*	*130*	*0*	*200000*	*15000*	117.01	13	-
26	*3000*	*300*	*0*	*200000*	*15000*	117.01	13	
27	*8000*	*130*	*0*	*200000*	*15000*	384.19	14	
28	*8000*	*300*	*0*	*200000*	*15000*	384.19	14	

The patterns are shown by grouping the rows in patterns and labeling the pattern with a number and a bracket For example the irradiance from the first factor set is 6561, being that the second set of factors have the exact same output the conclusion is formed that the single factor varied between the factor sets has no significant effect. The first column of patterns to the right of the table shows the patterns that indicate the lack of significant effect for platform velocity. The second column shows the lack of

significance for target velocity. The target velocity and weapon velocity columns were removed as well as the invalid outputs for one more comparison.

Table 16 – HELEEOS Power Trends

Platform Altitude	Laser Power	Slant Range	OUTPUT
3000	50000	3000	6561
3000	200000	3000	13364
3000	50000	15000	61.2
3000	200000	15000	117.01
8000	50000	15000	190.96
8000	200000	15000	384.19

From the irradiance outputs seen in Table 16 for the given engagement geometries, quadrupling the power almost doubles the irradiance. Note this statement is a speculation that would require more formal experimentation to draw that particular conclusion. However, the observations at least give some indication of the potential benefits from increasing the power level.

The conclusion from this section of analysis has already been referenced in the previous chapter. The effects of weapon velocity and target velocity have no significant effect for the ranges specified in the scenario. The effects of weapon altitude, slant range, and power level cannot be ignored and were therefore considered for factors in the design of experiments.

EADSIM Batch Run Verification

Zero Targets Destroyed Criteria

The total number of targets destroyed and last simulation engagement time were used to determine the outcome classification of complete, sufficiently complete, or incomplete for each simulation run. The number of replications at each factor level was

associated with the number of simulations resulting in zero targets destroyed when the factor level was used. A higher percentage of no targets destroyed indicates the factor level may be the cause.

Table 17 – Zero Targets Destroyed Summary

	Factor Levels	Total Replications Associated with Each Factor Level	Replications with No Targets Destroyed	Percentage of Replications with No Targets Destroyed
Propagation	LOW	1080	185	17.13
	HIGH	1080	81	7.50
Vulnerability	LOW	720	0	0.00
	MEDIUM	720	51	7.08
	HIGH	720	215	29.86
Priority	1	540	60	11.11
	2	540	86	15.93
	3	540	60	11.11
	4	540	60	11.11
Alt	LOW	720	0	0.00
	MEDIUM	720	15	2.08
	HIGH	720	251	34.86
Velocity	LOW	720	40	5.56
	MEDIUM	720	95	13.19
	HIGH	720	131	18.19
Scenario	1	216	27	12.50
	2	216	26	12.04
	3	216	27	12.50
	4	216	26	12.04
	5	216	27	12.50
	6	216	26	12.04
	7	216	26	12.04
	8	216	27	12.50
	9	216	26	12.04
	10	216	28	12.96

In Table 17, the factor levels are displayed in the first column. The next column shows the number of occurrences of the factor in the entire simulation design. After the post-processing script summarized the data, the data was filtered into a new database. A counter incremented each time zero targets destroyed was associated with a factor level. The results of the count are displayed in the 'Replications with No Targets Destroyed'

column. The last column divides the number of replications associated with no targets destroyed at each factor level by the total number of occurrences of the factor at each level.

If the percentages were relatively even across the entire factor, the level was not considered problematic. The priority factor seemed relatively even across the factor levels with the second priority level slightly higher than the other three. The second priority level changes the target prioritization to longest dwell time first. The selection of targets with longer dwell times first may be contributing to the increase of failures at that particular level. However, more importantly, the engagements with zero targets destroyed cannot even be assessed for completeness because no last engagement time was recorded.

Several other similar assessments could be made to reveal information about the high level altitudes relationship to zero targets destroyed, none of those assessments are given because the high altitude factor level will be discarded entirely. The next assessment examines the zero targets destroyed with all simulations removed related to the high altitude. If a particular factor level had a relatively higher percentage, it was considered as a potential problem and would be further investigated.

In Table 18, the results after the removal of the simulations associated with the high platform altitude show that of the remaining data several levels of several factors have no relationship to the zero count. In this case, the fifteen no targets destroyed simulations are shown within each factor in the table. To state the association of the related factor levels in words makes more intuitive sense. Essentially, the laser did not engage in the fifteen simulations when the power level was low, the vulnerability setting

was at the most difficult level, the priority was set to longest dwell time first, and the altitude was set at the second highest level. Additionally the increasing velocities meant the platform was flying more quickly over the target area. These 15 occurrences of zero targets destroyed in particular are classified as legitimate results.

Table 18 – Zero Targets Destroyed Without High Altitude

	Factor Levels	Total Replications Associated with Each Factor Level	Replications with No Targets Destroyed	Percentage of Replications with No Targets Destroyed
Propagation	LOW	720	15	2.08
	HIGH	720	0	0.00
Vulnerability	LOW	480	0	0.00
	MEDIUM	480	0	0.00
	HIGH	480	15	3.12
Priority	1	360	0	0.00
	2	360	15	4.16
	3	360	0	0.00
	4	360	0	0.00
Alt	LOW	720	0	0.00
	MEDIUM	720	15	2.08
Velocity	LOW	480	0	0.00
	MEDIUM	480	5	1.04
	HIGH	480	10	2.08
Scenario	1	144	2	1.38
	2	144	1	0.69
	3	144	2	1.38
	4	144	1	0.69
	5	144	2	1.38
	6	144	1	0.69
	7	144	1	0.69
	8	144	2	1.38
	9	144	1	0.69
	10	144	2	1.38

Accepting the simulation times with zero targets destroyed presents a problem when considering the last engagement time, the second criteria for accepting the runs due to the indications of incomplete simulations. The only measure to verify a particular run would be to assess its last engagement time. Obviously, if the ATL never engaged a target, no last engagement time was recorded. Thus to exercise extreme caution in

ensuring complete simulations and to prevent skewedness from removing a third of a factor level, the entire high altitude level was removed from the final analysis.

Small Last Engagement Time Criteria

Removing the high altitude factor level allows for investigating the rest of the factors except for the 15 zero target destroyed simulations not associated with the high altitude. Those 15 simulations are assumed to have not been aborted runs. The small last engagement time requires establishment of acceptance criteria. Evaluating whether or not the ATL has sufficiently passed the engagement zone and engaged a majority of targets is the aim of the assessment. Thus, the ending position of the ATL will qualify or disqualify the particular simulations being evaluated. A simulation with a last engagement time of 90 seconds where the ATL was traveling at 140 m/s compared to a simulation with a last engagement time of 90 seconds where the ATL was traveling at 300 m/s places the platform in two different places. Obviously the criteria for acceptance is velocity dependent.

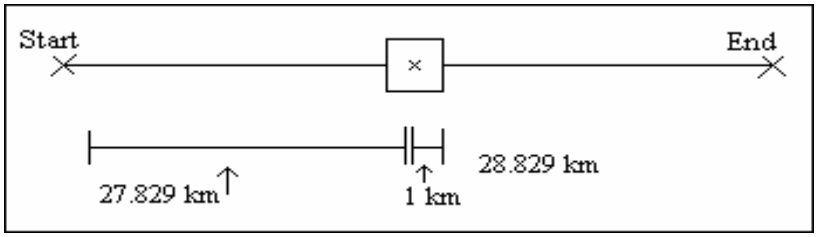

Figure 16 – Target Area

Figure 16 shows the target area and the flight path of the ATL rotated 90 degrees. The target zone ends after approximately 28800 meters traveled from the path origin. The assessment of simulation disqualification regarding short last engagement times was based on the calculation of the amount of time required to reach the end of the target

distribution area for each velocity factor level. A series of calculations similar to the EADSIM process can offer some justification for selecting the end of the engagement zone as the acceptance criteria. Calculate the distance traveled every second and the corresponding slant range every second relative to the altitudes using the Pythagorean theorem. From the calculated slant range a potential irradiance lookup value for every second can be determined. The irradiance value can be used to lookup a dwell time relative to the vulnerability level. Figure 17 shows the results of the calculations. Around 28,000 meters traveled, the amount of time required to kill the target begins to increase. Engagements started after that point begin to require more time and continue to move to a position requiring a higher dwell time.

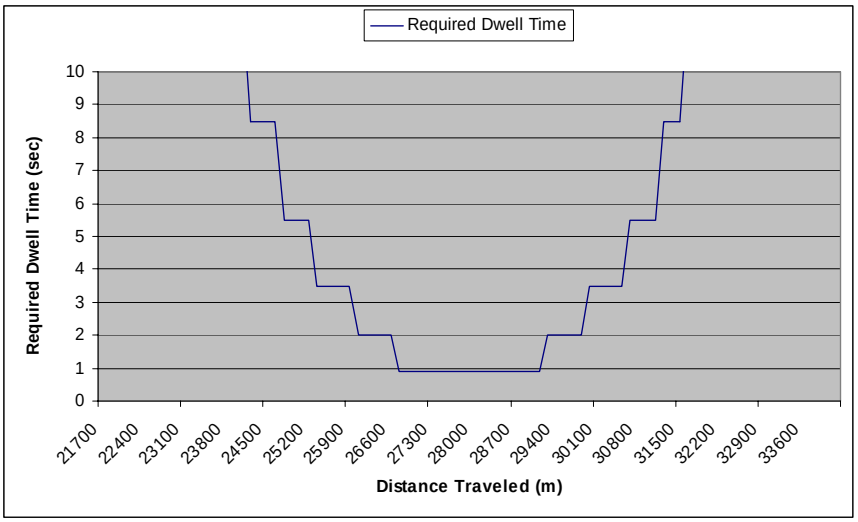

Figure 17 – Dwell Times vs. Distance Traveled

To qualify each simulation, the time required to reach the acceptance zone was calculated for each velocity. The acceptance point, 28829 meters, was divided by each velocity to produce the acceptance time for each simulation. The times are shown in Table 19.

Table 19 – Last Engagement Acceptance Time

Velocities (m/s)	140	220	300
Accepted Time (sec)	206.61	131.48	96.42

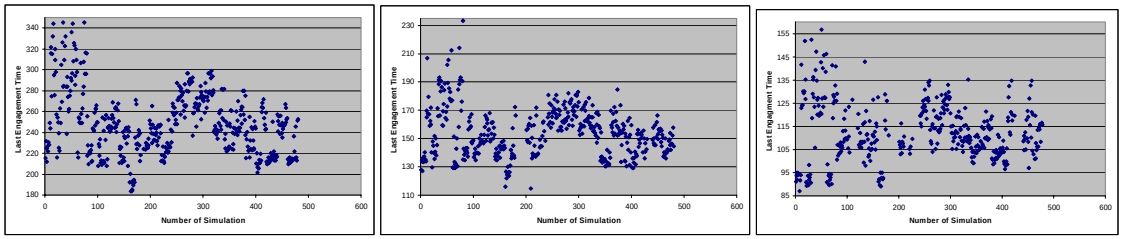

Figure 18 – Time Run Scatterplot

The three graphs in Figure 18 show the last engagement times for the 140 m/s, 220 m/s, and 300 m/s velocities respectively. A counting function revealed totals of 12 runs, 25 runs, and 33 runs that were below the acceptance time for each of the velocities respectively. Those simulations not passing the acceptance test are either entire sets of ten scenarios which would form a design point or small groups of 1-4 simulations within the ten scenario set. The entire design points that do not pass the acceptance test must be discarded entirely. However, for the smaller subsets of a design point, the number of targets destroyed can be compared to the other scenarios with the same factor level settings. If not too deviant, the points which did not pass the test may still be included in the final analysis. Based on the analysis shown in Appendix J, the individual simulations which did not pass the acceptance test were still accepted. The groups of simulations were discarded. From the remaining 1440 simulations from the previous exclusions another 60 points were excluded resulting in 1380 points for the factor effects analysis. The 1380 simulations form 138 design points for evaluation. Table 20 shows the final design points selected for analysis.

Table 20 – Final Design Point

	Factor Levels	Design Points with Factor Level	Percentage of Design Points with Factor Level
Propagation	LOW	66	47.83
	HIGH	72	52.17
Vulnerability	LOW	45	32.61
	MEDIUM	48	34.78
	HIGH	45	32.61
Priority	1	32	23.19
	2	35	25.36
	3	36	26.09
	4	35	25.36
Alt	LOW	66	47.83
	MEDIUM	72	52.17
Velocity	LOW	47	34.06
	MEDIUM	47	34.06
	HIGH	44	31.88

EADSIM Factor Effects

The two primary outputs from the process evaluated from the simulation executions are the number of targets destroyed, as well as the average dwell time. The goal of this section was to examine the effects of the factors on the different outputs. Determining the factor effects involved first building a first order regression model. The model was accepted as able to assess the factor effects if the model displayed aptness and constant variance. The model aptness was determined to be acceptable by having R-Squared values above 0.70 and passing a visual, subjective assessment ensuring the actual values were not too far outside the predicted response. Constant variance was determined by examining the residuals versus predicted plot for an even distribution of variance. Models where the variance seems non-constant could optionally be rebuilt including all the factor interactions and higher level terms or the response was transformed using a Box-Cox Y. When a model passed both the aptness assessment and

constant variance assessment, the effects screening test was executed to display the factor effects.

Factor Effects: Total Targets Destroyed

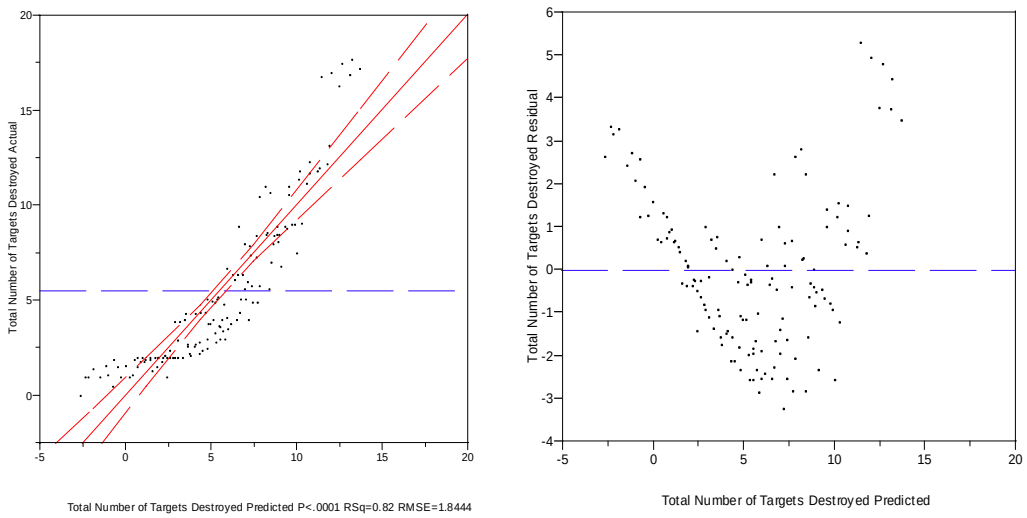

Figure 19 – Total Targets Destroyed

Table 21 – GOF: Targets Destroyed

R-Square	0.816942
R-Square Adj	0.807085
Root Mean Square Error	1.844439
Mean of Response	5.492029
Observations (or Sum Wgts)	138

Although the R-Square value of 0.816 from Table 21 is acceptable, the residuals shown in the graph on the right in Figure 19 indicates non-consistent variance. The residuals are roughly parabolic indicating that a full model with interactions may be required. Neither the transformation nor the full model sufficiently improved the residual versus predicted plot. In fact, the same problem occurred with the dwell times. The tactic we employed to improve the models predictive capability involved separating the data into two sections based on factor levels. While the particular factor could be

systematically investigated, a sensible start would be the altitude because of the relationship of light dissipation and the square of the distance.

Factor Effects: Total Targets Destroyed at Low Altitude

The JMP stepwise regression function with probabilities to leave and enter the model were both set to 0.10 and the direction set to mixed produced an enhanced model. The residual versus predicted plot shown in Figure 20 indicate the model has constant variance. The very high R-Squared value, Table 22, confirms that the model fits the data well and clearly is an improvement over the previous attempt. The coefficients used for the model are shown in Table 23.

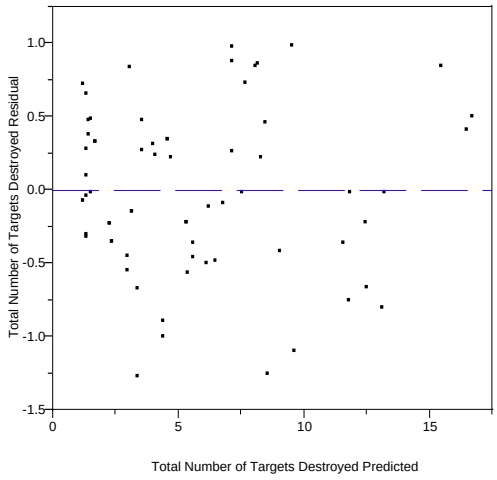

Figure 20 – Low Altitude Target Destroyed Residuals

Table 22 – GOF: Low Altitude Targets Destroyed

RSquare	0.981829
RSquare Adj	0.973754
Root Mean Square Error	0.674901
Mean of Response	5.777273
Observations (or Sum Wgts)	66

Table 23 – Parameter Estimates for Low Altitude Targets Destroyed

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	4.1684606	2.109548	1.98	0.0543
Power Level	0.0000711	0.000025	2.79	0.0077
Vulnerability Level	-0.000039	0.000034	-1.17	0.2478
TGTPRI3	17.384491	1.338487	12.99	<.0001
TGTPRI1	22.837269	6.103699	3.74	0.0005
Weapon Velocity	-0.014783	0.010249	-1.44	0.1561
Power Level*Vulnerability Level	-6.26e-10	4.17e-10	-1.50	0.1403
Power Level*TGTPRI3	-0.000033	0.000015	-2.17	0.0356
Vulnerability Level*TGTPRI3	-0.000083	0.00002	-4.17	0.0001
Power Level*Vulnerability Level*TGTPRI3	6.111e-10	2.46e-10	2.48	0.0170
Power Level*TGTPRI1	-0.000089	0.000067	-1.32	0.1944
Vulnerability Level*TGTPRI1	-0.000378	0.000136	-2.78	0.0079
Power Level*Vulnerability Level*TGTPRI1	3.0962e-9	1.445e-9	2.14	0.0375
Power Level*Weapon Velocity	-1.012e-7	1.186e-7	-0.85	0.3982
Vulnerability Level*Weapon Velocity	1.9358e-7	1.564e-7	1.24	0.2223
Power Level*Vulnerability Level*Weapon Velocity	4.861e-13	1.89e-12	0.26	0.7978
TGTPRI3*Weapon Velocity	-0.031007	0.00308	-10.07	<.0001
TGTPRI1*Weapon Velocity	-0.097951	0.032299	-3.03	0.0040
Power Level*TGTPRI1*Weapon Velocity	6.8709e-7	3.461e-7	1.99	0.0532
Vulnerability Level*TGTPRI1*Weapon Velocity	0.0000019	6.931e-7	2.69	0.0101
Power Level*Vulnerability Level*TGTPRI1*Weapon Velocity	-1.72e-11	7.24e-12	-2.37	0.0219

Now that an accurate model has been developed, the factor effects can be presented. Figure 21 shows the factor effects related to the low altitude setting. The far left vertical axis shows the number of targets killed and each graph displays the effect at the high and low factor levels assuming all other factors are held constant. The target priorities were broken up into individual sections. The horizontal axis has a zero and one representing when the particular priority setting was used or not used respectively.

The individual graphs represented in Figure 21 show the effect of each factor, with all other factors held constant, on the total number of targets destroyed. The trends suggest that in general increasing the power level increases the number of targets destroyed, raising the vulnerability level decreases the number of targets destroyed, and increasing the weapon velocity decreases the number of targets destroyed. Regarding the target selection priorities, the presence of the shortest dwell time and highest elevation

angle priorities show significant advantages over the longest dwell time and lowest elevation angle selection priorities. These results are not counterintuitive. In fact, the results being as expected adds to the validity of the modeling process.

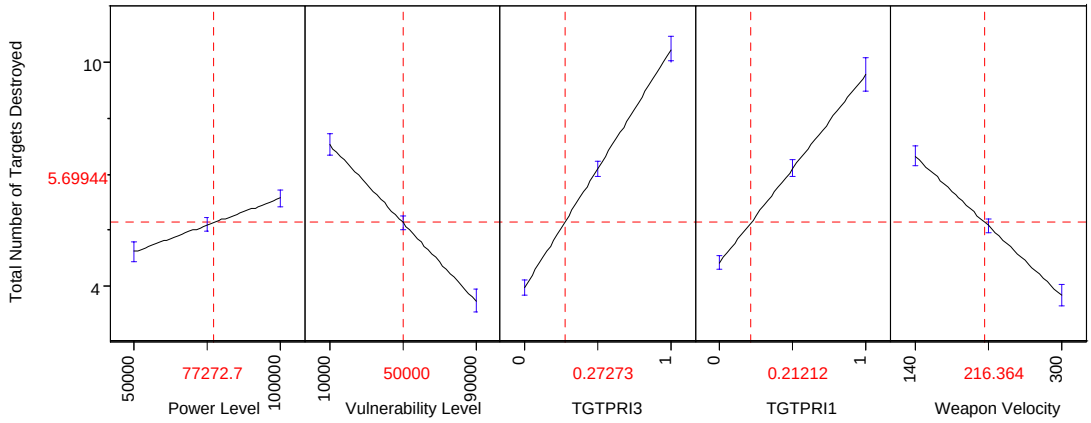

Figure 21 – Factor Effects: Low Altitude Targets Destroyed

The same process could be used to form a model with unique factors with every altitude. This method would result in development of highly accurate models. More accurate models with specific factors create unique parameters relative to altitude and output types. The same methods used to increase accuracy sacrifice the ability to use a general set of predictors. The effort to minimize changing the number of predictors was accomplished by using the same predictors established for the low level altitude with the response of targets destroyed to develop regression models for the remaining outputs. Potentially, the coefficients could be regressed against the altitude, including the transformations as an additional factor to predict trends in the change of the coefficients as the altitudes change.

