NAVAL POSTGRADUATE SCHOOL

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SYSTEMS ENGINEERING ANALYSIS CAPSTONE PROJECT REPORT

VIABLE SHORT-TERM DIRECTED ENERGY WEAPON NAVAL SOLUTIONS: A SYSTEMS ANALYSIS OF CURRENT PROTOTYPES

by

Team Bravo
Cohort 19

June 2013

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With conventional weapons nearing their peak capability, the need to identify alternative war fighting solutions suggests a look at Directed Energy Weapons (DEWs). The goal is to change the means by which warfare is conducted to improve operational efficiencies and overall effectiveness. The Naval Postgraduate School Systems Engineering and Analysis (SEA-19B) Capstone project team examined how existing directed energy technologies can provide performance across multiple warfare area domains and mission subsets for the U.S. Navy. The aim was to identify and characterize the capability gaps with conventional weapons systems, produce a coherent vision of naval missions that incorporate DEWs, and generate a roadmap for a DEW fleet. By conducting a thorough Analysis of Alternatives based on system performance, integration, schedule, and cost, the project team identified that the Tactical Laser System (with a laser beam power of 10 kW) provided the best overall capability to defend surface combatants, although none of the analyzed DEWs have the capability to replace a current conventional weapon. The Active Denial System (microwave) provided a niche capability in the Anti-Terrorism/Force Protection mission set.

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ABSTRACT

With conventional weapons nearing their peak capability, the need to identify alternative war fighting solutions suggests a look at Directed Energy Weapons (DEWs). The goal is to change the means by which warfare is conducted to improve operational efficiencies and overall effectiveness. The Naval Postgraduate School Systems Engineering and Analysis (SEA-19B) Capstone project team examined how existing directed energy technologies can provide performance across multiple warfare area domains and mission subsets for the U.S. Navy. The aim was to identify and characterize the capability gaps with conventional weapons systems, produce a coherent vision of naval missions that incorporate DEWs, and generate a roadmap for a DEW fleet. By conducting a thorough Analysis of Alternatives based on system performance, integration, schedule, and cost, the project team identified that the Tactical Laser System (with a laser beam power of 10 kW) provided the best overall capability to defend surface combatants, although none of the analyzed DEWs have the capability to replace a current conventional weapon. The Active Denial System (microwave) provided a niche capability in the Anti-Terrorism/Force Protection mission set.

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TABLE OF CONTENTS

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LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

LIST OF ACRONYMS AND ABBREVIATIONS

AAW	Air-to-Air Warfare
ABL	Airborne LASER
ADS	Active Denial System
AFB	Air Force Base
AMW	Amphibious Warfare
AOA	Analysis of Alternatives
API	Application Programming Interface
ATFP	Anti-Terrorism/Force Protection
ASCM	Anti-Ship Cruise Missile
ASW	Anti-Submarine Warfare
ATL	Advanced Tactical LASER
AW	Anti-air Warfare
BAE	British Aerospace
BMD	Ballistic Missile Defense
BWO	Backward Wave Oscillator
CAIV	Cost as an Independent Variable
CCR	Critical Capability Requirements
CE	Common Era
CIWS	Close-In Weapons System
CN	Cyanide
CO	Carbon Monoxide
COIL	Chemical Oxide Iodine LASER
CONOPS	Concept of Operations
CPT	Captain – Army and Air Force Rank
CSAR	Combat Search and Rescue
DDG	Arleigh Burke Class Guided Missile Destroyer
DE	Directed Energy
DEW	Directed Energy Weapons
DF	Deuterium Fluoride

DTA	Defense Technology Agency
EO	Electro - Optical
EM	ElectroMagnetic
ERGM	Extended Range Guided Munitions
FAC	Fast Attack Craft
FEL	Free Electron LASER
FIAC	Fast Inshore Attack Craft
FWHM	Full Width at Half Maximum
FSO	Flight Support Operations
DoD	Department of Defense
EMD	Engineering and Manufacturing Development
Ft or FT	Fort
GINA	Global Information Network Architecture
GUID	Globally Unique IDentifier
HBr [DBr]	Hydrogen Bromide [Deuterium Bromide]
HCl	Hydrogen Chloride
HF	Hydrogen Fluoride
HPM	High-Power Microwave
ICD	Initial Capabilities Document
JHPSSL	Joint High Power Solid State LASER
JMUA	Joint Military Utility Assessments
KW or kW	Kilo Watt
LASER	Light Amplification by Stimulated Emission of Radiation
LaWS	LASER Weapon System
LaWS+	LASER Weapon System Plus
LCS	Littoral Combat Ship
LNO	Liaison Officer
LOS	Line Of Sight
LT	Lieutenant- Naval Rank
LSF	Low Slow Flyer
LTC	Lieutenant Colonel- Army Rank

MANA	Map Aware Non-Uniform Automata
MANA-V	Map Aware Non-Uniform Automata - Vector
ME5	Military Expert Level 5- Singapore
MIRACL	Mid-Infrared Advanced Chemical LASER
Mk	Mark
MLD	Maritime LASER Demonstration
MODTRAN	MODerate resolution atmospheric TRANsmission
N9I	Warfare Integration, Office of the Chief of Naval Operations
NASA	National Aeronautics and Space Administration
NAVSEA	Naval Sea Systems Command
NCO	Non Combat Operations
Nd	Neodymium ions
NPS	Naval Postgraduate School
NTA	Navy Tactical Tasks
O&S	Operation and Support
ONR	Office of Naval Research
OPNAV	Office of the Chief of Naval Operations
PMS	Program Manager- NAVSEA
POE	Projected Operating Environments
PRL	Pulse Forming Lines
PFN	Pulse Forming Networks
R&D	Research And Development
RAM	Rolling Airframe Missile
RET	Retired
RHIB	Rigid-Hull Inflatable Boat
RIM	Radar Intercept Missile
RoE	Rules of Engagement
RPG	Rocket Propelled Grenade
SCAT	Small Craft Action Team
SE	Systems Engineer/Engineering
SEA	Systems Engineering Analysis

SEAD	Suppression of Enemy Air Defense
SEED	Simulation Experiments and Efficient Designs
SFTM	Surface Force Training Manual
SIPRNET	Secure Internet Protocol Router Network
SM	Standard Missile
SQL	Structured Query Language
SSOI	Selected Sources Of Information
SSL	Solid State LASER
SUW	Surface Warfare
TDSI	Temasek Defence Systems Institute
THEL	Tactical High-Energy LASER
TLS	Tactical LASER System
TOC	Total Ownership Cost
TRAC	TRADOC Analysis Center
TRADOC	U.S. Army Training and Doctrine Command
TRL	Technology Readiness Level
TRW	Thompson, Ramo, Wooldridge Incorporated
UML	Universal Modeling Language
UNCLAS	Unclassified
UAV	Unmanned Aerial Vehicle
UJTL	Universal Joint Task List
UNTL	Universal Naval Task List
U.S.	United States
USA	United States of America
VB	Visual Basic
VRDM	Vector Relationship Data Modeling
WBS	Work Breakdown Structure
YAG	Yttrium Aluminum Garnet

LIST OF TRADEMARKED COMPANIES

Several companies are referred to throughout this report. For sake of writing a coherent report, the companies are referred to with their common usage name as opposed to the official company name. These companies are:

- Big Kahuna Technologies refers to Big Kahuna Technologies Limited Liability Company, trademarked in 2007
- Boeing refers to The Boeing Company, trademarked in 1916
- Raytheon refers to Raytheon Company, trademarked in 1922
- BAE refers to British Aerospace (BAE) Systems Public Limited Company, trademarked in 1999
- Northrop Grumman refers to Northrop Grumman Corporation, trademarked in 1994
- TRW refers to TRW Incorporated, trademarked in 1901. Acquired in 2002 by Northrop Grumman

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EXECUTIVE SUMMARY

With conventional weapons nearing their peak capability, the need to identify alternative war fighting solutions suggests a look at Directed Energy Weapons (DEWs). The goal is to change the means by which warfare is conducted to improve operational efficiencies and overall effectiveness. DEW technologies have been paralyzed by runaway budgets and suboptimal performance without the emergence of an operational system. It is the purpose of this project to examine how mature directed energy technologies can provide the U.S. Government with a “return on investment” and “added value” in the near term.