Factor Effects: Total Targets Destroyed at Medium Altitude

To begin the investigation, the very same factors were included in the regression model. The model had the residual versus predicted plot shown in Figure 20. The plot does not represent constant variance, but a transformation was used to reshape the response.

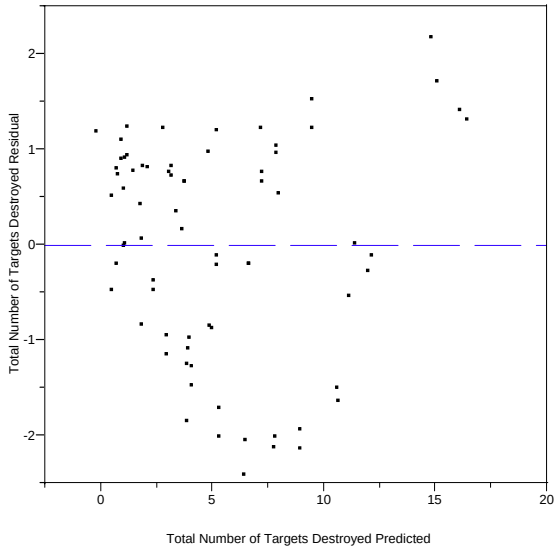

Figure 22 – Medium Altitude Target Destroyed Residuals

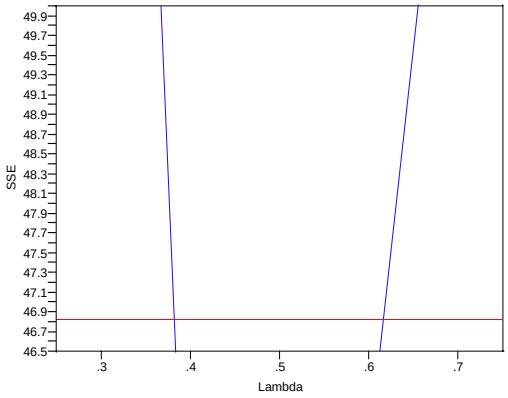

Figure 23 – Medium Altitude Targets Destroyed Transformation

The Box-Cox Y Transformation shows that λ values between 0.4 and 0.6 are acceptable. Equation (5) shows the transformation used on the number of targets destroyed. The Y' represents the new value the lowercase y represents the old value and the mean in the denominator refers to the geometric mean.

(5) $$Y' = \frac{(y^{\lambda} - 1)}{(\lambda \cdot \bar{y}^{\lambda - 1})}$$

where $\bar{y} = 3.501214488$, & $\lambda = .4$

The inverse transformation should be used to return responses predicted from parameter estimates and factor effects. The inverse transform is shown in Equation (6).

(6) $$y = \sqrt[\lambda]{Y' \cdot (\lambda \cdot \bar{y}^{\lambda - 1}) + 1}$$

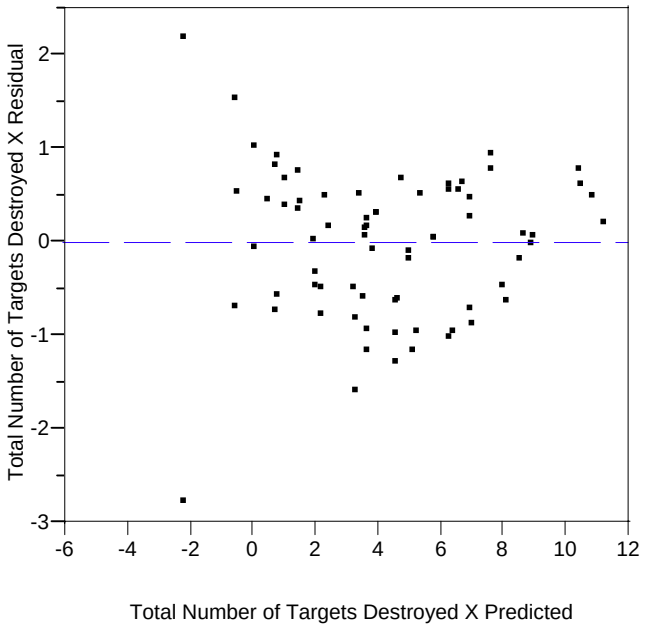

Figure 24 – Medium Altitude Target Destroyed Residuals Transformed

The transformation improved the residuals as shown in Figure 24 to a more normal error representation. Table 24 shows the R-Square value increased due to the transformation. The parameter estimates for the number of targets destroyed can be seen in the Table 25.

Table 24 – GOF: Medium Altitude Targets Destroyed Transformed

RSquare	0.941637
RSquare Adj	0.918749
Root Mean Square Error	0.922751
Mean of Response	4.203079
Observations (or Sum Wgts)	72

Table 25 – Parameter Estimates for Medium Altitude Targets Destroyed

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	6.3839714	2.619387	2.44	0.0183
Power Level	0.0000536	0.000033	1.63	0.1096
Vulnerability Level	-0.000016	0.000044	-0.38	0.7067
TGTPRI3	5.7843599	1.782551	3.24	0.0021
TGTPRI1	8.2606075	5.13669	1.61	0.1140
Weapon Velocity	-0.006895	0.011199	-0.62	0.5408
Power Level*Vulnerability Level	-8.43e-10	5.51e-10	-1.53	0.1323
Power Level*TGTPRI3	-0.000013	0.000019	-0.68	0.5013
Vulnerability Level*TGTPRI3	-0.000035	0.000026	-1.34	0.1868
Power Level*Vulnerability Level*TGTPRI3	2.989e-10	3.26e-10	0.92	0.3639
Power Level*TGTPRI1	-0.000049	0.000065	-0.76	0.4506
Vulnerability Level*TGTPRI1	-0.000102	0.000086	-1.19	0.2415
Power Level*Vulnerability Level*TGTPRI1	1.2311e-9	1.086e-9	1.13	0.2623
Power Level*Weapon Velocity	-1.747e-7	1.406e-7	-1.24	0.2197
Vulnerability Level*Weapon Velocity	-2.714e-7	1.861e-7	-1.46	0.1510
Power Level*Vulnerability Level*Weapon Velocity	4.443e-12	2.35e-12	1.89	0.0649
TGTPRI3*Weapon Velocity	-0.005631	0.004078	-1.38	0.1733
TGTPRI1*Weapon Velocity	-0.018244	0.022274	-0.82	0.4166
Power Level*TGTPRI1*Weapon Velocity	1.7299e-7	2.812e-7	0.62	0.5412
Vulnerability Level*TGTPRI1*Weapon Velocity	3.5118e-7	3.723e-7	0.94	0.3500
Power Level*Vulnerability Level*TGTPRI1*Weapon Velocity	-4.52e-12	4.71e-12	-0.96	0.3418

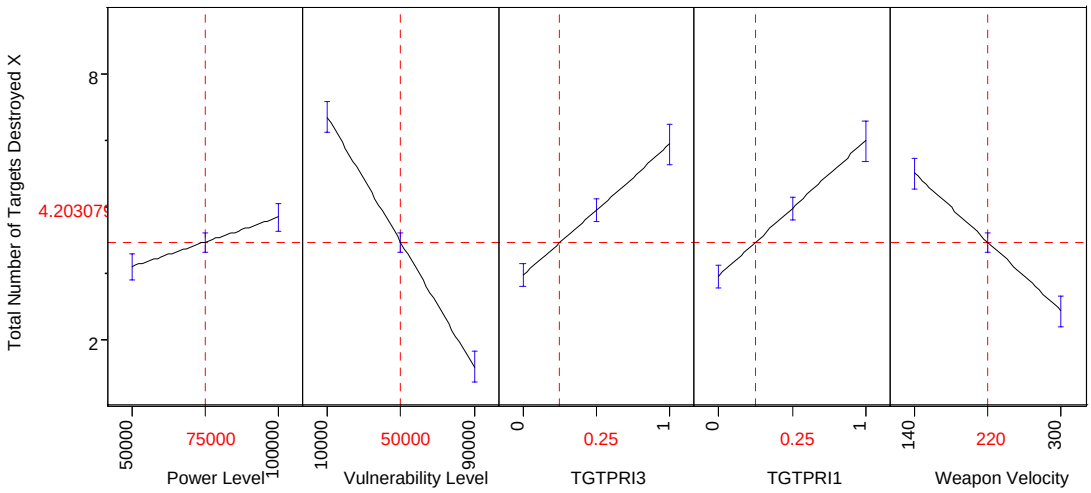

Figure 25 – Factor Effects Medium Altitude

The factors effects show the same general trends as mentioned earlier. The only difference is the transformation on the responses. Because of the transformation, the vertical axis must be untransformed to have any meaning. Using Equation (6), the values of 2, 4.20, and 8 on the vertical axis represent 2.23, 4.3, and 9.97. Also because the space on the graph is transformed a single tic mark on the vertical axis does not represent a single tic mark in the original space. In fact, the tic marks seem to represent a smaller and smaller range of values in the regular space as the number of total of targets destroyed in the transformed space decreases.

Factor Effects: Average Dwell Time Low Altitude

The residuals versus predicted plot for the low altitude average dwell times shown on the left in Figure 26 show an increasing variance as the predicted values increase. The Box-Cox Y Transformation suggested a range of values for lambda. Among those values the -0.4 was selected and the geometric mean calculation was 11.24319642.

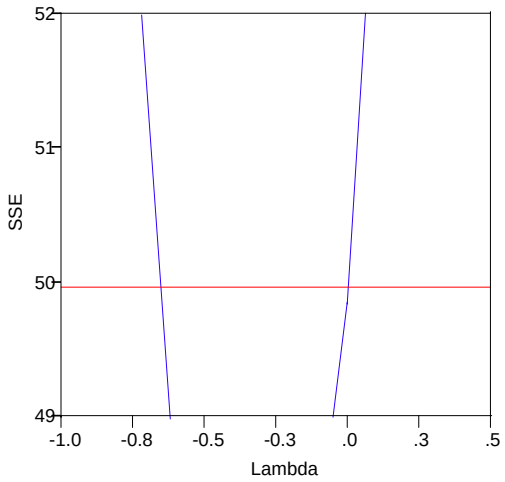

Figure 26 – Avg Dwell Time Low Altitude

The residuals versus predicted plot after the transformation shown in Figure 27 represent a model with constant variance.

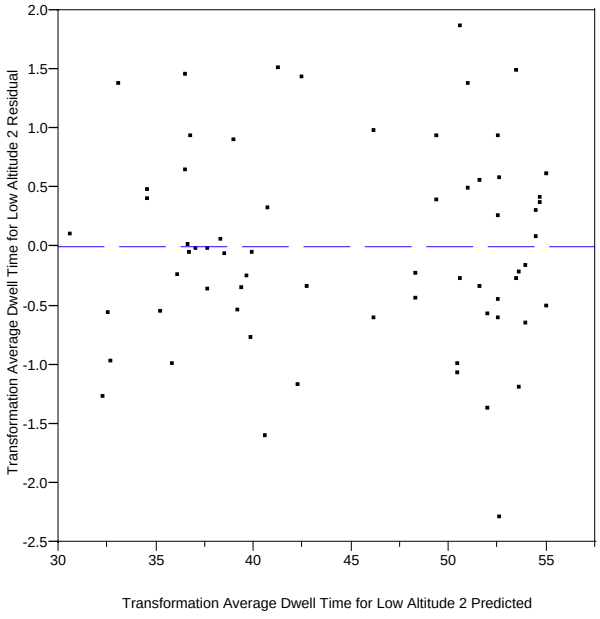

Figure 27 – Low Altitude Avg Dwell Time Transformation

Table 26 – GOF: Low Altitude Avg Dwell Time

RSquare	0.988544
RSquare Adj	0.983453
Root Mean Square Error	1.009683
Mean of Response	44.84001
Observations (or Sum Wgts)	66

Table 26 indicates a very high R-Squared values and the parameters that generated the high R-Squared value can be send in Table 27.

Table 27 – Parameter Estimates Low Altitude Avg Dwell Time

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	62.406991	3.155979	19.77	<.0001
Power Level	-0.000086	0.000038	-2.26	0.0290
Vulnerability Level	-0.000041	0.00005	-0.81	0.4226
TGTPRI3	-21.45037	2.002437	-10.71	<.0001
TGTPRI1	-31.57366	9.131407	-3.46	0.0012
Weapon Velocity	-0.033709	0.015334	-2.20	0.0331
Power Level*Vulnerability Level	6.952e-10	6.24e-10	1.11	0.2714
Power Level*TGTPRI3	0.0000077	0.000022	0.34	0.7348
Vulnerability Level*TGTPRI3	0.0000864	0.00003	2.91	0.0056
Power Level*Vulnerability Level*TGTPRI3	-5.44e-10	3.69e-10	-1.48	0.1468
Power Level*TGTPRI1	0.000152	0.000101	1.50	0.1393
Vulnerability Level*TGTPRI1	0.0003284	0.000203	1.61	0.1136
Power Level*Vulnerability Level*TGTPRI1	-2.988e-9	2.161e-9	-1.38	0.1736
Power Level*Weapon Velocity	5.5199e-8	1.774e-7	0.31	0.7571
Vulnerability Level*Weapon Velocity	1.011e-7	2.34e-7	0.43	0.6678
Power Level*Vulnerability Level*Weapon Velocity	7.033e-13	2.82e-12	0.25	0.8043
TGTPRI3*Weapon Velocity	0.0215868	0.004609	4.68	<.0001
TGTPRI1*Weapon Velocity	0.0901053	0.048321	1.86	0.0688
Power Level*TGTPRI1*Weapon Velocity	-8.821e-7	5.178e-7	-1.70	0.0953
Vulnerability Level*TGTPRI1*Weapon Velocity	-0.000002	0.000001	-1.60	0.1167
Power Level*Vulnerability Level*TGTPRI1*Weapon Velocity	1.624e-11	1.08e-11	1.50	0.1411

The factor effects displayed in Figure 28 indicate that increasing the power level decreases the average dwell time, the increasing vulnerability level increases the average dwell time, and the increasing weapon velocity decreases the average dwell time. The effect of target priorities indicate that the presence of the shortest dwell time and highest elevation angle decrease the average dwell time. Of those effects the effect of the weapon velocity is not intuitive. The reason for the decrease may be related to the first

and last engagement times. When the ATL moved faster the first target was destroyed quicker than on slower approaches. Additionally, the values on the vertical must be assessed using the inverse transformation, Equation (6) with the new lambda and geometric mean.

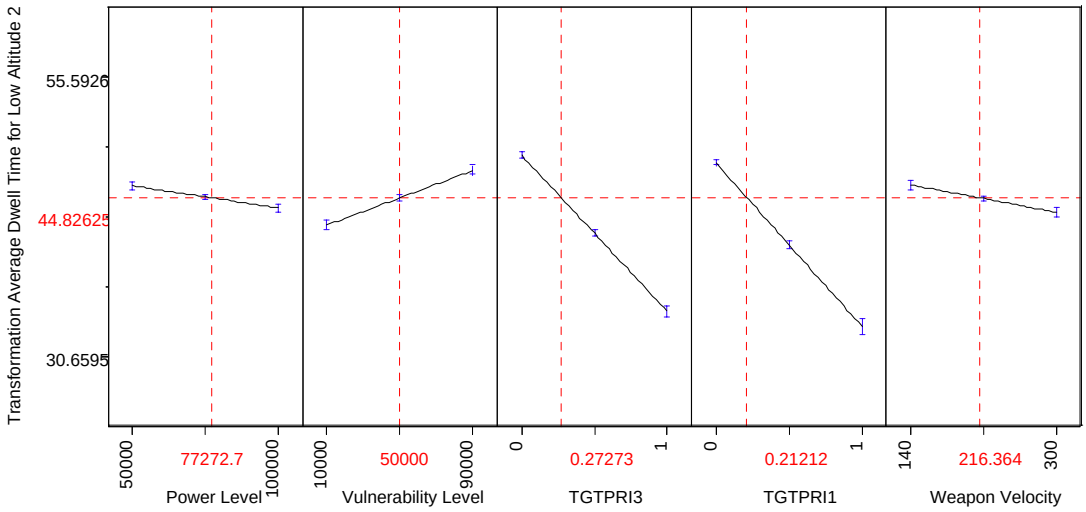

Figure 28 – Factor Effects Low Altitude Avg Dwell Times

Figure 28 shows the factor effect on the average dwell time. Again, because the factor effects are in transformed space the values on the axis also represent transformed space. For comparison, 30.65, 44.82, and 55.59 in the transformed space return to 29.47.95, and 95.96 in the original space. Additionally, the tic marks in the transformed space 36.85, 43.12, and 49.36 in the transformed space 41.88, 56.98, and 74.95 in the original space. Although the exact effect is difficult to interpret, the general trend is easily interpreted. The increasing power level and weapon velocity decrease the average dwell time. Increasing the vulnerability level increases the average dwell time. The target priority is a bit more difficult to interpret. The horizontal axis shows a zero and a one representing the presence or absence for each of the two priorities. The factor effects

measure the effect of a factor on the output given that all other variables in the model held constant. For example, the shortest dwell time effect measures the effect of the presence of the priority versus the absence of the priority with all other variables in the model held constant. Because all other variables in the model are held constant, the fact that the highest elevation angle is at zero does not change. Therefore, either of the longest dwell time or the lowest elevation angle priorities are being used for comparison. The fact that the confidence region, indicated by the small line at the end of the graph line above zero, is not very wide implies that the difference between the priorities not included in the model is not significant. Additionally that can be concluded from observing that neither of the two priorities were accepted into the model. The lines on the two priorities included in the model indicate that the presence of the shortest dwell time and highest elevation angle decrease the average dwell time.

Factor Effects: Average Dwell Time Medium Altitude

The residuals versus predicted plot shown in Figure 29 seem to indicate relatively constant variance. The Box-Cox Y Transformation also suggests the same conclusion because the minimization range for lambda is close to one.

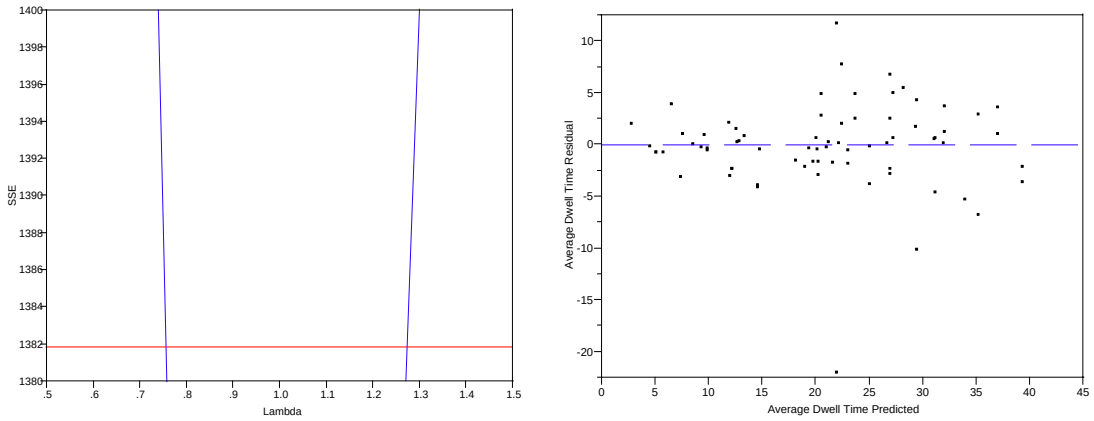

Figure 29 – Average Dwell Time Medium Altitude Residuals

Table 28 shows a high R-Squared value, but not nearly as high as the previous analysis sections. The parameter estimates for the average dwell time response specific to the medium altitude factor level are shown in Table 29.

Table 28 – GOF: Medium Altitude Avg Dwell Time

RSquare	0.831518
RSquare Adj	0.765446
Root Mean Square Error	5.012905
Mean of Response	20.84668
Observations (or Sum Wgts)	72

Table 29 – Parameter Estimates Medium Altitude Avg Dwell Times

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	40.552806	14.22999	2.85	0.0063
Power Level	-0.000253	0.000179	-1.42	0.1624
Vulnerability Level	0.0001492	0.000237	0.63	0.5313
TGTPRI3	-42.36378	9.683825	-4.37	<.0001
TGTPRI1	-26.15574	27.9054	-0.94	0.3530
Weapon Velocity	-0.004579	0.06084	-0.08	0.9403
Power Level*Vulnerability Level	1.9811e-9	2.994e-9	0.66	0.5112
Power Level*TGTPRI3	0.0002325	0.000106	2.20	0.0326
Vulnerability Level*TGTPRI3	0.0005149	0.00014	3.67	0.0006
Power Level*Vulnerability Level*TGTPRI3	-5.962e-9	1.772e-9	-3.36	0.0015
Power Level*TGTPRI1	0.0001637	0.000352	0.46	0.6442
Vulnerability Level*TGTPRI1	-0.000016	0.000466	-0.04	0.9720
Power Level*Vulnerability Level*TGTPRI1	-1.937e-9	5.9e-9	-0.33	0.7441
Power Level*Weapon Velocity	-2.234e-7	7.639e-7	-0.29	0.7711
Vulnerability Level*Weapon Velocity	-0.000001	0.000001	-1.46	0.1497
Power Level*Vulnerability Level*Weapon Velocity	1.209e-11	1.28e-11	0.95	0.3489
TGTPRI3*Weapon Velocity	0.0582755	0.022154	2.63	0.0112
TGTPRI1*Weapon Velocity	-0.02146	0.121006	-0.18	0.8599
Power Level*TGTPRI1*Weapon Velocity	3.8197e-7	0.000002	0.25	0.8036
Vulnerability Level*TGTPRI1*Weapon Velocity	0.0000024	0.000002	1.17	0.2460
Power Level*Vulnerability Level*TGTPRI1*Weapon Velocity	-1.87e-11	2.56e-11	-0.73	0.4692

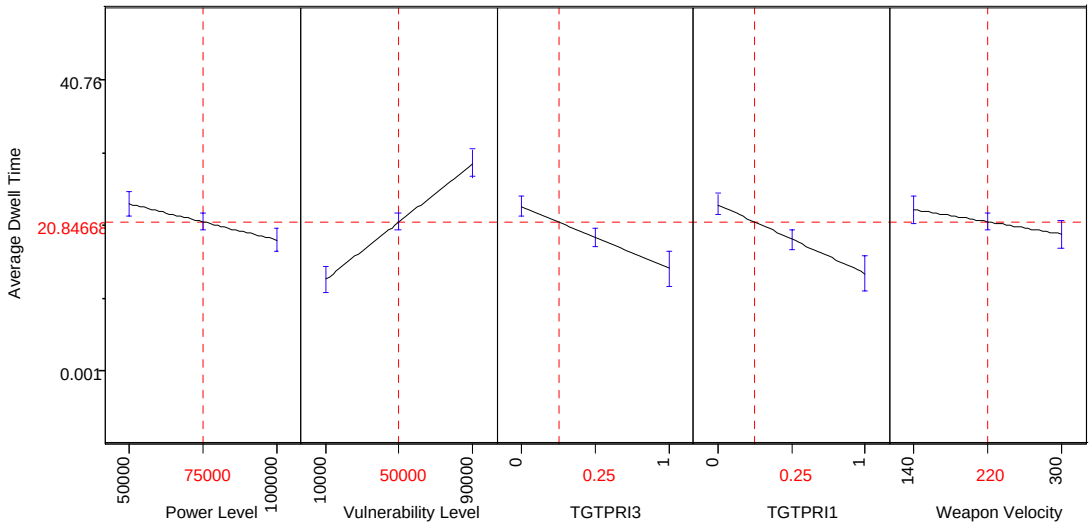

Figure 30 – Factor Effects Medium Altitude Avg Dwell Time

The trends of the factor effects are not different than the low altitude factor effects for the same response. The vertical axis values do not need to use the inverse transformation function which makes interpretation of the graphs easier.

Targets Destroyed Output

The results from the mission level simulation can provide valuable information that may aggregated to a higher level model. A summary histogram of the number of targets destroyed is shown in **Figure 31**. The histogram shows both the number of targets destroyed at the low altitude and the histogram on the right shows the number of targets destroyed at the medium altitude level. The number of targets destroyed at the low altitude and the medium altitude are both approximately 400.

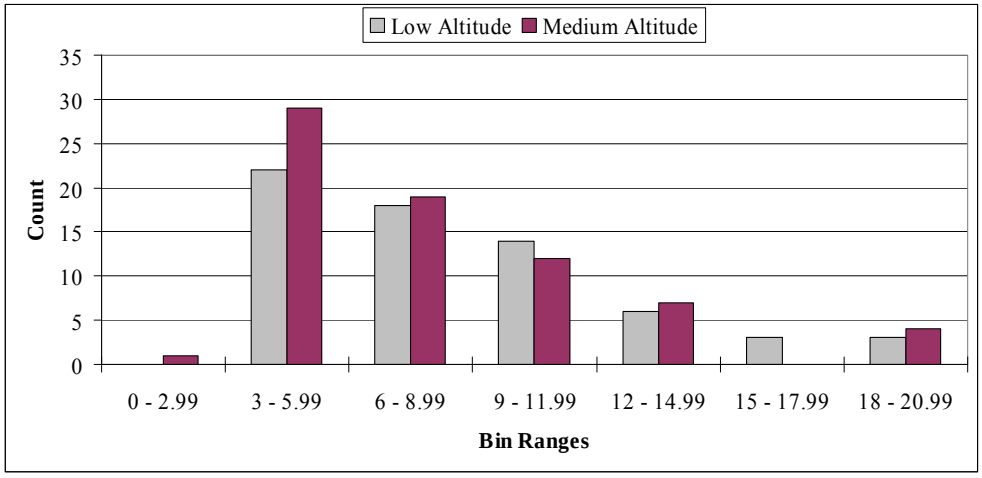

Figure 31 – Targets Destroyed Distribution

The histogram can be used to develop a cumulative distribution function (CDF). The inverse of the CDF, referred to as the CCDF and shown in Table 2, shows the probability a particular number of targets would be destroyed.

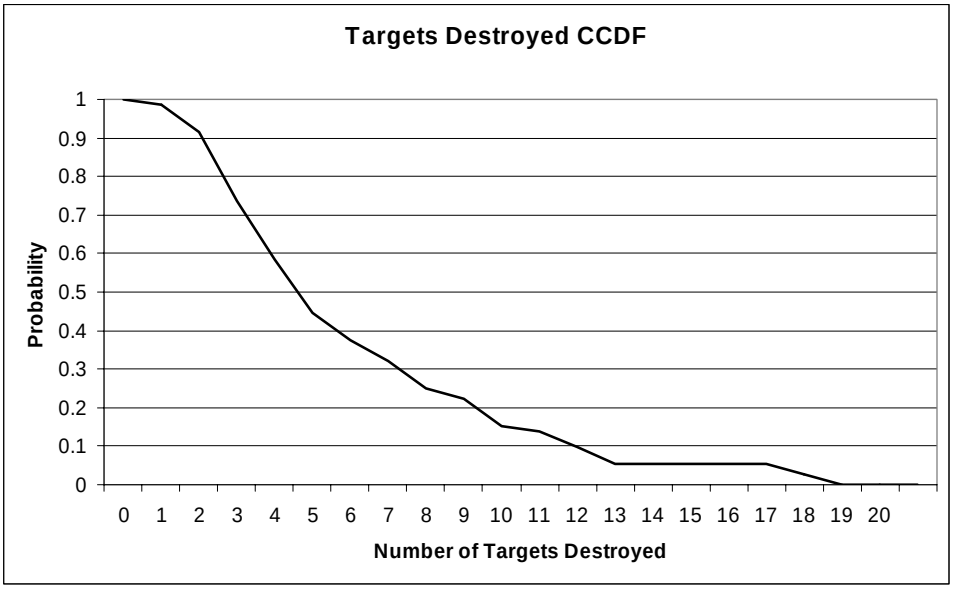

Figure 32 – Targets Destroyed CCDF

Summary

The analysis section began by assessing the outputs from HELEEOS. The platform altitude, power level, and slant range were the factors causing the greatest effects in irradiance. The ATL designed for experimentation in EADSIM varied the parameters established in the EADSIM runs. The results of the EADSIM executions were checked to ensure validity. Finally, the simulation runs were analyzed based on factor effects to number of targets killed and average engagement time.

V. Discussion, Conclusions, and Recommendations

Discussion

The purpose of this study was to investigate the military worth of the ATL through simulation aggregation. The study focused on exploring the difficulties of the aggregation, developing a methodology to aggregate the information, and examining the types of outputs and speculations that could be made from the results.

An investigation into the modeling difficulties of the laser revealed the general modeling differences compared to modeling conventional weapons, insight into two particular laser capable simulation models, and the problems associated with transferring information from a higher fidelity model to a lower fidelity model. Laser weapons require modeling energy losses due to propagation and absorption. The effect of the laser, resulting from the outcomes of the propagation and absorption, is dependent on the amount of energy deposited on a particular component. HEELEOS, an engagement level simulation, models the laser from leaving the transmitting device until the beam reaches the intended target at a specified distance. Maximum irradiance is the output of the HEELEOS simulation. Although EADSIM has some capability to model the effects of a laser, the code also allows for tabular input indicating the irradiance level based on user specified factors. The aggregation from an engagement level model to a mission level model allowed the detailed model to simulate part of the engagement for which it was specifically designed.

The methodology used to achieve the aggregation and execute simulations at the mission level became code dependent. Both HELEEOS and EADSIM are only equipped to perform a single execution or replications of a particular scenario. To explore the

effect of varying several factors, whether quantitative or qualitative, several scripts needed to be developed. The series of scripts generated the design of experiments, explored the factors in HELEEOS, developed the propagation table, executed all of the design points in EADSIM, and performed post-processing actions.

The specific scenario involved a single pass of the ATL over a target area consisting of twenty vehicles. The power of the ATL was varied as well as the platform altitude, platform velocity, and target prioritization. The vehicle vulnerabilities were also varied. Modeling the vehicle proved challenging because EADSIM will not allow ground targets to be considered as a threat. Some modifications allowed a stationary cruise missile placed on the ground to represent a vehicle. The vulnerability modeling was a key choice enabling the replacement. Selecting the intensity based modeling enable all of the information about target lethality to be determined by tables associated with the attacking platform. The vulnerabilities were calculated at several generic levels to determine the importance of the factor in exploring the military worth of the ATL.

The results give insight into the importance of individual factors in the particular scenario. Note that the results are not a prediction of exact values because the analysis was performed against notional data. The constraining sensitivity of the information prevented actual data from being included in the analysis. However, information about general laser characteristics was obtained and utilized as a basis for analysis, which implies that data trends within the limits of the scenario may have value in predicting trends. The results covered two general categories: HELEEOS exploration and EADSIM factor significance assessment.

Conclusions

The HELEEOS exploration showed that the velocity factors, though important to thermal blooming, did not have a significant effect in the developed scenario. The exploration of HELEEOS became part of the justification for factor choices. Additionally, the development of code to explore factors in HELEEOS was modified to develop the propagation tables. From the HELEEOS factor exploration the platform altitude, power level, and slant range changed the irradiance. The target and weapon velocities had no effect on the irradiance. The design of experiments, however, retained the weapon velocity due to the effect of the time spent in target area. The design of experiment included five factors, four quantitative and one qualitative: power level, vulnerability level, target selection priority, weapon altitude, and weapon velocity.

After executing the simulation, a post-processing script extracted the output from the results of each simulation and combined the output into a concise summary, the batch run verification identified the criteria for simulation completeness and assessed each simulation. The results of the analysis showed that some simulations should be excluded from the analysis section to prevent excessive error. Of the original proposed 216 design points, 138 design points were retained in the analysis section.

The results from the regression did not present unexpected results. However, because the results produced are expected the modeling process gains some validity. The factor effects showed that increasing the power level had an increasing effect on the number of targets destroyed, whereas, increasing the vulnerability level and the weapon velocity had decreasing effects on the number of targets destroyed. Of the targeting priorities, the shortest dwell time and highest elevation angle increased the number of

targets destroyed. Concerning the average dwell time, increasing the power level and weapon velocity decreased the average dwell time. Increasing the vulnerability level increased the average dwell time. The shortest dwell time and highest elevation angle selection priorities decreased the average dwell time.

Recommendations and Future Research

Because of the scope of the thesis and restrictions on time, some potentially valuable investigations could not be included. The recommendations briefly discuss these potentially valuable investigations, as well as their added benefit.

In this study, a laser propagation model improved over the previous use of a first order equation. The propagation is only one of the two general energy loss components. The second, absorption, should be modeled in greater detail to more accurately predict target vulnerability.

Design of experiments could greatly reduce the number of simulation executions. A basic combination of every possible factor combination was used because combining quantitative and qualitative variable at multiple levels becomes a very complicated design of experiments. Additionally, when reducing the amount of information gathered, the remaining information becomes more valuable and damaging when lost. The design of experiments only included a few of the originally suggested factors. Several factors were excluded and many more were not considered. Some potentially beneficial factors to also consider are as follows:

1. Target Position – The target setup was a random distribution of targets inside square area. While this was done to remove bias from target position as well as become the substitution for running replications. Realistically, targets will not be randomly distributed in a square area.

2. Attack Path – The attack path considered was nothing more than a change in direction. From the vulnerability table and the favorable results for the lowest velocity, it's conceivable that a favorable approach to the target includes a quick arrival to the position that minimizes the distance to all targets, a slow descent over the target area, followed by a quick egress.

3. Engage Distance – Because laser propagation is affected by distance, a minimum engage distance variable could reduce the engagement times resulting in greater chemical fuel efficiency if the laser is chemical based.

4. Jitter – The jitter affects the amount of energy being received by the target. The jitter is a realistic operational effect and should be included in any analysis used to predict real world operations.

5. Damage Thresholds – Any amount of energy distributed to the target was considered to effect the destruction of the target. However, realistically each material has an irradiance level that must be achieved before damage begins.

Other valuable changes would include complete automation of the entire process through a single script. Many important factors, even if not altered in an experiment, could be setup to vary by the script and left unchanged when unneeded. The script would then execute all the necessary EADSIM simulations and post-processing data summary.

Transitioning through the simulation hierarchy is one way to improve the simulation output at the lowest resolution pyramid levels. The significance of aggregation is derived from the type of decisions made at the lowest resolution levels. Many acquisition decisions are made based on low-resolution simulations. The resulting decisions may only rest on particular assumptions, addressing specific scenarios, instead of a more meaningful analysis of effects beginning with modeling the effects at the highest level of detail.

Appendix A: HELEEOS Comparison

```
function HELEEOS_Comparision;
%Declare the structure data as a global
global data
% DATA SETUP ********************************************

heleeosSetDefaults;
slantRng = [500 700 900 1100 1300 1500 1700 1900 2100 2300 2500 2700 2900 3100
3300 3500 3700 3900 4100 4300 4500 4700 4900 5100 5300 5500 5700 5900 6100 6300
6500 6700 6900 7100 7300 7500 7700 7900 8100 8300 8500 8700 8900 9100 9300 9500
9700 9900 10100 10300 10500 10700 10900 11100 11300 11500 11700 11900 12100
12300 12500 12700 12900 13100 13300 13500 13700 13900 14100 14300 14500 14700
14900 15100 15300];
platformAlt = [2000 4000 6000 8000];
data.In.platformAltitude = 2000;
data.In.targetAltitude = 10
data.In.wavefrontError = .000000263
data.In.laserPower = 50000;
data.In.windVelPerpen = 4; data.In.windVelParallel = 0;
data.In.groundWindVel = sqrt(data.In.windVelPerpen.^2+data.In.windVelParallel.^2);
data.In.platformVelParal = 77; %max speed of C-130 is 130 m/s
data.In.platformVelPerpe = 0;
data.In.targetVelParal = 205; %Set to Azar's
data.In.targetVelPerpe = 0;
data.In.sigmaJitter = 0
data.In.sigmaTotalJitter = 0
data.In.turbulanceMultiplier = .9

%  HELEEOS EXECUTION CYCLE ********************************
for j = 1:length(slantRng);
for i = 1:length(platformAlt);
   data.In.slantRange = slantRng(j);
   data.In.platformAltitude = platformAlt(i);
         heleeosCalc;
         FLUENCE(i,j) = data.Out.fluence;
   IrradainceBQMAX(i,j) = data.Out.irrDiffBQMAX;
   MAXALL(i,j) = data.Out.irrDiffTBTurbAtmosMAX;
   MAXnoTB(i,j) = data.Out.irrDiffTurbAtmosMAX;
end
end

MAXALL'
MAXnoTB'
return
```

Appendix B: HELEEOS Assumptions

- Chemical Oxygen Iodine Laser (COIL) device with an operating wavelength of 1.31525 μm
- Continuous Wave (CW) operation
- Focused beams, therefore spherical waves
- Coarse Scanning Mirrors (CSM) and Fast Scanning Mirrors (FSM) are available to correct both 'spot dancing' due to turbulence and shifts in beam centroid position due to thermal blooming.
- Uniform beam with 0.3 central obscuration
- Atmospheric absorption/extinction based on 1976 US Standard Atmosphere
- Range between the laser and target does not change appreciably during a single engagement
- The target is a flat plate oriented at some user-specified angle to the beam

(Bartell 2003)

Appendix C: EADSIM Laser Windows

The following figures show the specific changes available for modeling the laser in EADSIM .