The Naval Postgraduate School Systems Engineering and Analysis Cohort 19 Team B (SEA-19B) Capstone project team examined how existing directed energy technologies can provide performance across multiple warfare area domains and mission sub-sets for the U.S. Navy. The aim was to identify and characterize the capability gaps with current conventional weapons systems, produce a coherent vision of naval missions that incorporate DEWs, and generate a roadmap for a DEW equipped fleet. To accomplish this task, SEA-19B developed a custom metamodel using the Global Information Network Architecture (GINA) environment, adapted the Map Aware Non-uniform Automata (MANA) simulation tool to simulate DEWs, and conducted a Monte Carlo simulation of multiple combinations of weapons and threats to be simulated in a single sequence of engagements.

GINA is a software metamodeling environment that allows users to describe system of systems behavior semantically in lieu of coding software. This ability is achieved through a reflexive modeling paradigm that is self-describing and incorporates predefined relationship constructs which exist in the environment of project data. The flexibility through relationships provides a significant advantage over the conventional object orientation paradigm of software development by predefining a finite set of relationship types between objects that can be extrapolated to represent any relationship between objects of all types and kinds.

The reflexive nature of the GINA semantic descriptions and the ability of GINA to leverage inherent relationship constructs in GINA allowed SEA-19B to build an engagement-centric model, that described relationships between engagements, threats, weapons, environments, weapon platforms, warfare areas, and missions. The GINA model (herein referred to as the "model") was fully traceable, built on an iterative mapping method that linked the Navy's Universal Naval Task List (UNTL) to Required Operational Capabilities (ROC) and Critical Capabilities Requirements (CCRs), and representative of SEA-19B's tailored Systems Engineering process. The consequence of building the GINA model was that SEA-19B gained the ability to conduct cross-domain comparisons of weapon technologies in the context of engagements, missions, warfare areas, and environments in technology agnostic terms. The result was a means to construct and make a quantitatively and qualitatively objective comparison of DEWs and conventional weapons with a custom user interface to view and navigate the model data and results. External statistical analysis was then conducted using Minitab 16 to provide meaningful graphs of the raw data, modeled relationships, and complex object interactions in order to draw conclusions about DEW performance in various contexts.

The GINA model was deterministic in nature, using physics-based equations implemented through external calculation software, written by SEA-19B with the Microsoft .NET Framework. Integration of these external software programs into GINA was straightforward via the custom GINA model content manager built by Big Kahuna Technologies, LLC (the developer of GINA). Because of the GINA model's deterministic nature, two stochastic simulations were used to gain further insights about potential concepts of operations (CONOPS) for DEW employment, DEW effects on shipboard survivability, and weapon combinations in multithreat environments.

SEA-19B developed a method of translating nominal average times for Type I Engagements (traditional 'hard kill' engagements) at static ranges for targets into probability of kill for a static range using MANA. MANA is an agent-based simulation tool developed by the New Zealand Defense Force originally for ground combat simulations. MANA has since been adapted to nearly every other type of conventional warfare, but to the knowledge of SEA-19B and the NPS SEED Center not for DEW applications that need to accumulate energy to show damage effects as the DE beam tracks moving targets. MANA was then able to use that data to interpolate between a set of static ranges and probabilistic data to simulate DEW engagements, using a system of "life points" and "damage memory," in which energy gets accumulated on the target in discrete packets based on a given range and the original time for a Type I Engagement at that range. Using this method of discrete packet damage accumulation on the target, we simulated a DEW engagement. These simulations provided insights into potential CONOPS for DEW employment on a surface combatant and illustrated the value of multiple platforms applying DE beams for defense against swarms and "hardened," moving targets.