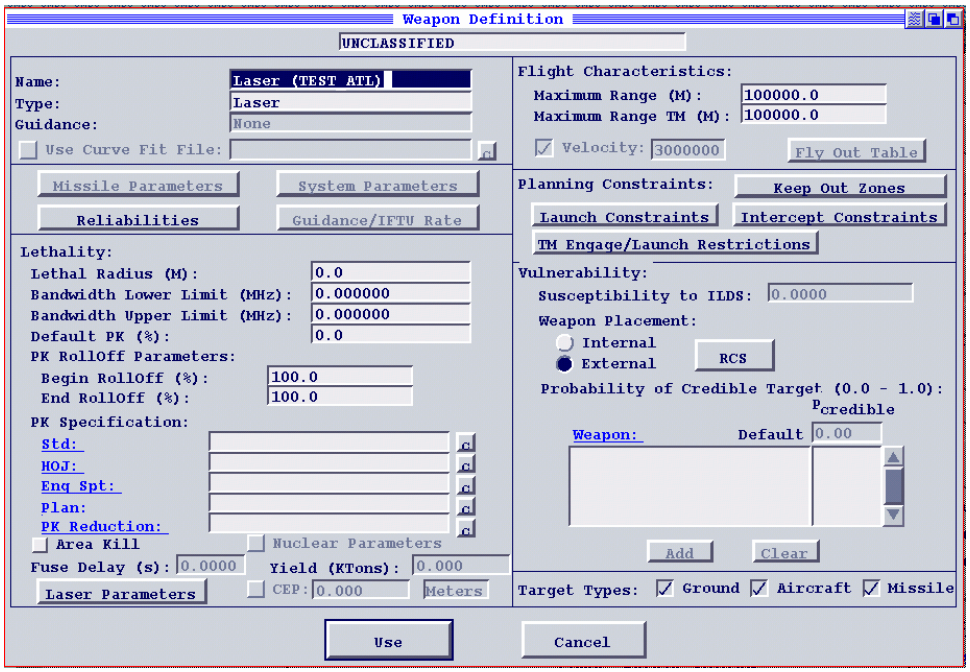

Figure 33 – Weapon Definition Window

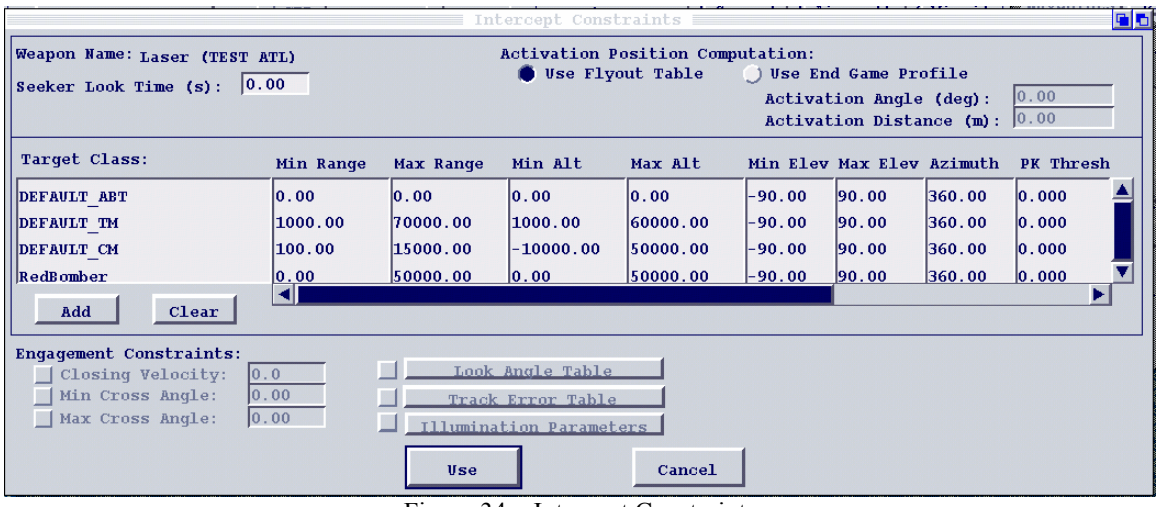

Figure 34 – Intercept Constraints

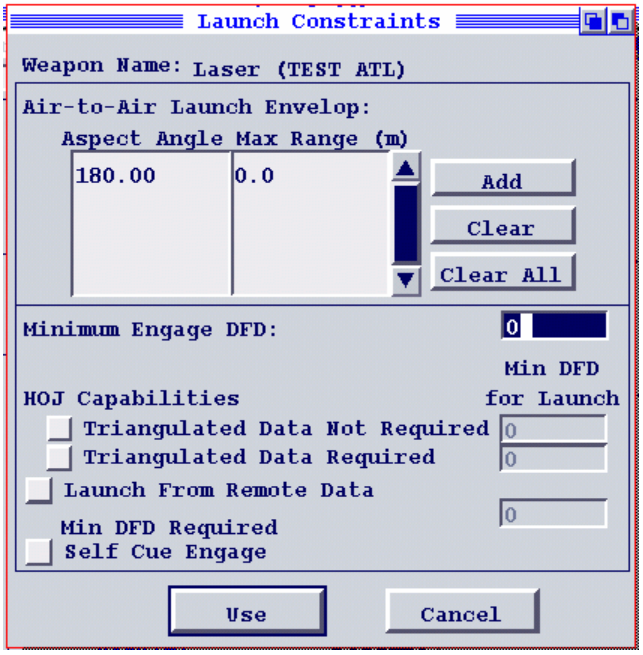

Figure 35 – Launch Constraints

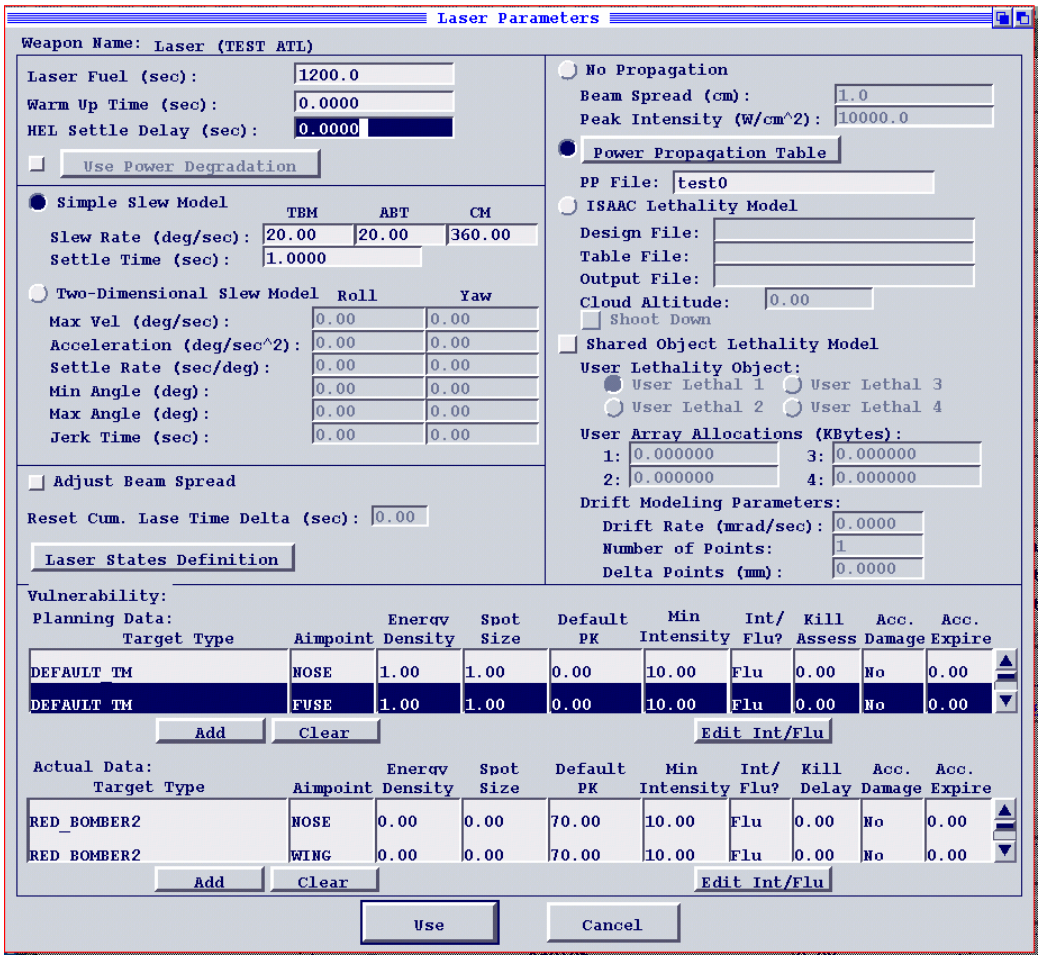

Figure 36 – Laser Parameters

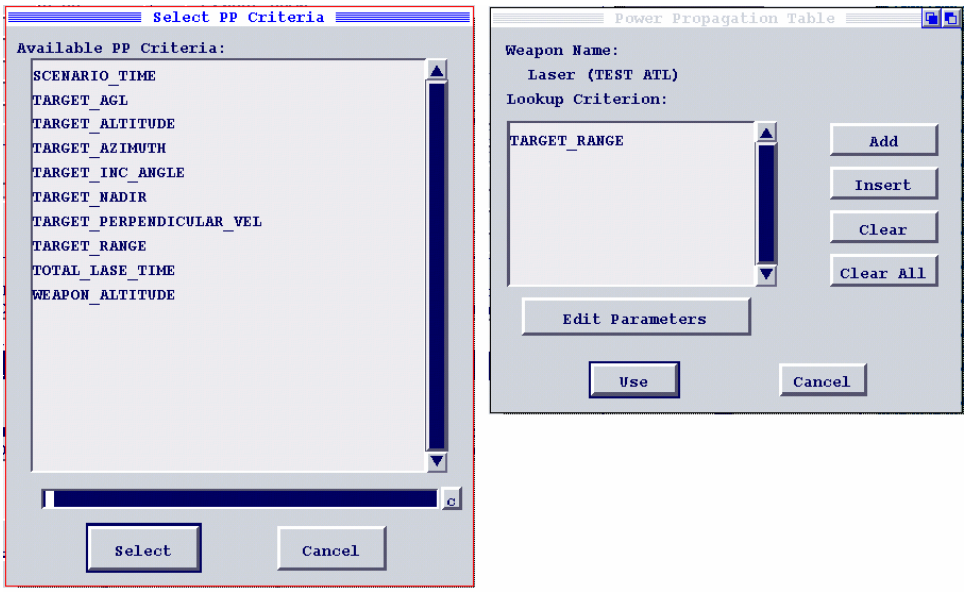

Figure 37 – Propagation Table Criteria

Appendix D: Target Distributions

Table 30 – Target Distributions 1-5

	Target	1	Target	2	Target	3	Target	4	Target	5
1	29.470	47.526	29.540	47.521	29.491	47.488	29.518	47.486	29.527	47.497
2	29.537	47.517	29.480	47.523	29.469	47.500	29.463	47.506	29.467	47.505
3	29.466	47.497	29.499	47.464	29.460	47.523	29.514	47.527	29.477	47.543
4	29.515	47.492	29.502	47.516	29.535	47.540	29.488	47.491	29.518	47.462
5	29.525	47.475	29.490	47.503	29.472	47.474	29.457	47.525	29.523	47.482
6	29.510	47.456	29.487	47.476	29.482	47.477	29.476	47.486	29.526	47.457
7	29.463	47.517	29.479	47.457	29.528	47.478	29.499	47.509	29.499	47.463
8	29.493	47.537	29.536	47.488	29.503	47.541	29.484	47.530	29.486	47.484
9	29.541	47.482	29.516	47.462	29.541	47.533	29.518	47.523	29.532	47.505
10	29.540	47.498	29.500	47.498	29.523	47.471	29.536	47.530	29.497	47.457

Table 31 – Target Distributions 6-10

	Target	6	Target	7	Target	8	Target	9	Target	10
1	29.470	47.473	29.482	47.488	29.472	47.542	29.507	47.492	29.460	47.484
2	29.499	47.541	29.536	47.488	29.520	47.501	29.523	47.529	29.514	47.471
3	29.516	47.457	29.538	47.522	29.457	47.501	29.521	47.466	29.503	47.496
4	29.465	47.537	29.520	47.495	29.482	47.493	29.490	47.477	29.484	47.461
5	29.535	47.497	29.500	47.527	29.474	47.539	29.481	47.534	29.493	47.462
6	29.508	47.482	29.500	47.517	29.540	47.471	29.510	47.492	29.533	47.483
7	29.504	47.516	29.493	47.488	29.518	47.520	29.482	47.497	29.470	47.519
8	29.485	47.509	29.503	47.522	29.481	47.524	29.463	47.478	29.464	47.497
9	29.477	47.462	29.463	47.519	29.520	47.536	29.497	47.484	29.508	47.461
10	29.526	47.472	29.464	47.471	29.510	47.518	29.495	47.521	29.459	47.477

Table 32 – Target Distributions 11-15

	Target	11	Target	12	Target	13	Target	14	Target	15
1	29.522	47.490	29.471	47.483	29.477	47.471	29.489	47.543	29.457	47.503
2	29.533	47.494	29.503	47.506	29.505	47.518	29.515	47.491	29.475	47.508
3	29.523	47.534	29.463	47.517	29.458	47.538	29.493	47.489	29.537	47.502
4	29.530	47.494	29.523	47.465	29.530	47.532	29.526	47.483	29.529	47.459
5	29.464	47.494	29.519	47.515	29.543	47.497	29.497	47.525	29.489	47.522
6	29.532	47.470	29.510	47.477	29.461	47.535	29.467	47.466	29.531	47.539
7	29.471	47.523	29.543	47.531	29.468	47.499	29.481	47.463	29.488	47.517
8	29.478	47.541	29.509	47.532	29.509	47.509	29.542	47.525	29.510	47.499
9	29.474	47.501	29.521	47.517	29.515	47.524	29.484	47.519	29.505	47.490
10	29.469	47.528	29.519	47.534	29.518	47.489	29.527	47.541	29.470	47.529

Table 33 – Target Distributions 16-21

	Target	16	Target	17	Target	18	Target	19	Target	20
1	29.499	47.495	29.545	47.519	29.468	47.545	29.520	47.481	29.493	47.466
2	29.483	47.510	29.528	47.539	29.475	47.470	29.469	47.482	29.494	47.519
3	29.528	47.516	29.503	47.492	29.474	47.499	29.470	47.473	29.527	47.537
4	29.472	47.540	29.498	47.504	29.504	47.488	29.470	47.514	29.531	47.479
5	29.522	47.476	29.540	47.484	29.459	47.491	29.484	47.496	29.517	47.463
6	29.531	47.488	29.487	47.502	29.472	47.544	29.479	47.471	29.505	47.505
7	29.504	47.458	29.468	47.504	29.515	47.475	29.542	47.508	29.490	47.539
8	29.534	47.513	29.516	47.461	29.525	47.534	29.526	47.485	29.460	47.464
9	29.524	47.534	29.461	47.502	29.461	47.511	29.491	47.472	29.516	47.497
10	29.473	47.495	29.468	47.530	29.491	47.461	29.539	47.515	29.521	47.521

Appendix E: Vulnerability Tables

Table 34 – Vulnerability Table High

	PK						
IRRIDIANCE	**0**	**50**	**60**	**70**	**80**	**90**	**100**
473.68	*190.00*	*190.00*	*209.00*	*228.00*	*247.00*	*266.00*	*285.00*
500.00	*180.00*	*180.00*	*198.00*	*216.00*	*234.00*	*252.00*	*270.00*
529.41	*170.00*	*170.00*	*187.00*	*204.00*	*221.00*	*238.00*	*255.00*
562.50	*160.00*	*160.00*	*176.00*	*192.00*	*208.00*	*224.00*	*240.00*
600.00	*150.00*	*150.00*	*165.00*	*180.00*	*195.00*	*210.00*	*225.00*
642.86	*140.00*	*140.00*	*154.00*	*168.00*	*182.00*	*196.00*	*210.00*
692.31	*130.00*	*130.00*	*143.00*	*156.00*	*169.00*	*182.00*	*195.00*
750.00	*120.00*	*120.00*	*132.00*	*144.00*	*156.00*	*168.00*	*180.00*
818.18	*110.00*	*110.00*	*121.00*	*132.00*	*143.00*	*154.00*	*165.00*
900.00	*100.00*	*100.00*	*110.00*	*120.00*	*130.00*	*140.00*	*150.00*
1000.00	*90.00*	*90.00*	*99.00*	*108.00*	*117.00*	*126.00*	*135.00*
1125.00	*80.00*	*80.00*	*88.00*	*96.00*	*104.00*	*112.00*	*120.00*
1285.71	*70.00*	*70.00*	*77.00*	*84.00*	*91.00*	*98.00*	*105.00*
1500.00	*60.00*	*60.00*	*66.00*	*72.00*	*78.00*	*84.00*	*90.00*
1800.00	*50.00*	*50.00*	*55.00*	*60.00*	*65.00*	*70.00*	*75.00*
2250.00	*40.00*	*40.00*	*44.00*	*48.00*	*52.00*	*56.00*	*60.00*
3000.00	*30.00*	*30.00*	*33.00*	*36.00*	*39.00*	*42.00*	*45.00*
4500.00	*20.00*	*20.00*	*22.00*	*24.00*	*26.00*	*28.00*	*30.00*
4615.38	*19.50*	*19.50*	*21.45*	*23.40*	*25.35*	*27.30*	*29.25*
4736.84	*19.00*	*19.00*	*20.90*	*22.80*	*24.70*	*26.60*	*28.50*
4864.86	*18.50*	*18.50*	*20.35*	*22.20*	*24.05*	*25.90*	*27.75*
5000.00	*18.00*	*18.00*	*19.80*	*21.60*	*23.40*	*25.20*	*27.00*
5142.86	*17.50*	*17.50*	*19.25*	*21.00*	*22.75*	*24.50*	*26.25*
5294.12	*17.00*	*17.00*	*18.70*	*20.40*	*22.10*	*23.80*	*25.50*
5454.55	*16.50*	*16.50*	*18.15*	*19.80*	*21.45*	*23.10*	*24.75*
5625.00	*16.00*	*16.00*	*17.60*	*19.20*	*20.80*	*22.40*	*24.00*
5806.45	*15.50*	*15.50*	*17.05*	*18.60*	*20.15*	*21.70*	*23.25*
6000.00	*15.00*	*15.00*	*16.50*	*18.00*	*19.50*	*21.00*	*22.50*
6206.90	*14.50*	*14.50*	*15.95*	*17.40*	*18.85*	*20.30*	*21.75*
6428.57	*14.00*	*14.00*	*15.40*	*16.80*	*18.20*	*19.60*	*21.00*
6666.67	*13.50*	*13.50*	*14.85*	*16.20*	*17.55*	*18.90*	*20.25*
6923.08	*13.00*	*13.00*	*14.30*	*15.60*	*16.90*	*18.20*	*19.50*
7200.00	*12.50*	*12.50*	*13.75*	*15.00*	*16.25*	*17.50*	*18.75*
7500.00	*12.00*	*12.00*	*13.20*	*14.40*	*15.60*	*16.80*	*18.00*
7826.09	*11.50*	*11.50*	*12.65*	*13.80*	*14.95*	*16.10*	*17.25*
8181.82	*11.00*	*11.00*	*12.10*	*13.20*	*14.30*	*15.40*	*16.50*
8571.43	*10.50*	*10.50*	*11.55*	*12.60*	*13.65*	*14.70*	*15.75*
9000.00	*10.00*	*10.00*	*11.00*	*12.00*	*13.00*	*14.00*	*15.00*

9473.68	*9.50*	*9.50*	*10.45*	*11.40*	*12.35*	*13.30*	*14.25*
10000.00	*9.00*	*9.00*	*9.90*	*10.80*	*11.70*	*12.60*	*13.50*
10588.24	*8.50*	*8.50*	*9.35*	*10.20*	*11.05*	*11.90*	*12.75*
11250.00	*8.00*	*8.00*	*8.80*	*9.60*	*10.40*	*11.20*	*12.00*
12000.00	*7.50*	*7.50*	*8.25*	*9.00*	*9.75*	*10.50*	*11.25*
12857.14	*7.00*	*7.00*	*7.70*	*8.40*	*9.10*	*9.80*	*10.50*
13846.15	*6.50*	*6.50*	*7.15*	*7.80*	*8.45*	*9.10*	*9.75*
15000.00	*6.00*	*6.00*	*6.60*	*7.20*	*7.80*	*8.40*	*9.00*
16363.64	*5.50*	*5.50*	*6.05*	*6.60*	*7.15*	*7.70*	*8.25*
18000.00	*5.00*	*5.00*	*5.50*	*6.00*	*6.50*	*7.00*	*7.50*
20000.00	*4.50*	*4.50*	*4.95*	*5.40*	*5.85*	*6.30*	*6.75*
22500.00	*4.00*	*4.00*	*4.40*	*4.80*	*5.20*	*5.60*	*6.00*
25714.29	*3.50*	*3.50*	*3.85*	*4.20*	*4.55*	*4.90*	*5.25*
30000.00	*3.00*	*3.00*	*3.30*	*3.60*	*3.90*	*4.20*	*4.50*
36000.00	*2.50*	*2.50*	*2.75*	*3.00*	*3.25*	*3.50*	*3.75*
45000.00	*2.00*	*2.00*	*2.20*	*2.40*	*2.60*	*2.80*	*3.00*
60000.00	*1.50*	*1.50*	*1.65*	*1.80*	*1.95*	*2.10*	*2.25*
90000.00	*1.00*	*1.00*	*1.10*	*1.20*	*1.30*	*1.40*	*1.50*
94736.84	*0.95*	*0.95*	*1.05*	*1.14*	*1.24*	*1.33*	*1.43*
100000.00	*0.90*	*0.90*	*0.99*	*1.08*	*1.17*	*1.26*	*1.35*
105882.35	*0.85*	*0.85*	*0.94*	*1.02*	*1.11*	*1.19*	*1.28*
112500.00	*0.80*	*0.80*	*0.88*	*0.96*	*1.04*	*1.12*	*1.20*
120000.00	*0.75*	*0.75*	*0.83*	*0.90*	*0.98*	*1.05*	*1.13*
128571.43	*0.70*	*0.70*	*0.77*	*0.84*	*0.91*	*0.98*	*1.05*
138461.54	*0.65*	*0.65*	*0.72*	*0.78*	*0.85*	*0.91*	*0.98*
150000.00	*0.60*	*0.60*	*0.66*	*0.72*	*0.78*	*0.84*	*0.90*
163636.36	*0.55*	*0.55*	*0.61*	*0.66*	*0.72*	*0.77*	*0.83*
180000.00	*0.50*	*0.50*	*0.55*	*0.60*	*0.65*	*0.70*	*0.75*
200000.00	*0.45*	*0.45*	*0.50*	*0.54*	*0.59*	*0.63*	*0.68*
225000.00	*0.40*	*0.40*	*0.44*	*0.48*	*0.52*	*0.56*	*0.60*
257142.86	*0.35*	*0.35*	*0.39*	*0.42*	*0.46*	*0.49*	*0.53*
300000.00	*0.30*	*0.30*	*0.33*	*0.36*	*0.39*	*0.42*	*0.45*
360000.00	*0.25*	*0.25*	*0.28*	*0.30*	*0.33*	*0.35*	*0.38*
450000.00	*0.20*	*0.20*	*0.22*	*0.24*	*0.26*	*0.28*	*0.30*
600000.00	*0.15*	*0.15*	*0.17*	*0.18*	*0.20*	*0.21*	*0.23*
900000.00	*0.10*	*0.10*	*0.11*	*0.12*	*0.13*	*0.14*	*0.15*
9000000.00	*0.01*	*0.01*	*0.01*	*0.01*	*0.01*	*0.01*	*0.02*

Table 35 – Vulnerability Table Medium

	PK						
IRRIDIANCE	**0**	**50**	**60**	**70**	**80**	**90**	**100**
263.16	*190.00*	*190.00*	*209.00*	*228.00*	*247.00*	*266.00*	*285.00*
277.78	*180.00*	*180.00*	*198.00*	*216.00*	*234.00*	*252.00*	*270.00*
294.12	*170.00*	*170.00*	*187.00*	*204.00*	*221.00*	*238.00*	*255.00*
312.50	*160.00*	*160.00*	*176.00*	*192.00*	*208.00*	*224.00*	*240.00*
333.33	*150.00*	*150.00*	*165.00*	*180.00*	*195.00*	*210.00*	*225.00*
357.14	*140.00*	*140.00*	*154.00*	*168.00*	*182.00*	*196.00*	*210.00*
384.62	*130.00*	*130.00*	*143.00*	*156.00*	*169.00*	*182.00*	*195.00*
416.67	*120.00*	*120.00*	*132.00*	*144.00*	*156.00*	*168.00*	*180.00*
454.55	*110.00*	*110.00*	*121.00*	*132.00*	*143.00*	*154.00*	*165.00*
500.00	*100.00*	*100.00*	*110.00*	*120.00*	*130.00*	*140.00*	*150.00*
555.56	*90.00*	*90.00*	*99.00*	*108.00*	*117.00*	*126.00*	*135.00*
625.00	*80.00*	*80.00*	*88.00*	*96.00*	*104.00*	*112.00*	*120.00*
714.29	*70.00*	*70.00*	*77.00*	*84.00*	*91.00*	*98.00*	*105.00*
833.33	*60.00*	*60.00*	*66.00*	*72.00*	*78.00*	*84.00*	*90.00*
1000.00	*50.00*	*50.00*	*55.00*	*60.00*	*65.00*	*70.00*	*75.00*
1250.00	*40.00*	*40.00*	*44.00*	*48.00*	*52.00*	*56.00*	*60.00*
1666.67	*30.00*	*30.00*	*33.00*	*36.00*	*39.00*	*42.00*	*45.00*
2500.00	*20.00*	*20.00*	*22.00*	*24.00*	*26.00*	*28.00*	*30.00*
2564.10	*19.50*	*19.50*	*21.45*	*23.40*	*25.35*	*27.30*	*29.25*
2631.58	*19.00*	*19.00*	*20.90*	*22.80*	*24.70*	*26.60*	*28.50*
2702.70	*18.50*	*18.50*	*20.35*	*22.20*	*24.05*	*25.90*	*27.75*
2777.78	*18.00*	*18.00*	*19.80*	*21.60*	*23.40*	*25.20*	*27.00*
2857.14	*17.50*	*17.50*	*19.25*	*21.00*	*22.75*	*24.50*	*26.25*
2941.18	*17.00*	*17.00*	*18.70*	*20.40*	*22.10*	*23.80*	*25.50*
3030.30	*16.50*	*16.50*	*18.15*	*19.80*	*21.45*	*23.10*	*24.75*
3125.00	*16.00*	*16.00*	*17.60*	*19.20*	*20.80*	*22.40*	*24.00*
3225.81	*15.50*	*15.50*	*17.05*	*18.60*	*20.15*	*21.70*	*23.25*
3333.33	*15.00*	*15.00*	*16.50*	*18.00*	*19.50*	*21.00*	*22.50*
3448.28	*14.50*	*14.50*	*15.95*	*17.40*	*18.85*	*20.30*	*21.75*
3571.43	*14.00*	*14.00*	*15.40*	*16.80*	*18.20*	*19.60*	*21.00*
3703.70	*13.50*	*13.50*	*14.85*	*16.20*	*17.55*	*18.90*	*20.25*
3846.15	*13.00*	*13.00*	*14.30*	*15.60*	*16.90*	*18.20*	*19.50*
4000.00	*12.50*	*12.50*	*13.75*	*15.00*	*16.25*	*17.50*	*18.75*
4166.67	*12.00*	*12.00*	*13.20*	*14.40*	*15.60*	*16.80*	*18.00*
4347.83	*11.50*	*11.50*	*12.65*	*13.80*	*14.95*	*16.10*	*17.25*
4545.45	*11.00*	*11.00*	*12.10*	*13.20*	*14.30*	*15.40*	*16.50*
4761.90	*10.50*	*10.50*	*11.55*	*12.60*	*13.65*	*14.70*	*15.75*
5000.00	*10.00*	*10.00*	*11.00*	*12.00*	*13.00*	*14.00*	*15.00*
5263.16	*9.50*	*9.50*	*10.45*	*11.40*	*12.35*	*13.30*	*14.25*

5555.56	*9.00*	*9.00*	*9.90*	*10.80*	*11.70*	*12.60*	*13.50*
5882.35	*8.50*	*8.50*	*9.35*	*10.20*	*11.05*	*11.90*	*12.75*
6250.00	*8.00*	*8.00*	*8.80*	*9.60*	*10.40*	*11.20*	*12.00*
6666.67	*7.50*	*7.50*	*8.25*	*9.00*	*9.75*	*10.50*	*11.25*
7142.86	*7.00*	*7.00*	*7.70*	*8.40*	*9.10*	*9.80*	*10.50*
7692.31	*6.50*	*6.50*	*7.15*	*7.80*	*8.45*	*9.10*	*9.75*
8333.33	*6.00*	*6.00*	*6.60*	*7.20*	*7.80*	*8.40*	*9.00*
9090.91	*5.50*	*5.50*	*6.05*	*6.60*	*7.15*	*7.70*	*8.25*
10000.00	*5.00*	*5.00*	*5.50*	*6.00*	*6.50*	*7.00*	*7.50*
11111.11	*4.50*	*4.50*	*4.95*	*5.40*	*5.85*	*6.30*	*6.75*
12500.00	*4.00*	*4.00*	*4.40*	*4.80*	*5.20*	*5.60*	*6.00*
14285.71	*3.50*	*3.50*	*3.85*	*4.20*	*4.55*	*4.90*	*5.25*
16666.67	*3.00*	*3.00*	*3.30*	*3.60*	*3.90*	*4.20*	*4.50*
20000.00	*2.50*	*2.50*	*2.75*	*3.00*	*3.25*	*3.50*	*3.75*
25000.00	*2.00*	*2.00*	*2.20*	*2.40*	*2.60*	*2.80*	*3.00*
33333.33	*1.50*	*1.50*	*1.65*	*1.80*	*1.95*	*2.10*	*2.25*
50000.00	*1.00*	*1.00*	*1.10*	*1.20*	*1.30*	*1.40*	*1.50*
52631.58	*0.95*	*0.95*	*1.05*	*1.14*	*1.24*	*1.33*	*1.43*
55555.56	*0.90*	*0.90*	*0.99*	*1.08*	*1.17*	*1.26*	*1.35*
58823.53	*0.85*	*0.85*	*0.94*	*1.02*	*1.11*	*1.19*	*1.28*
62500.00	*0.80*	*0.80*	*0.88*	*0.96*	*1.04*	*1.12*	*1.20*
66666.67	*0.75*	*0.75*	*0.83*	*0.90*	*0.98*	*1.05*	*1.13*
71428.57	*0.70*	*0.70*	*0.77*	*0.84*	*0.91*	*0.98*	*1.05*
76923.08	*0.65*	*0.65*	*0.72*	*0.78*	*0.85*	*0.91*	*0.98*
83333.33	*0.60*	*0.60*	*0.66*	*0.72*	*0.78*	*0.84*	*0.90*
90909.09	*0.55*	*0.55*	*0.61*	*0.66*	*0.72*	*0.77*	*0.83*
100000.00	*0.50*	*0.50*	*0.55*	*0.60*	*0.65*	*0.70*	*0.75*
111111.11	*0.45*	*0.45*	*0.50*	*0.54*	*0.59*	*0.63*	*0.68*
125000.00	*0.40*	*0.40*	*0.44*	*0.48*	*0.52*	*0.56*	*0.60*
142857.14	*0.35*	*0.35*	*0.39*	*0.42*	*0.46*	*0.49*	*0.53*
166666.67	*0.30*	*0.30*	*0.33*	*0.36*	*0.39*	*0.42*	*0.45*
200000.00	*0.25*	*0.25*	*0.28*	*0.30*	*0.33*	*0.35*	*0.38*
250000.00	*0.20*	*0.20*	*0.22*	*0.24*	*0.26*	*0.28*	*0.30*
333333.33	*0.15*	*0.15*	*0.17*	*0.18*	*0.20*	*0.21*	*0.23*
500000.00	*0.10*	*0.10*	*0.11*	*0.12*	*0.13*	*0.14*	*0.15*
5000000.00	*0.01*	*0.01*	*0.01*	*0.01*	*0.01*	*0.01*	*0.02*

Table 36 – Vulnerability Table Low

	PK						
IRRIDIANCE	**0**	**50**	**60**	**70**	**80**	**90**	**100**
52.63	*190.00*	*190.00*	*209.00*	*228.00*	*247.00*	*266.00*	*285.00*
55.56	*180.00*	*180.00*	*198.00*	*216.00*	*234.00*	*252.00*	*270.00*
58.82	*170.00*	*170.00*	*187.00*	*204.00*	*221.00*	*238.00*	*255.00*
62.50	*160.00*	*160.00*	*176.00*	*192.00*	*208.00*	*224.00*	*240.00*
66.67	*150.00*	*150.00*	*165.00*	*180.00*	*195.00*	*210.00*	*225.00*
71.43	*140.00*	*140.00*	*154.00*	*168.00*	*182.00*	*196.00*	*210.00*
76.92	*130.00*	*130.00*	*143.00*	*156.00*	*169.00*	*182.00*	*195.00*
83.33	*120.00*	*120.00*	*132.00*	*144.00*	*156.00*	*168.00*	*180.00*
90.91	*110.00*	*110.00*	*121.00*	*132.00*	*143.00*	*154.00*	*165.00*
100.00	*100.00*	*100.00*	*110.00*	*120.00*	*130.00*	*140.00*	*150.00*
111.11	*90.00*	*90.00*	*99.00*	*108.00*	*117.00*	*126.00*	*135.00*
125.00	*80.00*	*80.00*	*88.00*	*96.00*	*104.00*	*112.00*	*120.00*
142.86	*70.00*	*70.00*	*77.00*	*84.00*	*91.00*	*98.00*	*105.00*
166.67	*60.00*	*60.00*	*66.00*	*72.00*	*78.00*	*84.00*	*90.00*
200.00	*50.00*	*50.00*	*55.00*	*60.00*	*65.00*	*70.00*	*75.00*
250.00	*40.00*	*40.00*	*44.00*	*48.00*	*52.00*	*56.00*	*60.00*
333.33	*30.00*	*30.00*	*33.00*	*36.00*	*39.00*	*42.00*	*45.00*
500.00	*20.00*	*20.00*	*22.00*	*24.00*	*26.00*	*28.00*	*30.00*
512.82	*19.50*	*19.50*	*21.45*	*23.40*	*25.35*	*27.30*	*29.25*
526.32	*19.00*	*19.00*	*20.90*	*22.80*	*24.70*	*26.60*	*28.50*
540.54	*18.50*	*18.50*	*20.35*	*22.20*	*24.05*	*25.90*	*27.75*
555.56	*18.00*	*18.00*	*19.80*	*21.60*	*23.40*	*25.20*	*27.00*
571.43	*17.50*	*17.50*	*19.25*	*21.00*	*22.75*	*24.50*	*26.25*
588.24	*17.00*	*17.00*	*18.70*	*20.40*	*22.10*	*23.80*	*25.50*
606.06	*16.50*	*16.50*	*18.15*	*19.80*	*21.45*	*23.10*	*24.75*
625.00	*16.00*	*16.00*	*17.60*	*19.20*	*20.80*	*22.40*	*24.00*
645.16	*15.50*	*15.50*	*17.05*	*18.60*	*20.15*	*21.70*	*23.25*
666.67	*15.00*	*15.00*	*16.50*	*18.00*	*19.50*	*21.00*	*22.50*
689.66	*14.50*	*14.50*	*15.95*	*17.40*	*18.85*	*20.30*	*21.75*
714.29	*14.00*	*14.00*	*15.40*	*16.80*	*18.20*	*19.60*	*21.00*
740.74	*13.50*	*13.50*	*14.85*	*16.20*	*17.55*	*18.90*	*20.25*
769.23	*13.00*	*13.00*	*14.30*	*15.60*	*16.90*	*18.20*	*19.50*
800.00	*12.50*	*12.50*	*13.75*	*15.00*	*16.25*	*17.50*	*18.75*
833.33	*12.00*	*12.00*	*13.20*	*14.40*	*15.60*	*16.80*	*18.00*
869.57	*11.50*	*11.50*	*12.65*	*13.80*	*14.95*	*16.10*	*17.25*
909.09	*11.00*	*11.00*	*12.10*	*13.20*	*14.30*	*15.40*	*16.50*
952.38	*10.50*	*10.50*	*11.55*	*12.60*	*13.65*	*14.70*	*15.75*
1000.00	*10.00*	*10.00*	*11.00*	*12.00*	*13.00*	*14.00*	*15.00*
1052.63	*9.50*	*9.50*	*10.45*	*11.40*	*12.35*	*13.30*	*14.25*

1111.11	*9.00*	*9.00*	*9.90*	*10.80*	*11.70*	*12.60*	*13.50*
1176.47	*8.50*	*8.50*	*9.35*	*10.20*	*11.05*	*11.90*	*12.75*
1250.00	*8.00*	*8.00*	*8.80*	*9.60*	*10.40*	*11.20*	*12.00*
1333.33	*7.50*	*7.50*	*8.25*	*9.00*	*9.75*	*10.50*	*11.25*
1428.57	*7.00*	*7.00*	*7.70*	*8.40*	*9.10*	*9.80*	*10.50*
1538.46	*6.50*	*6.50*	*7.15*	*7.80*	*8.45*	*9.10*	*9.75*
1666.67	*6.00*	*6.00*	*6.60*	*7.20*	*7.80*	*8.40*	*9.00*
1818.18	*5.50*	*5.50*	*6.05*	*6.60*	*7.15*	*7.70*	*8.25*
2000.00	*5.00*	*5.00*	*5.50*	*6.00*	*6.50*	*7.00*	*7.50*
2222.22	*4.50*	*4.50*	*4.95*	*5.40*	*5.85*	*6.30*	*6.75*
2500.00	*4.00*	*4.00*	*4.40*	*4.80*	*5.20*	*5.60*	*6.00*
2857.14	*3.50*	*3.50*	*3.85*	*4.20*	*4.55*	*4.90*	*5.25*
3333.33	*3.00*	*3.00*	*3.30*	*3.60*	*3.90*	*4.20*	*4.50*
4000.00	*2.50*	*2.50*	*2.75*	*3.00*	*3.25*	*3.50*	*3.75*
5000.00	*2.00*	*2.00*	*2.20*	*2.40*	*2.60*	*2.80*	*3.00*
6666.67	*1.50*	*1.50*	*1.65*	*1.80*	*1.95*	*2.10*	*2.25*
10000.00	*1.00*	*1.00*	*1.10*	*1.20*	*1.30*	*1.40*	*1.50*
10526.32	*0.95*	*0.95*	*1.05*	*1.14*	*1.24*	*1.33*	*1.43*
11111.11	*0.90*	*0.90*	*0.99*	*1.08*	*1.17*	*1.26*	*1.35*
11764.71	*0.85*	*0.85*	*0.94*	*1.02*	*1.11*	*1.19*	*1.28*
12500.00	*0.80*	*0.80*	*0.88*	*0.96*	*1.04*	*1.12*	*1.20*
13333.33	*0.75*	*0.75*	*0.83*	*0.90*	*0.98*	*1.05*	*1.13*
14285.71	*0.70*	*0.70*	*0.77*	*0.84*	*0.91*	*0.98*	*1.05*
15384.62	*0.65*	*0.65*	*0.72*	*0.78*	*0.85*	*0.91*	*0.98*
16666.67	*0.60*	*0.60*	*0.66*	*0.72*	*0.78*	*0.84*	*0.90*
18181.82	*0.55*	*0.55*	*0.61*	*0.66*	*0.72*	*0.77*	*0.83*
20000.00	*0.50*	*0.50*	*0.55*	*0.60*	*0.65*	*0.70*	*0.75*
22222.22	*0.45*	*0.45*	*0.50*	*0.54*	*0.59*	*0.63*	*0.68*
25000.00	*0.40*	*0.40*	*0.44*	*0.48*	*0.52*	*0.56*	*0.60*
28571.43	*0.35*	*0.35*	*0.39*	*0.42*	*0.46*	*0.49*	*0.53*
33333.33	*0.30*	*0.30*	*0.33*	*0.36*	*0.39*	*0.42*	*0.45*
40000.00	*0.25*	*0.25*	*0.28*	*0.30*	*0.33*	*0.35*	*0.38*
50000.00	*0.20*	*0.20*	*0.22*	*0.24*	*0.26*	*0.28*	*0.30*
66666.67	*0.15*	*0.15*	*0.17*	*0.18*	*0.20*	*0.21*	*0.23*
100000.00	*0.10*	*0.10*	*0.11*	*0.12*	*0.13*	*0.14*	*0.15*
1000000.00	*0.01*	*0.01*	*0.01*	*0.01*	*0.01*	*0.01*	*0.02*

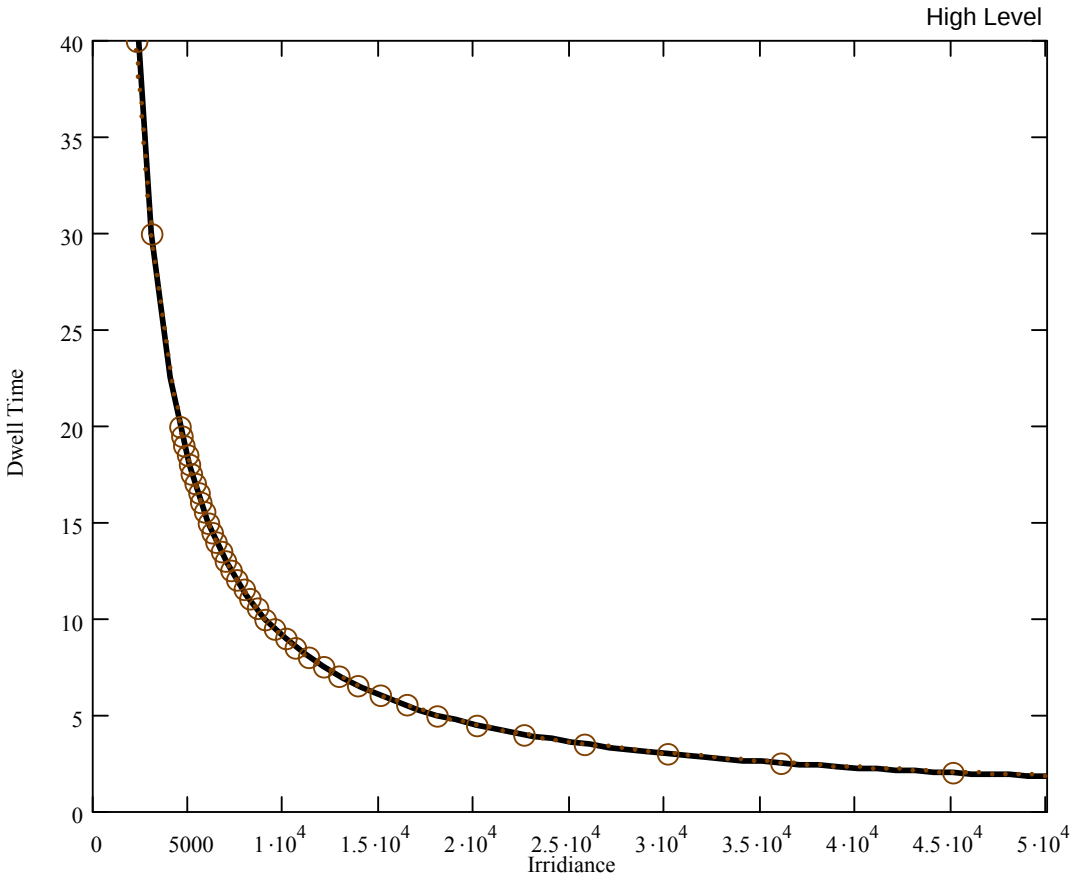

Figure 38 – High Level Vulnerability Fit

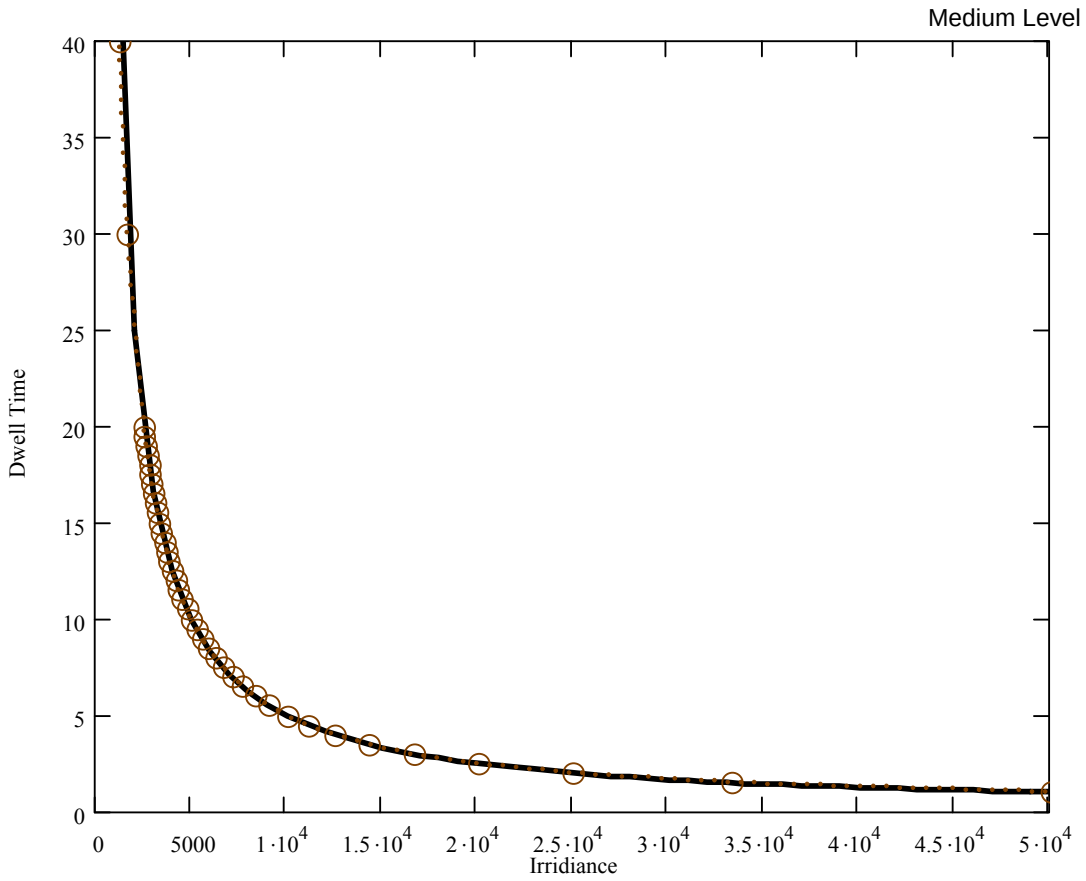

Figure 39 – Medium Level Vulnerability Fit

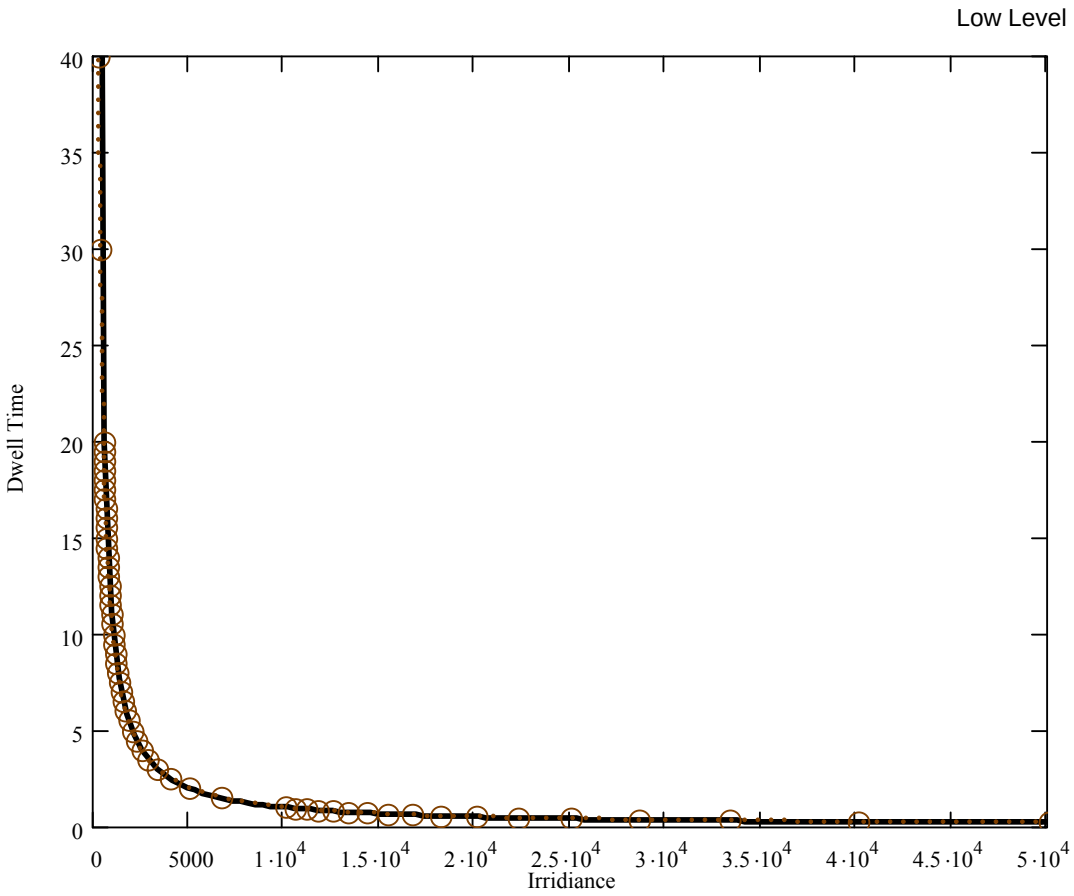

Figure 40 – Low Level Vulnerability Fit

Appendix F: Propagation Tables

Table 37 – Propagation Table Low

50000 Watts/cm²	**Weapon Altitude *(meters)***		
Slant Range *(meters)*	**1000**	**4500**	**8000**
1000	*150660*	*184070*	*198880*
1500	*57540*	*75940*	*83780*
2000	*27840*	*39400*	*44220*
2500	*15490*	*23420*	*26700*
3000	*9440*	*15210*	*17590*
3500	*6140*	*10510*	*12330*
4000	*4190*	*7600*	*9050*
4500	*2960*	*5700*	*6870*
5000	*2160*	*4390*	*5370*
5500	*1620*	*3460*	*4290*
6000	*1230*	*2780*	*3490*
6500	*960*	*2270*	*2880*
7000	*750*	*1880*	*2410*
7500	*600*	*1570*	*2040*
8000	*480*	*1330*	*1750*
8500	*390*	*1130*	*1510*
9000	*320*	*970*	*1310*
10000	*220*	*730*	*1010*
12000	*110*	*440*	*640*
15000	*50*	*230*	*370*
25000	*10*	*50*	*90*