SEA-19B built a Monte Carlo simulation in Excel to accommodate multiple weapons per agent in a straightforward manner. Whereas, MANA was not easily configured to handle multiple combinations of weapons and threats to be simulated in a single sequence of engagements based on the same physics principles behind the GINA model, the Monte Carlo simulation was used for the multiple combinations of weapons and threats. The Monte Carlo simulation allowed SEA-19B to gain insights into the interactions between multiple weapon systems and the effect of DEWs on shipboard survivability.

In addition to modeling and simulation, SEA-19B conducted a cost analysis of the identified alternatives, as well as evaluated the shipboard integration aspects of each system type with respect to the DDG-51 class destroyer platform. Instead of conducting a total life cycle cost calculation, the objective was to determine and estimate the integration costs, as well as to ascertain the implementation cost of select directed energy technologies. After determining the baseline costs, the scope of the project cost estimate work was decomposed into smaller discrete components, whereby all required work breakdown structure (WBS) sub-elements were identified. For each system, the cost estimate was calculated by analogy (with like-kind systems), and based on a cost factors approach (a baseline costing figure is decomposed and reconciled with known aggregate project data that is applicable to the task at hand). In terms of shipboard integration, the assessment examined primarily size, weight, and power (SWaP) considerations. Weapons coverage and the level of integration with current combat systems were also examined but played a smaller role than the SWaP considerations.

By conducting a thorough Analysis of Alternatives based on multiple stakeholder perspectives with respect to system performance, integration, schedule, and cost, the project team identified that the Tactical LASER System (with a LASER beam power of 10 kW operating at 1.6 micron wavelength) provided the best overall combination of (1) capability to defend surface combatants in the near term and (2) cost/schedule to purchase and integrate the system although none of the analyzed DEWs have the capability to replace a current conventional weapon. Additionally, the Active Denial System (operating at 95 GHz radiation) was identified as the best option when looking at Cost as an Independent Variable (CAIV). The Active Denial System (100 kW microwave) provided a niche capability in the Anti-Terrorism/Force Protection (AT/FP) mission set which currently lacks a non-lethal standoff weapon.

ACKNOWLEDGMENTS

The support we have received from our family and friends helped make the countless hours and time spent away over the past ten months bearable. We never would have made it this far without the patience, love and encouragement demonstrated by them all. SEA-19B would like to express our gratitude to our project advisor Dr. Gary Langford for his guidance throughout the progression of this project and always maintaining a positive attitude and actively participating which allowed a smooth transition and integration of the U.S. and TDSI students into one effective team. This project could not have been completed without the support of the following NPS Faculty and Staff, and interested parties. We cannot thank you all enough for your tireless efforts in making this project a success.

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CAPT Jeff Kline, CRUSER Director (RET)
CAPT Trip Barber Deputy Director, OPNAV N81 (RET)
CAPT Wayne Hughes, NPS Professor of Practice (RET)
CAPT William G. Glenney IV, Deputy Director CNO SSG
CAPT James Eagle, Chairman, Systems Engineering Analysis (RET)
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Mr. Frank Busalacchi, Chief Technology Officer, Big Kahuna Technologies, LLC.
Mr. Mike Morris, Big Kahuna Technologies, LLC.
Mr. Jack Rief, Big Kahuna Technologies, LLC.
Mr. Ryan Hale, Contractor, ITACS

Teamwork is the ability to work together toward a common vision. The ability to direct individual accomplishments toward organizational objectives. It is the fuel that allows common people to attain uncommon results.

– Andrew Carnegie

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I. INTRODUCTION

Even today the mere concept of directed energy weapons (DEW) seems cutting edge and carries with it a bit of a science fiction undertone. However, in reality the idea is not new and has been the subject of research for quite some time. Even before the time of Christ, Archimedes experimented with the premise of directed energy. Through an array of mirrors he concentrated sunlight in an attempt to set ablaze the ships of the invading Roman fleet. It is justifiable to credit him with constructing the first primitive "death ray" in 212 BC during the siege of Syracuse (MIT 2.009ers 2005). More recently, Nikola Tesla spent nearly 30 years working with charged particle beams, studying their characteristics of projection through open air. He first published his work on directed energy in 1934 (Tesla Invents Peace Ray 2011). Years later, during the height of the Cold War, the Soviet Union conducted experiments on the effects of high intensity electromagnetic (EM) radiation on people at least as early as 1973. The Soviets determined that a relatively small amount of power at microwave frequencies was required to make people physically ill by exposure to EM radiation (Mcree 1980). In the roughly 40 years since, countless research and development (R&D) efforts related to DEW have been conducted by various nations around the globe. As a whole, the combined efforts of various programs over a span of 30 years have resulted in U.S. government, as well as private, spending totaling in the billions. To date, no resulting "program of record" has been initiated in the United States. Many promising concepts have been evaluated and their respective prototypes built; however, the idea of applying directed energy to warfare seems to have achieved little traction in proportion to the money spent.

It should be noted that throughout this report, the terms DE and DEW are both heavily utilized. For the sake of clarification, DE refers to the entire gamut of technologies that makeup Directed Energy from beams such as LASERs and plasma weapons to area effect technologies such as high-powered microwaves and electromagnetic pulse bombs, to technologies that appear more like conventional weapons like the rail gun. When DEW is used, it refers to a specific Directed Energy

Weapon system like the LASER Weapon System (LaWS) or Active Denial System (ADS).

A. PROJECT TEAM

The Systems Engineering Analysis (SEA) Cohort 19 Team B (SEA-19B) project team was comprised of 23 officers and defense professionals from the United States, Taiwan, Israel, and Singapore. The varied backgrounds, cultures, and mindsets of our team were essential to the overall success of the project. The Surface Warfare Officers composed the majority of the SEA-19B members, all having similar professional experiences. The addition of personnel from Taiwan, Israel, and Singapore from different branches of the military and civilian professions incorporated viewpoints molded by unique differences in professional and cultural experiences. These individual viewpoints contributed an equally valued approach to achieving our objectives and goals throughout the project.

The team was organized into various roles that included Project Leader, Lead Systems Engineer (SE), Speaker, Modeling Lead, Temasek Defence Systems Institute (TDSI) Lead, and Team Engineers. The Project Leader worked on the integration task and was responsible for the overall management of the team (which included scheduling team meetings, monitoring the progress of the project, serving as a liaison between the team and faculty advisors, and allocating assignments). The Lead SE was responsible for managing the overall SE process of the project and served as the chief editor of this thesis paper. The Speaker had the distinction of presenting all briefs in addition to being knowledgeable of all facets of the project and participating in all tasks spanning the SE portions to modeling. The Modeling Lead was responsible for managing the development, execution, and analysis of all computer models and simulations of the project, as well as heading the group of engineers who built the four models and two simulations. The TDSI Lead had duties that paralleled the Project Leader in terms of managing the TDSI students and their assignments for the various Team tasks. Team Engineers worked on all areas of the project from SE portions to Modeling. Team Engineer duties included research, writing, editing, conducting stakeholder interviews, and accomplishing tasks as assigned by the Project Leader, Lead SE, or TDSI Lead.