Table 38 – Propagation Table Medium

100000 Watts/cm²	**Weapon Altitude *(meters)***		
Slant Range *(meters)*	**1000**	**4500**	**8000**
1000	*246560*	*305610*	*333800*
1500	*92100*	*123070*	*137270*
2000	*44040*	*62990*	*71480*
2500	*24320*	*37100*	*42760*
3000	*14750*	*23930*	*27990*
3500	*9550*	*16450*	*19510*
4000	*6500*	*11850*	*14250*
4500	*4590*	*8850*	*10790*
5000	*3340*	*6800*	*8400*
5500	*2490*	*5350*	*6690*
6000	*1900*	*4290*	*5430*
6500	*1470*	*3490*	*4480*
7000	*1160*	*2890*	*3740*
7500	*920*	*2410*	*3170*
8000	*740*	*2040*	*2710*
8500	*610*	*1730*	*2330*
9000	*500*	*1490*	*2030*
10000	*340*	*1120*	*1560*
12000	*180*	*680*	*990*
15000	*70*	*360*	*560*
25000	*10*	*70*	*140*

Table 39 – Propagation Table High

200000 Watts/cm^2	**Weapon Altitude *(meters)***		
Slant Range *(meters)*	**1000**	**4500**	**8000**
1000	*390230*	*490930*	*542330*
1500	*142660*	*193020*	*217710*
2000	*67450*	*97500*	*111860*
2500	*36980*	*56920*	*66310*
3000	*22310*	*36480*	*43120*
3500	*14400*	*24950*	*29900*
4000	*9770*	*17910*	*21750*
4500	*6880*	*13330*	*16400*
5000	*5000*	*10220*	*12730*
5500	*3730*	*8020*	*10120*
6000	*2840*	*6410*	*8200*
6500	*2200*	*5220*	*6750*
7000	*1730*	*4300*	*5630*
7500	*1370*	*3590*	*4760*
8000	*1110*	*3030*	*4060*
8500	*900*	*2580*	*3490*
9000	*740*	*2210*	*3030*
10000	*510*	*1660*	*2330*
12000	*260*	*1000*	*1470*
15000	*110*	*530*	*830*
25000	*10*	*110*	*210*

Appendix G: Design of Experiment

The following design of experiments shows all the points that were executed by the simulation code including the points eliminated in the analysis sections.

Prop	Vul	Priority	Alt	Velocity	Run
50000	10000	1	1000	140	1
50000	10000	1	1000	220	2
50000	10000	1	1000	300	3
50000	10000	1	4500	140	4
50000	10000	1	4500	220	5
50000	10000	1	4500	300	6
50000	10000	1	8000	140	7
50000	10000	1	8000	220	8
50000	10000	1	8000	300	9
50000	10000	2	1000	140	10
50000	10000	2	1000	220	11
50000	10000	2	1000	300	12
50000	10000	2	4500	140	13
50000	10000	2	4500	220	14
50000	10000	2	4500	300	15
50000	10000	2	8000	140	16
50000	10000	2	8000	220	17
50000	10000	2	8000	300	18
50000	10000	3	1000	140	19
50000	10000	3	1000	220	20
50000	10000	3	1000	300	21
50000	10000	3	4500	140	22
50000	10000	3	4500	220	23
50000	10000	3	4500	300	24
50000	10000	3	8000	140	25
50000	10000	3	8000	220	26
50000	10000	3	8000	300	27
50000	10000	4	1000	140	28
50000	10000	4	1000	220	29
50000	10000	4	1000	300	30
50000	10000	4	4500	140	31
50000	10000	4	4500	220	32
50000	10000	4	4500	300	33
50000	10000	4	8000	140	34
50000	10000	4	8000	220	35
50000	10000	4	8000	300	36
50000	50000	1	1000	140	37
50000	50000	1	1000	220	38
50000	50000	1	1000	300	39

50000	50000	1	4500	140	40
50000	50000	1	4500	220	41
50000	50000	1	4500	300	42
50000	50000	1	8000	140	43
50000	50000	1	8000	220	44
50000	50000	1	8000	300	45
50000	50000	2	1000	140	46
50000	50000	2	1000	220	47
50000	50000	2	1000	300	48
50000	50000	2	4500	140	49
50000	50000	2	4500	220	50
50000	50000	2	4500	300	51
50000	50000	2	8000	140	52
50000	50000	2	8000	220	53
50000	50000	2	8000	300	54
50000	50000	3	1000	140	55
50000	50000	3	1000	220	56
50000	50000	3	1000	300	57
50000	50000	3	4500	140	58
50000	50000	3	4500	220	59
50000	50000	3	4500	300	60
50000	50000	3	8000	140	61
50000	50000	3	8000	220	62
50000	50000	3	8000	300	63
50000	50000	4	1000	140	64
50000	50000	4	1000	220	65
50000	50000	4	1000	300	66
50000	50000	4	4500	140	67
50000	50000	4	4500	220	68
50000	50000	4	4500	300	69
50000	50000	4	8000	140	70
50000	50000	4	8000	220	71
50000	50000	4	8000	300	72
50000	90000	1	1000	140	73
50000	90000	1	1000	220	74
50000	90000	1	1000	300	75
50000	90000	1	4500	140	76
50000	90000	1	4500	220	77
50000	90000	1	4500	300	78
50000	90000	1	8000	140	79
50000	90000	1	8000	220	80
50000	90000	1	8000	300	81
50000	90000	2	1000	140	82
50000	90000	2	1000	220	83
50000	90000	2	1000	300	84
50000	90000	2	4500	140	85
50000	90000	2	4500	220	86

50000	90000	2	4500	300	87
50000	90000	2	8000	140	88
50000	90000	2	8000	220	89
50000	90000	2	8000	300	90
50000	90000	3	1000	140	91
50000	90000	3	1000	220	92
50000	90000	3	1000	300	93
50000	90000	3	4500	140	94
50000	90000	3	4500	220	95
50000	90000	3	4500	300	96
50000	90000	3	8000	140	97
50000	90000	3	8000	220	98
50000	90000	3	8000	300	99
50000	90000	4	1000	140	100
50000	90000	4	1000	220	101
50000	90000	4	1000	300	102
50000	90000	4	4500	140	103
50000	90000	4	4500	220	104
50000	90000	4	4500	300	105
50000	90000	4	8000	140	106
50000	90000	4	8000	220	107
50000	90000	4	8000	300	108
100000	10000	1	1000	140	109
100000	10000	1	1000	220	110
100000	10000	1	1000	300	111
100000	10000	1	4500	140	112
100000	10000	1	4500	220	113
100000	10000	1	4500	300	114
100000	10000	1	8000	140	115
100000	10000	1	8000	220	116
100000	10000	1	8000	300	117
100000	10000	2	1000	140	118
100000	10000	2	1000	220	119
100000	10000	2	1000	300	120
100000	10000	2	4500	140	121
100000	10000	2	4500	220	122
100000	10000	2	4500	300	123
100000	10000	2	8000	140	124
100000	10000	2	8000	220	125
100000	10000	2	8000	300	126
100000	10000	3	1000	140	127
100000	10000	3	1000	220	128
100000	10000	3	1000	300	129
100000	10000	3	4500	140	130
100000	10000	3	4500	220	131
100000	10000	3	4500	300	132
100000	10000	3	8000	140	133

100000	10000	3	8000	220	134
100000	10000	3	8000	300	135
100000	10000	4	1000	140	136
100000	10000	4	1000	220	137
100000	10000	4	1000	300	138
100000	10000	4	4500	140	139
100000	10000	4	4500	220	140
100000	10000	4	4500	300	141
100000	10000	4	8000	140	142
100000	10000	4	8000	220	143
100000	10000	4	8000	300	144
100000	50000	1	1000	140	145
100000	50000	1	1000	220	146
100000	50000	1	1000	300	147
100000	50000	1	4500	140	148
100000	50000	1	4500	220	149
100000	50000	1	4500	300	150
100000	50000	1	8000	140	151
100000	50000	1	8000	220	152
100000	50000	1	8000	300	153
100000	50000	2	1000	140	154
100000	50000	2	1000	220	155
100000	50000	2	1000	300	156
100000	50000	2	4500	140	157
100000	50000	2	4500	220	158
100000	50000	2	4500	300	159
100000	50000	2	8000	140	160
100000	50000	2	8000	220	161
100000	50000	2	8000	300	162
100000	50000	3	1000	140	163
100000	50000	3	1000	220	164
100000	50000	3	1000	300	165
100000	50000	3	4500	140	166
100000	50000	3	4500	220	167
100000	50000	3	4500	300	168
100000	50000	3	8000	140	169
100000	50000	3	8000	220	170
100000	50000	3	8000	300	171
100000	50000	4	1000	140	172
100000	50000	4	1000	220	173
100000	50000	4	1000	300	174
100000	50000	4	4500	140	175
100000	50000	4	4500	220	176
100000	50000	4	4500	300	177
100000	50000	4	8000	140	178
100000	50000	4	8000	220	179
100000	50000	4	8000	300	180

100000	90000	1	1000	140	181
100000	90000	1	1000	220	182
100000	90000	1	1000	300	183
100000	90000	1	4500	140	184
100000	90000	1	4500	220	185
100000	90000	1	4500	300	186
100000	90000	1	8000	140	187
100000	90000	1	8000	220	188
100000	90000	1	8000	300	189
100000	90000	2	1000	140	190
100000	90000	2	1000	220	191
100000	90000	2	1000	300	192
100000	90000	2	4500	140	193
100000	90000	2	4500	220	194
100000	90000	2	4500	300	195
100000	90000	2	8000	140	196
100000	90000	2	8000	220	197
100000	90000	2	8000	300	198
100000	90000	3	1000	140	199
100000	90000	3	1000	220	200
100000	90000	3	1000	300	201
100000	90000	3	4500	140	202
100000	90000	3	4500	220	203
100000	90000	3	4500	300	204
100000	90000	3	8000	140	205
100000	90000	3	8000	220	206
100000	90000	3	8000	300	207
100000	90000	4	1000	140	208
100000	90000	4	1000	220	209
100000	90000	4	1000	300	210
100000	90000	4	4500	140	211
100000	90000	4	4500	220	212
100000	90000	4	4500	300	213
100000	90000	4	8000	140	214
100000	90000	4	8000	220	215
100000	90000	4	8000	300	216

The points were generated by the following macro:

```
Sub Control_File_Generation()
'
' Control_File_Generation Macro
' Macro recorded 2/10/2004 by ron
'

'
```

```
Workbooks("Results.xls").Activate
Worksheets("Factor Levels").Activate

Range("B1").Select
PP_table = ActiveCell.Value
Range("C1").Select
LL_table = ActiveCell.Value
Range("D1").Select
Priority = ActiveCell.Value
Range("E1").Select
Altitude = ActiveCell.Value
Range("F1").Select
Velocity = ActiveCell.Value
Range("G1").Select
Approach = ActiveCell.Value
Range("H1").Select
Scenario = ActiveCell.Value

'PP_table = 2
'LL_table = 2
'Priority = 2
'Altitude = 2
'Velocity = 2
'Approach = 1
'Scenario = 2

cur_row = 2
For a = 1 To PP_table 'Prop Table
For B = 1 To LL_table 'Vul Table
For c = 1 To Priority 'Tgt_Pri
For D = 1 To Altitude 'ALT_Alt
For e = 1 To Velocity 'ATL_vel
For f = 1 To Approach 'ATL_path
For g = 1 To Scenario 'vehicle number

   cur_row = cur_row + 1

   Range("A" & cur_row).Select
   ActiveCell.FormulaR1C1 = cur_row - 2

   Range("B" & cur_row).Select
   ActiveCell.FormulaR1C1 = a
   Range("C" & cur_row).Select
   ActiveCell.FormulaR1C1 = B
   Range("D" & cur_row).Select
```

```
    ActiveCell.FormulaR1C1 = c

    Range("E" & cur_row).Select
    ActiveCell.FormulaR1C1 = D
    Range("F" & cur_row).Select
    ActiveCell.FormulaR1C1 = e

    Range("G" & cur_row).Select
    ActiveCell.FormulaR1C1 = f
    Range("H" & cur_row).Select
    ActiveCell.FormulaR1C1 = g

Next g
Next f
Next e
Next D
Next c
Next B
Next a

End Sub
```

Appendix H: PERL Script

```
#!/bin/perl -w

#BSUB -q regular
#BSUB -n 20
#BSUB -W 5:00
#BSUB -J xptest
#BSUB -o xptest
#BSUB -e xptest
#BSUB -P WPBAFITO25047ACM

$site = "ASC";                                  # default site
#$jobsFileName = "currentjobs";      # temp file
#$jobPattern = "MC_EADSIM";       # job name pattern we are looking for
#$jobLimit = 50;                             # how many jobs in the queue at a time
#$submitCount = 5;              # how many jobs to submit during a single script execution
$eadsimJobFile = "eadsimJob";         # batch control files for eadsim run
$controlFile = "jobcontrol";   # table of values for runs
#$jobSubmitted = 0;
$count = 0;

my $num_children = 20; # number of child processes spawned; same as number of
                # processors

#####
#                 check out the command line arguments
#####

$i = 0;
while( defined( $ARGV[$i] ) )
{
        $_ = $ARGV[$i];
        if ( /ARL/ || /arl/ )
        {
                $site = "ARL";
        }
        if ( /ASC/ || /asc/ )
        {
                $site = "ASC";
        }
        $i++;
}
```

```
#print "\n\n Running at Site: $site\n\n";



#####
#                   how many of the EADSIM jobs are running?
#####


#$noJobs = checkJobs ();
#print "number of jobs found = $noJobs\n\n";

#$jobSubmitted = 0;
#$i = 0;

#while ( $i < $submitCount && $noJobs < $jobLimit )
#{
#         $i = $i + 1;
#         $jobSubmitted = submitJob();

#         $noJobs = checkJobs();
#}

# if ( $jobSubmitted )
#{
#         print "at now + 1 minute  < runperl \n";
#         #system( "at now + 1 minute < runperl " );
#}
#else
#{
#         print "at now + 30 minutes < runperl \n";
          #system( "at now + 30 minutes < runperl " );
#}

my $runscript = "/hafs11/mcook/eadsim_script/run_eadsim";
my ($found, $j, $pid, $counter);

my $continue = 1;

#print "\n\n MasterLoop:\n\n";

while ($continue) {
  $continue = 0;
```

```
  for ($j = 0; $j < $num_children; ++$j) {
    $found = createInputFiles(\$counter);

    $continue += $found;

    if (! $found) {
      last;
    }

    unless ($pid = fork) {
      if (defined $pid) {
        exec $runscript, $counter;
      }
    }
  }

  wait if ($continue);
}

##############################################
#                   subroutines start here
##############################################

##############################################
#                              checkJobs
##############################################
sub checkJobs
{

        my ($ jCount );

        #print "\n\n Checking Number of Jobs:\n\n";


        $_ = $site;                 #check status of running jobs, depending on site
        if ( /ARL/ )
        {
                system("qstat > $jobsFileName");
        }
        if ( /ASC/ )
        {
                system("bjobs > $jobsFileName");
        }

        #####
```

```
	#		let check on the EADSIM jobs running now
	#####

	open( JOBSFILE, "<$jobsFileName" ) || die "cannot open $jobsFileName to look
for running jobs";

	$jCount = 0;

	# print "***List of running jobs found\n";
	while (<JOBSFILE>)
	{
		if ( /$jobPattern/ )
		{
			# print $_;
			$jCount++;
		}
	}
	# print "***\n\n";

	close( JOBSFILE );
#print "returning $jCount from checkJobs\n";

	return $jCount;
}



##############################################
#			submitJob
##############################################
sub submitJob
{
	$found = createInputFiles();

	createBatchCommands();

	if ( $found )
	{
		###
		#	now submit the job
		###
		$_ = $site;
		if ( /ASC/ )
		{
			print "bsub < $eadsimJobFile\n";
```

```
#                       system( "bsub < $eadsimJobFile" );
                }
                if ( /ARL/ )
                {
#                       print "qsub $xpatchJobFile\n";
#                       system( "qsub $xpatchJobFile" );
                }
        }

        return( $found );
}

##############################################
#                       createBatchCommands
##############################################
sub createBatchCommands
{
print "Inside createBatchCommands - building $eadsimJobFile\n";

        open( EADSIMJOB, ">$eadsimJobFile" ) || die "cannot open $eadsimJobFile";

        $_ = $site;
        if ( /ARL/ )
        {
                print EADSIMJOB "#!/bin/csh\n";
                print EADSIMJOB "#\$ -S /bin/csh\n";
                print EADSIMJOB "#\$ -l 4hr\n";
                print EADSIMJOB "#\$ -cwd\n";
                print EADSIMJOB "#\$ -N $jobPattern$count\n";
                print EADSIMJOB "#\$ -P WPBAFITO25047ACM\n";
                print EADSIMJOB "#\$ -l hostname=zornig.arl.hpc.mil\n";
                print EADSIMJOB "\n";

                print EADSIMJOB "endif\n";
        }

        if ( /ASC/ )
        {
                print EADSIMJOB "#!/bin/csh -f \n";
                print EADSIMJOB "#BSUB -q regular\n";
                print EADSIMJOB "#BSUB -n 1\n";
                print EADSIMJOB "#BSUB -W 0:10\n";
                print EADSIMJOB "#BSUB -J $jobPattern$count\n";
                print EADSIMJOB "#BSUB -o mc$count\n";
                print EADSIMJOB "#BSUB -e mc$count\n";
```

```
                print EADSIMJOB "#BSUB -P WPBAFITO25047ACM\n";
                print EADSIMJOB "\n";
                print EADSIMJOB "cd /hafs11/mcook\n";
                print EADSIMJOB "eadsim A0_BASELINE_2_$count\n";
                print EADSIMJOB
"/app/eadsim/Platform/o3k/v10.00/execute/SGI65/ngpp E LASER_REPORT_$count
A0_BASELINE_2_${count}_1\n";
#
# REMOVE SCENARIO FILE
                print EADSIMJOB "rm
/hafs11/mcook/eadsim/data/scenario/A0_BASELINE_2_${count}.scn\n";
# REMOVE LAYDOWN FILES
                print EADSIMJOB "rm
/hafs11/mcook/eadsim/data/scenario/BLUE_FORCE_${count}.lay\n";
                print EADSIMJOB "rm
/hafs11/mcook/eadsim/data/scenario/RED_FORCE_${count}.lay\n";
#
# REMOVE PLAYBACK FILES
                print EADSIMJOB "rm
/hafs11/mcook/eadsim/data/playback/A0_BASELINE_2_${count}_#.pb\n";
                print EADSIMJOB "rm
/hafs11/mcook/eadsim/data/playback/A0_BASELINE_2_${count}_#.fplog\n";
                print EADSIMJOB "rm
/hafs11/mcook/eadsim/data/playback/A0_BASELINE_2_${count}_#.stathdr\n";
# REMOVE STATQUERY FILES
                print EADSIMJOB "rm
/hafs11/mcook/eadsim/data/statquery/LASER_REPORT_${count}_#.engquery\n";
#
                print EADSIMJOB "exit\n";
        }

        close( EADSIMJOB );
}

##############################################
#                       createInputFiles
##############################################
sub createInputFiles
{

      my ($counter) = @_;
        my ( $found ) ;
        my ( $line );
        my ( @words );
        #print "\n\n Creating Input Files\n\n";
```

```
$pt = 0;          # propagation table
$vul_tbl = 0;   # vulnerability table
$tgt_pri = 0;   # target priority
$atl_alt = 0;    # ATL parameters
$atl_vel = 0;
$atl_lat_start = 0;
$atl_lon_start = 0;
$atl_lat_end = 0;
$atl_lon_end = 0;
$lat_t1 = 0;     # 20 truck parameters
$lon_t1 = 0;
$lat_t2 = 0;
$lon_t2 = 0;
$lat_t3 = 0;
$lon_t3 = 0;
$lat_t4 = 0;
$lon_t4 = 0;
$lat_t5 = 0;
$lon_t5 = 0;
$lat_t6 = 0;
$lon_t6 = 0;
$lat_t7 = 0;
$lon_t7 = 0;
$lat_t8 = 0;
$lon_t8 = 0;
$lat_t9 = 0;
$lon_t9 = 0;
$lat_t10 = 0;
$lon_t10 = 0;
$lat_t11 = 0;
$lon_t11 = 0;
$lat_t12 = 0;
$lon_t12 = 0;
$lat_t13 = 0;
$lon_t13 = 0;
$lat_t14 = 0;
$lon_t14 = 0;
$lat_t15 = 0;
$lon_t15 = 0;
$lat_t16 = 0;
$lon_t16 = 0;
$lat_t17 = 0;
$lon_t17 = 0;
$lat_t18 = 0;
```

```
	$lon_t18 = 0;
	$lat_t19 = 0;
	$lon_t19 = 0;
	$lat_t20 = 0;
	$lon_t20 = 0;

	open( CONTROLFILE, "<$controlFile" ) || die " cannot open control file:
$controlFile\n";
	open( NEWFILE, ">newFile" ) || die "cannot open temp newFile\n";

	#print "\n\n Accessing Control File....\n\n";
	$found = 0;

	$_ = <CONTROLFILE>;		## read and copy first line in control file --
header information
	print NEWFILE $_;

	while ( <CONTROLFILE> ) ## read the remainder of the lines, looking for
values for next submission
	{
		#print "line from $controlFile: $_\n";

		@words = split;		# split input line into tokens

		if ( /ready/ && $found == 0 )
		{

			print NEWFILE "$` run\n";
			$found = 1;
			$count = $words[0];
			$pt = $words[1];
			$vul_tbl = $words[2];
			$tgt_pri = $words[3];
			$atl_alt = $words[4] *1000;
			$atl_vel = $words[5];
			$atl_lat_start = $words[6];
			$atl_lon_start = $words[7];
			$atl_lat_end = $words[8];
			$atl_lon_end = $words[9];
			$lat_t1 = $words[10];
			$lon_t1 = $words[11];
			$lat_t2 = $words[12];
			$lon_t2 = $words[13];
			$lat_t3 = $words[14];
			$lon_t3 = $words[15];
```

```
                        $lat_t4 = $words[16];
                        $lon_t4 = $words[17];
                        $lat_t5 = $words[18];
                        $lon_t5 = $words[19];
                        $lat_t6 = $words[20];
                        $lon_t6 = $words[21];
                        $lat_t7 = $words[22];
                        $lon_t7 = $words[23];
                        $lat_t8 = $words[24];
                        $lon_t8 = $words[25];
                        $lat_t9 = $words[26];
                        $lon_t9 = $words[27];
                        $lat_t10 = $words[28];
                        $lon_t10 = $words[29];
                        $lat_t11 = $words[30];
                        $lon_t11 = $words[31];
                        $lat_t12 = $words[32];
                        $lon_t12 = $words[33];
                        $lat_t13 = $words[34];
                        $lon_t13 = $words[35];
                        $lat_t14 = $words[36];
                        $lon_t14 = $words[37];
                        $lat_t15 = $words[38];
                        $lon_t15 = $words[39];
                        $lat_t16 = $words[40];
                        $lon_t16 = $words[41];
                        $lat_t17 = $words[42];
                        $lon_t17 = $words[43];
                        $lat_t18 = $words[44];
                        $lon_t18 = $words[45];
                        $lat_t19 = $words[46];
                        $lon_t19 = $words[47];
                        $lat_t20 = $words[48];
                        $lon_t20 = $words[49];
                        $priority = "ATL_GROUND_$pt$vul_tbl$tgt_pri";

                }
                else
                {
                        print NEWFILE $_;    # simply copy line to new file
                }
        }

#
#       if there is another job to run, build three specific files from template files
```

```
#               blue_force.tmp --> blue_force_count.lay
#               red_force.tmp --> red_force_count.lay
#               A0_baseline_2.tmp --> A0_baseline_2_count.scn
#

        if ( $found )
        {
                $jobSubmitted = $count;

                ###
                #       start with blue_force.lay
                ###

                open( BLUE_TMP, "<BLUE_FORCE.tmp" ) || die "could not open
BLUE_FORCE.tmp\n";
                open( BLUE_LAYDOWN,
">/hafs11/mcook/eadsim/data/scenarios/BLUE_FORCE_$count.lay" ) || die "could not
open blue laydown file\n";

                #print "\n\n Creating Blue Laydown\n\n";

                while( <BLUE_TMP> )
                {
                        if ( /%ATL_TYPE/ )
                        {
                                print BLUE_LAYDOWN "$priority:|\n";
                        }
                        elsif ( /%ATL_Lat_Start/ )
                        {
                                @words = split;                 # split input line into tokens
                                print BLUE_LAYDOWN "$atl_lat_start $atl_lon_start
$atl_alt $words[3] $words[4] $words[5] $words[6] $atl_vel $words[8] $words[9]\n";
                        }
                        elsif ( /%ATL_Lat_End/ )
                        {
                                @words = split;
                                print BLUE_LAYDOWN "$atl_lat_end $atl_lon_end
$atl_alt $words[3] $words[4] $words[5] $words[6] $atl_vel $words[8] $words[9]\n";
                        }
                        else
                        {
                                print BLUE_LAYDOWN $_;
                        }
                }
```

```
		close( BLUE_TMP );
		close( BLUE_LAYDOWN );


		###
		#  now red_force.lay
		###

		open( RED_TMP, "<RED_FORCE.tmp" ) || die "could not open
RED_FORCE.tmp\n";
		open ( RED_LAYDOWN,
">/hafs11/mcook/eadsim/data/scenarios/RED_FORCE_$count.lay" ) || die "could not
open red laydown file\n";

		#print "\n\n Creating Red Laydown\n\n";

		while( <RED_TMP> )
		{
			if ( /%Lat_Truck01/ )
			{
				@words = split;
				print RED_LAYDOWN "$lat_t1 $lon_t1 $words[2]
$words[3] $words[4] $words[5] $words[6] $words[7] $words[8] $words[9]\n";
			}
			elsif ( /%Lat_Truck02/ )
			{
				@words = split;
				print RED_LAYDOWN "$lat_t2 $lon_t2 $words[2]
$words[3] $words[4] $words[5] $words[6] $words[7] $words[8] $words[9]\n";
			}
			elsif ( /%Lat_Truck03/ )
			{
				@words = split;
				print RED_LAYDOWN "$lat_t3 $lon_t3 $words[2]
$words[3] $words[4] $words[5] $words[6] $words[7] $words[8] $words[9]\n";
			}
			elsif ( /%Lat_Truck04/ )
			{
				@words = split;
				print RED_LAYDOWN "$lat_t4 $lon_t4 $words[2]
$words[3] $words[4] $words[5] $words[6] $words[7] $words[8] $words[9]\n";
			}
			elsif ( /%Lat_Truck05/ )
			{
				@words = split;
```

```
                        print RED_LAYDOWN "$lat_t5 $lon_t5 $words[2]
$words[3] $words[4] $words[5] $words[6] $words[7] $words[8] $words[9]\n";
                }
                elsif ( /%Lat_Truck06/ )
                {
                        @words = split;
                        print RED_LAYDOWN "$lat_t6 $lon_t6 $words[2]
$words[3] $words[4] $words[5] $words[6] $words[7] $words[8] $words[9]\n";
                }
                elsif ( /%Lat_Truck07/ )
                {
                        @words = split;
                        print RED_LAYDOWN "$lat_t7 $lon_t7 $words[2]
$words[3] $words[4] $words[5] $words[6] $words[7] $words[8] $words[9]\n";
                }
                elsif ( /%Lat_Truck08/ )
                {
                        @words = split;
                        print RED_LAYDOWN "$lat_t8 $lon_t8 $words[2]
$words[3] $words[4] $words[5] $words[6] $words[7] $words[8] $words[9]\n";
                }
                elsif ( /%Lat_Truck09/ )
                {
                        @words = split;
                        print RED_LAYDOWN "$lat_t9 $lon_t9 $words[2]
$words[3] $words[4] $words[5] $words[6] $words[7] $words[8] $words[9]\n";
                }
                elsif ( /%Lat_Truck10/ )
                {
                        @words = split;
                        print RED_LAYDOWN "$lat_t10 $lon_t10 $words[2]
$words[3] $words[4] $words[5] $words[6] $words[7] $words[8] $words[9]\n";
                }
                elsif ( /%Lat_Truck11/ )
                {
                        @words = split;
                        print RED_LAYDOWN "$lat_t11 $lon_t11 $words[2]
$words[3] $words[4] $words[5] $words[6] $words[7] $words[8] $words[9]\n";
                }
                elsif ( /%Lat_Truck12/ )
                {
                        @words = split;
                        print RED_LAYDOWN "$lat_t12 $lon_t12 $words[2]
$words[3] $words[4] $words[5] $words[6] $words[7] $words[8] $words[9]\n";
                }
```

```
                elsif ( /%Lat_Truck13/ )
                {
                        @words = split;
                        print RED_LAYDOWN "$lat_t13 $lon_t13 $words[2]
$words[3] $words[4] $words[5] $words[6] $words[7] $words[8] $words[9]\n";
                }
                elsif ( /%Lat_Truck14/ )
                {
                        @words = split;
                        print RED_LAYDOWN "$lat_t14 $lon_t14 $words[2]
$words[3] $words[4] $words[5] $words[6] $words[7] $words[8] $words[9]\n";
                }
                elsif ( /%Lat_Truck15/ )
                {
                        @words = split;
                        print RED_LAYDOWN "$lat_t15 $lon_t15 $words[2]
$words[3] $words[4] $words[5] $words[6] $words[7] $words[8] $words[9]\n";
                }
                elsif ( /%Lat_Truck16/ )
                {
                        @words = split;
                        print RED_LAYDOWN "$lat_t16 $lon_t16 $words[2]
$words[3] $words[4] $words[5] $words[6] $words[7] $words[8] $words[9]\n";
                }
                elsif ( /%Lat_Truck17/ )
                {
                        @words = split;
                        print RED_LAYDOWN "$lat_t17 $lon_t17 $words[2]
$words[3] $words[4] $words[5] $words[6] $words[7] $words[8] $words[9]\n";
                }
                elsif ( /%Lat_Truck18/ )
                {
                        @words = split;
                        print RED_LAYDOWN "$lat_t18 $lon_t18 $words[2]
$words[3] $words[4] $words[5] $words[6] $words[7] $words[8] $words[9]\n";
                }
                elsif ( /%Lat_Truck19/ )
                {
                        @words = split;
                        print RED_LAYDOWN "$lat_t19 $lon_t19 $words[2]
$words[3] $words[4] $words[5] $words[6] $words[7] $words[8] $words[9]\n";
                }
                elsif ( /%Lat_Truck20/ )
                {
                        @words = split;
```

```
                        print RED_LAYDOWN "$lat_t20 $lon_t20 $words[2]
$words[3] $words[4] $words[5] $words[6] $words[7] $words[8] $words[9]\n";
                }
                else
                {
                        print RED_LAYDOWN $_;
                }

        }

        close( RED_TMP );
        close( RED_LAYDOWN );

        ###
        #       finally end with the scenario file
        ###

        open( SCN_TMP, "<A0_BASELINE_2.tmp" ) || die "could not open
A0_BASELINE_2.tmp\n";
        open( NEW_SCN,
">/hafs11/mcook/eadsim/data/scenarios/A0_BASELINE_2_$count.scn" ) || die "could
not open scenario file\n";

        #print "\n\n Creating Scenario File... \n\n";

        while( <SCN_TMP> )
        {
                if ( /%RED_FORCE/ )
                {
                        print NEW_SCN "RED_FORCE_$count\n";
                }
                elsif ( /%BLUE_FORCE/ )
                {
                        print NEW_SCN "BLUE_FORCE_$count\n";
                }
                elsif ( /^(A0_BASELINE_2)(\..+)/ )
                {
                        print NEW_SCN "$1_${count}$2\n";
                }else
                {
                        print NEW_SCN $_;
                }
        }

        close( SCN_TMP );
```

```
                close( NEW_SCN );

                open( STAT_TMP, "<LASER_REPORT.tmp" ) || die "could not open
LASER_REPORT.tmp\n";
                open( STAT_SCN,
">/hafs11/mcook/eadsim/data/statquery/LASER_REPORT_$count.engquery" ) || die
"could not open query file\n";

                #print "\n\n Creating Stat Template ...\n\n";

                while( <STAT_TMP> )

                {
                  s/\$count/$count/;
                  print STAT_SCN $_;
                }


                close( STAT_TMP );
                close( STAT_SCN );


        }
        else
        {
                $jobSubmitted = 0;
        }

        close ( CONTROLFILE );
        close ( NEWFILE );

        unlink( "$controlFile" );
        rename( "newFile", "$controlFile" );

      $$counter = $count;
        return( $found );
}
```

Additionally the following code was used to execute eadsim, the ngpp, move the data files off of the limited home directory, and clean up all extraneous files.

```
#!/bin/csh

set count = $1

cd /hafs11/mcook
eadsim A0_BASELINE_2_$count
/app/eadsim/Platform/o3k/v10.00/execute/SGI65/ngpp E LASER_REPORT_$count
A0_BASELINE_2_${count}_1
rm /hafs11/mcook/eadsim/data/playback/A0_BASELINE_2_${count}_1.pb
#rm /hafs11/mcook/eadsim/data/playback/A0_BASELINE_2_${count}_1.fplog
rm /hafs11/mcook/eadsim/data/playback/A0_BASELINE_2_${count}_1.stathdr
rm /hafs11/mcook/eadsim/data/scenarios/A0_BASELINE_2_${count}.scn
#rm /hafs11/mcook/eadsim/data/scenarios/A0_BASELINE_2_${count}_MC.scn
rm /hafs11/mcook/eadsim/data/scenarios/BLUE_FORCE_${count}.lay
rm /hafs11/mcook/eadsim/data/scenarios/RED_FORCE_${count}.lay
rm /hafs11/mcook/eadsim/data/statquery/LASER_REPORT_${count}.engquery
cp /hafs11/mcook/eadsim/output/LASER_REPORT_AH_${count}_1.engrpt
$ARC/results
cp /hafs11/mcook/eadsim/output/LASER_REPORT_LS_${count}_1.engrpt
$ARC/results
rm /hafs11/mcook/eadsim/output/LASER_REPORT_AH_${count}_1.engrpt
rm /hafs11/mcook/eadsim/output/LASER_REPORT_LS_${count}_1.engrpt
#rm /hafs11/mcook/eadsim/output/c3i/A0_BASELINE_2_${count}_1.c3ilog
#rm /hafs11/mcook/eadsim/output/c3i/A0_BASELINE_2_${count}_1.c3ipstat
rm /hafs11/mcook/eadsim/output/c3i/A0_BASELINE_2_${count}_1.engstat
#rm /hafs11/mcook/eadsim/output/c3i/A0_BASELINE_2_${count}_1.faillog
rm /hafs11/mcook/eadsim/output/c3i/A0_BASELINE_2_${count}_1.iffstat
rm /hafs11/mcook/eadsim/output/c3i/A0_BASELINE_2_${count}_1.laserstat
#rm /hafs11/mcook/eadsim/output/c3i/A0_BASELINE_2_${count}_1.trkerror
#rm /hafs11/mcook/eadsim/output/c3i/A0_BASELINE_2_${count}_1.trkevent
#rm /hafs11/mcook/eadsim/output/det/A0_BASELINE_2_${count}_1.detlog
#rm /hafs11/mcook/eadsim/output/det/A0_BASELINE_2_${count}_1.detspds
#rm /hafs11/mcook/eadsim/output/det/A0_BASELINE_2_${count}_1.detstat
```

Appendix I: Analysis Macro

```
Sub Post_Processing()
'
' Post_Processing Macro
' Macro written 2/11/2004 by Michael T Cook

'Turn Off Displaying Application Errors
Application.DisplayAlerts = False
cur_row = 1
'
For I = 264 To 264

'BUILD FILE NAMES

'RootDir$ = "\\FS-AFIT-29\mcook\My Documents\Thesis\Results\LS\"
RootDir$ = "C:\Documents and Settings\Michael T Cook\My
Documents\AFIT\Results\results_v2\LS\"

ReportName$ = "LASER_REPORT_LS_"
ReportNumber$ = I
Suffix$ = "_1.engrpt"
OldName$ = ReportName$ & ReportNumber$ & Suffix$
NewName$ = "LS_" & I

O_File$ = RootDir$ & ReportName$ & ReportNumber$ & Suffix$

'OPEN FILE

   ChDir RootDir$
   Workbooks.OpenText Filename:= _
      O_File$ _
      , Origin:=437, StartRow:=1, DataType:=xlDelimited, TextQualifier:= _
      xlDoubleQuote, ConsecutiveDelimiter:=True, Tab:=True, Semicolon:=False, _
      Comma:=False, Space:=True, Other:=False, FieldInfo:=Array(Array(1, 1), _
      Array(2, 1), Array(3, 1)), TrailingMinusNumbers:=True

'COPY TO RESULTS.XLS
   Range("B62").Select
   Range(Selection, ActiveCell.SpecialCells(xlLastCell)).Select
   Selection.Copy
   Windows("Results.xls").Activate
   Worksheets("Temp_Storage").Activate
   Range("A1").Select
   ActiveSheet.Paste
```

```
    Application.CutCopyMode = False

'Find Number of Failures

    Selection.Find(What:="Failures", After:=ActiveCell, LookIn:=xlFormulas, _
        LookAt:=xlPart, SearchOrder:=xlByRows, SearchDirection:=xlNext, _
        MatchCase:=False, SearchFormat:=False).Activate
    ActiveCell.Offset(rowOffset:=0, columnOffset:=1).Activate
    Failures = ActiveCell.Value

    Selection.Find(What:="Successes", After:=ActiveCell, LookIn:=xlFormulas, _
        LookAt:=xlPart, SearchOrder:=xlByRows, SearchDirection:=xlNext, _
        MatchCase:=False, SearchFormat:=False).Activate
    ActiveCell.Offset(rowOffset:=0, columnOffset:=1).Activate
    Successes = ActiveCell.Value

'Sort the Data based on Successes
If Successes > 0 Then
    Columns("A:E").Select
    Selection.Sort Key1:=Range("C1"), Order1:=xlDescending, Header:=xlGuess, _
        OrderCustom:=1, MatchCase:=False, Orientation:=xlTopToBottom, _
        DataOption1:=xlSortNormal

    'Collect Successful Dwell Times
    SuccessfulValueRows$ = "E1:E" & Successes
    Range(SuccessfulValueRows$).Select
    Selection.Copy
    Range("H1").Select
    Selection.PasteSpecial Paste:=xlPasteAll, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=True

   'Collect Successful Target Engagements
    TargetValueRows$ = "D1:D" & Successes
      Range(TargetValueRows$).Select
    Selection.Copy
    Range("H2").Select
    Selection.PasteSpecial Paste:=xlPasteAll, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=True

   'Remove Failed Dwell Times
    For j = 1 To Failures
        RowRemove$ = Successes + 1 & ":" & Successes + 1
        Rows(RowRemove$).Select
        Selection.Delete Shift:=xlUp
    Next j
```

```
    Else
End If
'CREATE MEASURES OF EFFECTIVENESS

    'Total Number of Kills
    If Successes > 0 Then
        Range("H3").Select
        ActiveCell.FormulaR1C1 = "=COUNTIF(C[-3],"">0"")"
    Else
        Range("H3").Select
        ActiveCell.FormulaR1C1 = 0
    End If


    'Average Dwell Time
    If Successes > 0 Then
        Range("I3").Select
        ActiveCell.FormulaR1C1 = "=AVERAGE(C[-4])"
    Else
        Range("I3").Select
        ActiveCell.FormulaR1C1 = 0
    End If

    'Std Dev Dwell Time
    If Successes > 1 Then
        Range("J3").Select
        ActiveCell.FormulaR1C1 = "=STDEV(C[-5])"
    Else
        Range("J3").Select
        ActiveCell.FormulaR1C1 = 0
    End If

    'Min Dwell Time
    Range("K3").Select
    ActiveCell.FormulaR1C1 = "=MIN(C[-6])"

    'Max Dwell Time
    Range("L3").Select
    ActiveCell.FormulaR1C1 = "=MAX(C[-7])"

    'Cummulative Dwell Time
    Range("M3").Select
    ActiveCell.FormulaR1C1 = "=SUM(C[-8])"

    'Record Failed Number
```

```
    Range("N3").Select
    ActiveCell.FormulaR1C1 = Failures

    'Report Potential Simulation Failure
    If Successes > 1 Then
       LastSimTime_Cell$ = "A" & Successes
       Range(LastSimTime_Cell$).Select
       LastSimTime = ActiveCell.Value

       Range("O3").Select
       ActiveCell.FormulaR1C1 = LastSimTime

       If LastSimTime < 400 Then flag = 4
       If LastSimTime < 300 Then flag = 3
       If LastSimTime < 200 Then flag = 2
       If LastSimTime < 100 Then flag = 1
       Else
       flag = 0
    End If
    Range("P3").Select
    ActiveCell.FormulaR1C1 = flag

    'Record Run Number
    Range("Q3").Select
    ActiveCell.FormulaR1C1 = I

    'Format some columns
    Range("I3:M3").Select
    Selection.NumberFormat = "0.0000"

'MOVE TO SUMMARY SHEET
    Range("H3:Q3").Select
    Selection.Copy
    Sheets("Summary").Select
    cur_row = I + 1
    PasteCell$ = "H" & cur_row
    Range(PasteCell$).Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
       :=False, Transpose:=False

    'Copy Times
    Sheets("Temp_Storage").Select
    Range("H1:AA1").Select
    Selection.Copy
    Sheets("Targets_Destroyed").Select
```

```
    PasteCell$ = "A" & cur_row * 2

    Range(PasteCell$).Select
    ActiveCell.Offset(rowOffset:=0, columnOffset:=1).Activate
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
       :=False, Transpose:=False
    Range(PasteCell$).Select
    ActiveCell.FormulaR1C1 = I


    'Copy Targets
    Sheets("Temp_Storage").Select
    Range("H2:AA2").Select
    Selection.Copy
    Sheets("Targets_Destroyed").Select
    PasteCell$ = "A" & (cur_row * 2) + 1

    Range(PasteCell$).Select
    ActiveCell.Offset(rowOffset:=0, columnOffset:=1).Activate
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
       :=False, Transpose:=False
    Range(PasteCell$).Select
    ActiveCell.FormulaR1C1 = I

'Clear Cell Contents
    Worksheets("Temp_Storage").Select
    Cells.Select
    Selection.ClearContents

'REMOVE SHEET FROM FILE (UNUSED)

     Windows(OldName$).Activate
     ActiveWindow.Close

Next I
End Sub
```

Appendix J: Excluded Design Points

The following data points were excluded from the analysis:

Table 40 – Specific Design Points Excluded

Velocities (m/s)		
140	**220**	**300**
721-730	731-740	741-750
		291-300
		111-120
		21-30

The design point removed corresponds to the highest number listed in the set of simulations.