Table 1 contains a list of the team members, their roles on the project, and brief professional backgrounds with the number of years' experience in that area:

Table 1. Capstone Project Team

Last	First	Rank	Title	Curriculum	Community/Specialty
Shene	Richard	LT	Project Leader	SEA	Surface Warfare-Gunnery Officer (1 Year) Auxiliaries Officer (1 Year) Riverine Detachment Officer-in-
deLongpre	Jeffrey	LT	Lead SE	SEA	Surface Warfare-Main Propulsion Officer (3 Years), Training Officer (2 Years) Awesome (29 Years)
Ciullo	Daniel	LT	Modeling Lead	SEA	Surface Warfare-First Lieutenat (2 Years) Navigator (2
Nowakowsk	Jakub	LT	Speaker	SEA	Surface Warfare-Damage Control Assistant (2 Years), Training Officer (2 Years); Nuclear Machinist Mate / Engineering Laboratory Technician (7 Years)
Cheng	Po-yu	CPT	Team Engineer	SEA	Simulator Maintenance Engineer (4 years)
White	Rosevelt	LT	Team Engineer	SEA	Surface Warfare -Gunnery Officer (1 Year), Electronic Warfare Officer (6 Months), Repair Division Officer (1 Year) Training Officer (2 Years)
McArthur	Sim	LTC	Team Engineer	SEA	Army Officer Field Artillery (11 years), Operations Research Systems Analysis (5 years)
Taylor	Earvin	LT	Team Engineer	SEA	Surface Warfare-Electrical Officer (2 Years) N4 Assistant (2 Years)
Teo	Harn Chin		TDSI Lead	Systems Engineering	Singapore (Defense Industry) Senior Systems Engineer and CAPM (PMI) with experience in MALE UAV projects (4 years)
Heng	Yinghui		Team Engineer	ECE Comms	Singapore (Defence Science and Technology Agency) Communications Systems Engineering and Project Manager
Wong	Chia Sern		Team Engineer	ECE Networks	Singapore (Defence Science and Technology Agency) Networking Engineer and Project Manager
Neo	Yong Shern	ME5	Team Engineer	Guided Weapons	Republic of Singapore Airforce Weapons Systems Engineer
Choon	Junwei		Team Engineer	Guided Weapons	Singapore (Defense Industry) Guidance, Navigation, and Controls Engineer
Wong	Wai Keat	CPT	Team Engineer	Info Assurance	Republic of Singapore Army Signal Officer
Phua	Yee Ling		Team Engineer	Info Assurance	Singapore (Defense Industry) Senior Software Engineer
Lee	Hsu Ann Daryl		Team Engineer	Secured Comms	Singapore (Defense Industry) Systems Engineer
Sheo	Boon Chew Winson	ME5	Team Engineer	Systems Engineering	Republic of Singapore Army Logistics & Maintenance Support, Policy and
Soh	Sze Shiang	ME5	Team Engineer	Systems Engineering	Republic of Singapore Army Artillery and personnel Trained Personnel Training, Ops and Capability Development
Lim	Zhifeng	CPT	Team Engineer	Systems Engineering	Republic of Singapore Army Infantry Officer
Lee	Guan Hock		Team Engineer	Systems Engineering	Singapore (Defense Industry) Assistant Principal Engineer in design, commissioning, and testing of shipboard systems
Leo	Valentine		Team Engineer	Systems Engineering	Singapore (Defense Industry) Asst Manager in design and development in land systems (3 years)
Chow	Wen Chong Julian		Team Engineer	Systems Engineering	Singapore (Defence Science and Technology Agency) Senior Engineer C4I-Development in Navy C2 Projects C2 S/W Developer and Project Manager
Zlatsin	Philip	CPT	Team Engineer	Ops Research	Israeli Air Force Analyst