Table 41 – Specific Simulations with Low Last Engagement Times

Velocities (m/s)		
140	**220**	**300**
1803	919	
1806	1571	
	1572	
	1575	
	1751	
	1811	
	1813	
	1814	
	11	
	13	
	102	
	281	
	282	
	285	
	290	

Of the specific points the following graphs show the comparison with the other points run at the same level with different scenarios. The specific simulation number is included as part of the figure title. The simulations listed in the figure title represent the last few points after the line break in the figure.

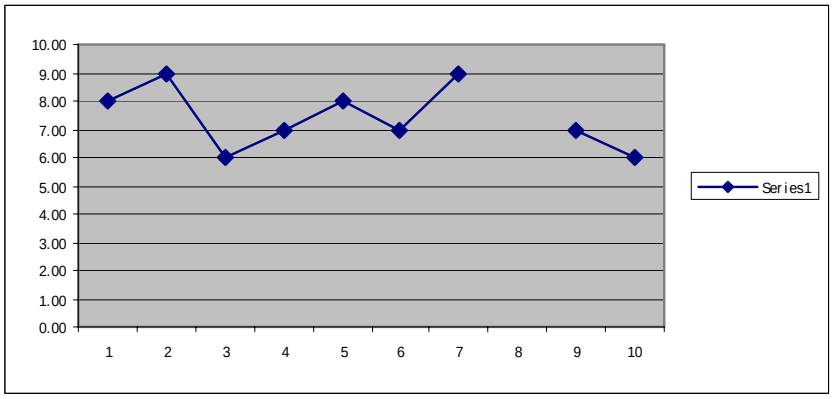

Figure 41 – Simulations 1803, 1806

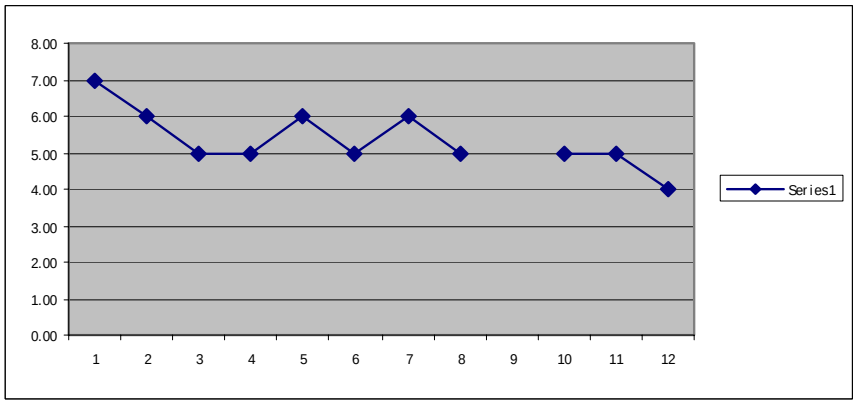

Figure 42 – Simulations 1811, 1813, 1814

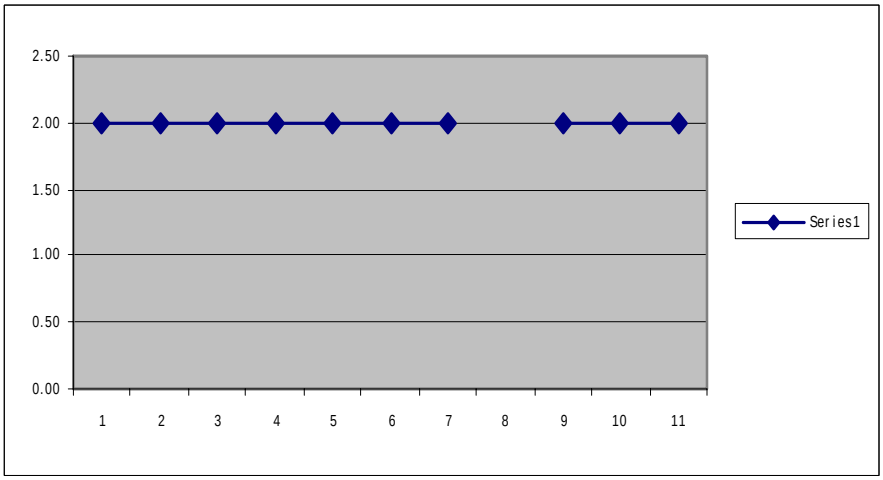

Figure 43 – Simulations 1571, 1572, 1575

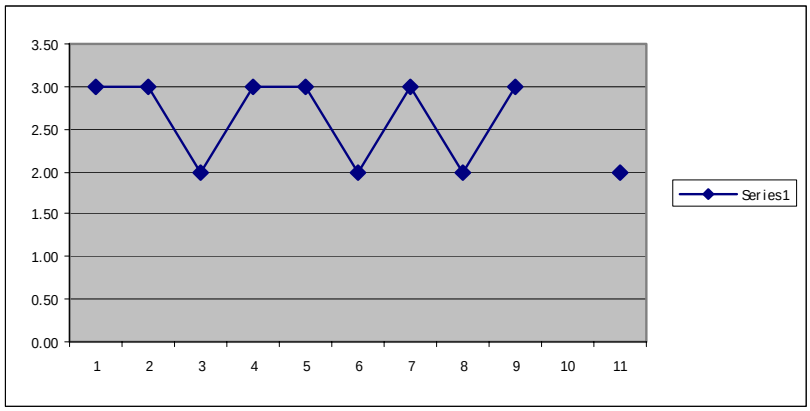

Figure 44 – Simulation 1751

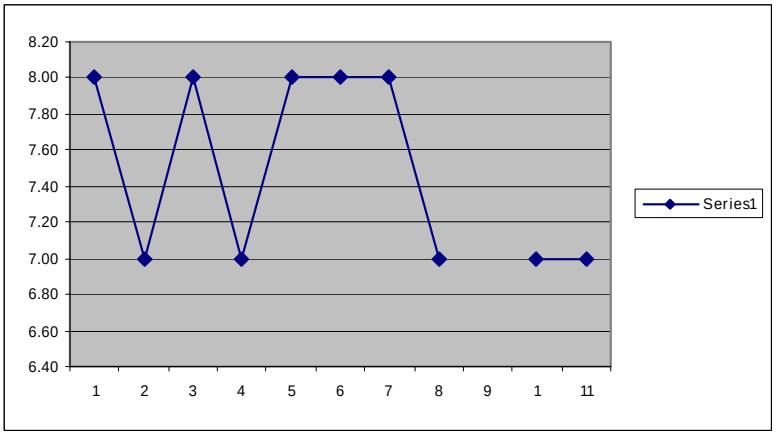

Figure 45 – Simulations 11, 13

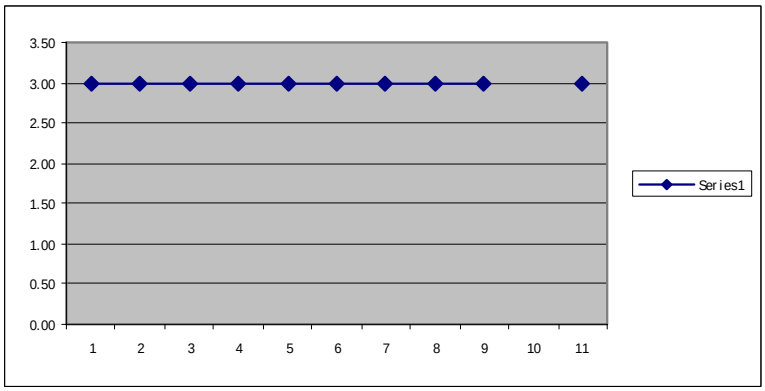

Figure 46 – Simulation 102

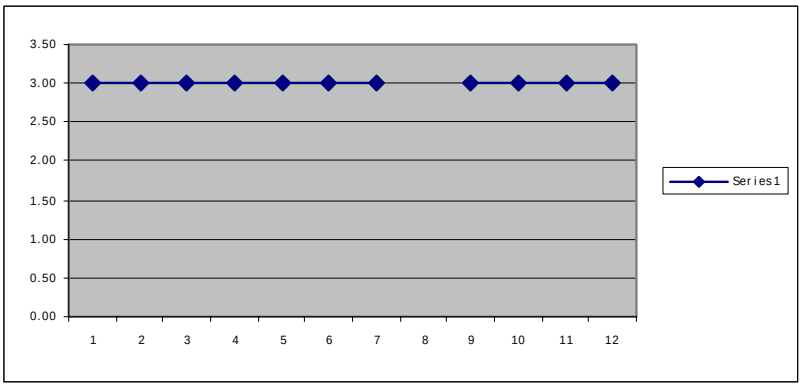

Figure 47 – Simulations 281, 282, 285, 290

Appendix K: Results

The results displayed in this appendix show the results of all the design points.

1 – Simulation Design Point Number
2 – Average Number of Targets Killed
3 – Average of Average Dwell Times
4 – Average of Standard Deviations of Dwell Times
5 – Average of Minimum of Dwell Times
6 – Average of Maximum of Dwell Times

Table 42 – Design Point Results

1	2	3	4	5	6
1	13.2	5.645262	11.77651	0.373	43.665
2	7.5	5.901304	11.56799	0.26	32.904
3	4.9	6.6327	12.16675	0.309	27.95
4	16.8	10.64107	14.7935	2.15	55.651
5	10.6	8.685026	13.5963	2.04	47.042
6	8.4	8.687056	12.76842	2.22	40.215
7	15	15.08347	14.02012	5.45	52.117
8	9.5	14.17219	12.96516	5.555	44.726
9	7	13.00829	12.00808	5.571	38.996
10	4.9	24.13168	18.21981	6.86	49.212
11	3	21.048	12.13569	11.843	34.608
12	2	18.7425	13.02137	9.535	27.95
13	8	24.7452	21.43628	5.937	61.456
14	5	21.30967	14.23378	6.232	40.727
15	3.9	22.58008	15.70402	7.427	41.495
16	8.4	28.22193	19.73294	8.936	59.61
17	5.2	26.33097	16.65448	9.509	50.62
18	4	26.328	14.77138	11.549	42.899
19	16.3	6.030821	11.40817	0.3	43.665
20	11.2	4.914394	9.73243	0.204	32.883
21	8.4	4.853611	9.458236	0.232	27.969
22	17	10.60421	14.93438	2.05	56.719
23	11.4	9.127379	13.34933	2	47.042
24	8.5	9.047	12.80137	2.175	40.215
25	15	14.95854	14.17765	5.5	52.888
26	9.9	14.44037	12.8718	5.528	44.726
27	7.1	13.13886	12.029	5.664	38.996
28	4.9	25.60415	19.599	6.653	52.191
29	3	19.04067	14.14705	7.009	34.395
30	2.1	18.069	12.66483	9.007	27.534
31	7.9	24.22349	21.57536	5.05	63.067
32	5.1	24.9657	18.70637	5.855	51.614
33	4	21.36	15.90072	4.455	40.576
34	8.5	28.39464	19.98427	8.719	59.663

35	5.2	26.43567	16.69555	9.413	50.555
36	4	23.72275	14.91652	7.991	42.507
37	8.5	6.931475	11.40446	1.244	35.819
38	6	6.209776	9.670088	1.072	25.715
39	4.9	5.5086	8.561453	1.001	20.454
40	7	16.65043	12.42432	9.06	43.932
41	4.4	16.9287	11.42171	9.524	34.978
42	3	18.19933	10.21987	10.2	29.622
43	3.5	37.25283	13.40164	28.433	54.353
44	1.8	43.023	4.908735	39.552	46.494
45	0	0	0	0	0
46	2.4	29.01167	6.756532	23.057	34.687
47	2	20.915	9.227743	14.39	27.44
48	1.5	21.8805	3.022881	19.743	24.018
49	2.6	35.83467	11.72709	26.521	46.125
50	1.8	32.3605	9.922829	25.344	39.377
51	1	30.332	0	30.332	30.332
52	1.6	53.94	4.10829	51.035	56.845
53	0	0	0	0	0
54	0	0	0	0	0
55	11	6.510203	10.39031	1.014	36.024
56	7.3	6.334208	9.018986	0.976	26.379
57	4.8	6.9154	8.653284	1.288	21.126
58	6.8	17.47563	12.47267	9.801	44.153
59	4	19.86395	11.46331	10.85	35.428
60	2.8	20.79	10.81015	11.614	31.016
61	3.4	39.6485	12.21366	30.349	54.43
62	1.2	45.7125	0.676701	45.234	46.191
63	0	0	0	0	0
64	2.5	28.19383	6.480009	22.376	34.179
65	2	20.567	8.946315	14.241	26.893
66	2	17.2695	8.012227	11.604	22.935
67	2.8	33.36483	10.8368	24.807	44.588
68	2	28.03	13.84374	18.241	37.819
69	1.9	24.6155	7.573821	19.26	29.971
70	2	46.531	12.4168	37.751	55.311
71	1	48.61	0	48.61	48.61
72	0	0	0	0	0
73	4.4	11.18133	14.20837	2.632	33.435
74	3.6	8.939	11.42844	2.212	24.329
75	2.9	8.311167	9.20361	2.492	18.279
76	4	26.91168	13.57069	17.373	45.539
77	2.2	31.19917	10.43695	23.323	39.053
78	1.5	32.2115	2.250721	30.62	33.803
79	0	0	0	0	0
80	0	0	0	0	0
81	0	0	0	0	0

82	1.3	32.4325	0.334462	32.196	32.669
83	1	29.849	0	29.849	29.849
84	1	19.43	0	19.43	19.43
85	1.8	40.757	4.303452	37.714	43.8
86	0.5	19.441	0	19.441	19.441
87	0	0	0	0	0
88	0	0	0	0	0
89	0	0	0	0	0
90	0	0	0	0	0
91	8.9	7.582899	10.47078	1.78	33.751
92	5.1	9.499867	9.769091	2.143	24.604
93	3.9	8.377517	7.827896	2.668	18.722
94	3.8	28.72792	12.79296	18.648	45.817
95	2.2	31.76367	10.62888	23.933	39.919
96	1	33.718	0	33.718	33.718
97	0	0	0	0	0
98	0	0	0	0	0
99	0	0	0	0	0
100	2	27.9745	4.575688	24.739	31.21
101	1.6	23.921	2.791658	21.947	25.895
102	1.4	17.818	1.637659	16.66	18.976
103	2	38.1395	5.657561	34.139	42.14
104	1.5	33.932	3.422397	31.512	36.352
105	1	33.752	0	33.752	33.752
106	0	0	0	0	0
107	0	0	0	0	0
108	0	0	0	0	0
109	16.9	4.970674	9.749622	0.265	39.838
110	11.8	4.116723	8.373291	0.172	29.302
111	8.9	3.811278	8.190475	0.16	25.205
112	17.5	5.047072	5.116407	1.58	21.803
113	11.7	4.437598	4.922011	1.5	18.501
114	8.9	4.442208	4.921573	1.5	16.661
115	14.8	6.688286	3.923693	3.5	18.241
116	9.7	6.179122	3.797522	3.5	15.841
117	7.1	5.766679	2.998504	3.5	12.107
118	8	15.6245	12.7227	3.497	40.279
119	5.1	13.76613	10.43722	4.059	30.567
120	3.8	12.63142	8.521316	6.645	24.542
121	11	10.52045	6.350104	3.678	23.28
122	6.4	9.996286	5.540357	3.933	18.149
123	4.4	9.60575	5.353447	4.514	17.203
124	9.8	10.44294	3.8128	5.588	17.102
125	5.7	10.29447	3.819005	6.456	16.651
126	3.9	9.650583	3.753017	6.473	14.627
127	17.2	4.79208	9.596002	0.216	39.838
128	12.2	4.051199	8.241817	0.157	29.302

129	9	3.886517	8.13782	0.172	25.205
130	17.7	4.884754	5.090124	1.5	21.803
131	12	4.4575	4.918415	1.515	18.501
132	8.8	4.372917	4.889899	1.5	16.661
133	15.1	6.552308	3.980711	3.5	18.241
134	10	6.204	3.809022	3.5	15.841
135	7	6.051857	2.873483	3.742	12.107
136	8.1	15.73757	12.76596	3.245	40.368
137	5.1	13.48537	10.13268	3.46	29.672
138	4	10.943	9.725833	2.325	24.465
139	10.7	10.79783	6.3384	3.325	23.132
140	6.4	9.951786	5.542819	3.4	18.114
141	4.4	9.40445	5.605069	3.605	17.2
142	9.6	10.6215	3.86133	5.235	17.101
143	5.7	10.10673	3.995477	5.9	16.651
144	4	9.15	4.128585	5.332	14.58
145	11.8	5.774017	10.18517	0.791	36.815
146	8.6	5.235528	8.913038	0.636	27.331
147	6.1	4.941719	8.457572	0.681	22.134
148	9	14.24438	14.87059	5.96	52.46
149	5.8	13.08357	13.12162	5.711	38.703
150	4.1	13.24315	11.57153	6.095	30.475
151	5.2	28.20127	16.77834	17.377	58.185
152	3.2	27.681	15.39951	17.117	45.931
153	2	26.677	9.427148	20.011	33.343
154	3.4	24.65417	10.31377	14.491	35.815
155	2.1	21.56633	10.66799	13.939	29.545
156	2	17.272	9.226329	10.748	23.796
157	3.3	33.7945	15.45172	20.82	51.939
158	2	28.7075	14.1782	18.682	38.733
159	1.9	25.5185	11.95505	17.065	33.972
160	2.4	42.4825	13.4016	32.555	54.214
161	1.2	46.129	2.828427	44.129	48.129
162	0.9	32.625	0	32.625	32.625
163	12.3	5.697086	10.22192	0.701	37.08
164	8.5	5.517486	8.901589	0.604	27.57
165	5.6	5.935967	8.659691	0.991	22.435
166	9.1	14.14382	14.78724	5.86	52.46
167	5.6	14.28073	13.04935	6.237	38.703
168	4	14.402	10.93109	7.495	30.475
169	5.1	28.23573	16.86027	17.163	58.185
170	3.1	29.03525	14.87442	18.012	45.931
171	1.9	27.7105	7.965558	22.078	33.343
172	3.5	22.73025	11.48663	11.509	35.432
173	2.7	19.5165	8.680666	13.526	28.435
174	2	16.3305	9.041774	9.937	22.724
175	3.6	29.61942	17.79842	13.382	51.768

176	2.6	26.39383	12.68173	17.133	38.5
177	2	23.41	14.54236	13.127	33.693
178	2.9	39.0265	14.39996	27.081	54.072
179	2	35.371	17.6013	22.925	47.817
180	1.2	35.4305	1.733119	34.205	36.656
181	7.4	7.569823	11.54718	1.325	34.157
182	5.2	6.678517	10.11766	1.257	25.025
183	4.3	6.25235	9.064372	1.214	20.215
184	6.4	19.1241	13.59805	10.561	46.481
185	3.8	18.763	12.10357	10.868	35.72
186	2.9	21.55567	10.55103	12.515	31.54
187	2.9	42.42933	14.58333	30.904	56.802
188	0	0	0	0	0
189	0	0	0	0	0
190	2	30.1595	4.568617	26.929	33.39
191	1.8	24.4765	5.14703	20.837	28.116
192	1.1	23.8235	0.31042	23.604	24.043
193	2.1	37.31317	12.23467	28.56	46.325
194	1.1	38.2975	0.822365	37.716	38.879
195	1	31.842	0	31.842	31.842
196	1	55.842	0	55.842	55.842
197	0	0	0	0	0
198	0	0	0	0	0
199	10.5	6.536405	10.1993	1.125	35.088
200	6.7	6.479489	9.244224	1.255	25.736
201	4.3	8.647	9.153669	1.951	21.569
202	5.8	20.90323	13.90694	11.128	47.007
203	3.7	19.98733	12.18024	11.903	36.649
204	2.7	22.39933	10.65174	13.385	31.638
205	2.8	43.61333	13.8211	33.156	56.919
206	0	0	0	0	0
207	0	0	0	0	0
208	2	29.978	4.632964	26.702	33.254
209	1.9	21.8015	7.029349	16.831	26.772
210	1.9	17.2365	5.780598	13.149	21.324
211	2.4	35.8455	11.34515	27.769	45.43
212	2	28.573	12.06466	20.042	37.104
213	1.6	26.643	5.045914	23.075	30.211
214	2	46.766	10.32517	39.465	54.067
215	0	0	0	0	0
216	0	0	0	0	0

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14. ABSTRACT

Fielding High Energy Laser (HEL) weapon systems presents technological challenges as well as employment and financial challenges. The risk associated with the challenges mandates the development process include computer simulation models capable of predicting weapon system performance from the engineering level to assessing the military worth of employing HEL systems in combat scenarios. This research effort focuses on developing laser performance data at a higher fidelity engagement model and integrating the performance data into a mission level model. The propagation of the laser from the transmitting aperture to the target is modeled at the engagement level through the employment of the High Energy Laser End-to-End Operational Simulation (HELEEOS), developed by the AFIT Center for Directed Energy (CDE). The output from HELEEOS directly transfers into data lookup tables for the Extended Air Defense Simulation Model (EADSIM). The EADSIM simulations asses the combat performance of a proposed new HEL weapon, the Advanced Tactical Laser (ATL), in a well-defined mission level scenario based on HEL Joint Technology Office (JTO) requirements for future HEL systems. EADSIM is a mission level simulation model included in the Air Force Analytical Tool Kit. Specifically the research explores the development of the necessary information requirements for HELEEOS and EADSIM to accurately model ATL effects and evaluates challenges related to modeling HEL engagements in EADSIM. Results include discussion on EADSIM HEL weapons modeling capabilities, recommendations on general mission level characteristics that should be modeled, and appropriate measures of performance for campaign-level modeling.

15. SUBJECT TERMS
High Energy Laser, HEL, Laser, Combat Simulation, Combat Model, Aggregation, Advanced Tactical Laser, ATL, HELEEOS, EADSIM, THUNDER

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