B. TASKING STATEMENT

In recent conflicts, the United States military has relied on superior technology to compensate for superior numbers or other advantages of our enemies. The ability for insurgents in Iraq and Afghanistan to blend in with the noncombatant population is one example of an advantage. Technological advancement in offensive naval weapons has outpaced advancement in defensive naval systems, as shown by the great advances to strike capability in the form of Tomahawks and experimentation in the railgun and the extended range guided munition (ERGM), but with little traction on increasing armor, reducing radar cross section, or defensive weapons (some notable exceptions are standard missiles and the Close-In Weapons System (CIWS)). It would appear the U.S. Navy has long held onto the adage of "A sudden powerful transition to the offensive—the flashing sword of vengeance—is the greatest moment for the defense" (Clausewitz 1976, 370) or more commonly heard as 'the best defense is a good offense.' The criticality of offensive power has been characterized as well in the Hughes' Salvo Equation (Equation 1) which relates the number of ships put out of action by their tactics, number, circumstances, and power (both offensive and defensive).

$$\Delta B = \frac{\alpha A - b_3 B}{b_1}$$

Equation 1. Number of force B ships put out of action by force A

Where ΔB is the number of force B ships put out of action, α is the striking power of each force A ship, A is the number of force A ships firing, b_3 is the defensive power of each force B ship, B is the number of force B ships present, and b_1 is the staying power of each force B ship (Hughes 2000, 268).

There is an analogous equation for the change in force A. Specifically for naval combat, the force which gets the first strike has a tremendous advantage as the opposing force will likely be damaged prior to its initial salvo in return. Using this equation, there are four interpretations that will result in a reduction in the number of casualties to friendly ships (force B).

- Shoot first. If friendly forces fire first, the enemy likely would not be able to return fire, thereby reducing friendly casualties.

- Reduce α. Reducing the effectiveness of enemy weapons would reduce the number of casualties, but is not something which is realistically achievable.
- Increase b_1. Increasing the survivability of friendly ships would reduce the number of casualties through means of increased armor or improved damage control systems. Armor although relatively inexpensive to implement, increases operational costs by dramatically increasing operational costs (specifically fuel). Improving damage control systems would help as well, but a missile could still strike a crucial point.
- Increase b_3. Increasing the defensive power of friendly ships would reduce the number of missile hits, thereby reducing casualties. Defensive weapons like Standard Missiles (SM) or the Close-In Weapons System (CIWS) currently fulfill this task.

In any conflict short of total war, U.S. commanders generally do not want to engage a ship which may or may not be hostile, so allowing the enemy to take the first shot has nearly become a necessity (or may be so depending on the Rules of Engagement (RoE) for a specific area or situation). The possibility of taking the first shot coupled with the lethality of modern anti-ship cruise missiles (ASCMs), having an inexpensive, reliable, and effective defense against the ASCM threat would be a welcome addition by improving the survivability of ships. DE has the potential to provide this defense to U.S. forces by augmenting or potentially replacing current systems such as the SM family and CIWS, thereby increasing b_3. SEA-19B was tasked with exploring the feasibility of deploying an operational DEW on a U.S. Navy ship in the next four years and to determine if there is a comparative or augmentation advantage over current conventional systems.

The tasking for the capstone project of SEA-19B was directed by OPNAV N9I, the Systems Engineering Analysis curriculum sponsor, through Captain (Retired) Jim Eagle, the Systems Engineering Analysis curriculum chairman, and Professor Gary Langford, the capstone project faculty advisor. The tasking for SEA-19B was to:

> Design a family of systems or a system of systems of Directed Energy Weapons (DEW) that can be integrated with manned and unmanned forces to address a broad spectrum of missions commensurate with the needs of the U.S. Navy. Consider current fleet structure and funded programs as the baseline system of systems to conduct current missions. Develop the concept(s) of operations for the range of current and future missions that incorporate DEW, then develop alternative fleet architectures for

> platforms, ships, manning, command and control, communications, logistics, and operational procedures to advantage DEW capabilities. Consider the potential technology gaps for both DEW and integrating DEW into Naval forces; determine a more streamlined architecture for the combined DEW – Navy forces; and identify and characterize the "gap" fillers. Iterate the task, as approved by your primary faculty advisor. Produce a coherent vision of U.S. Navy missions that incorporate DEW; identify the requirements for support and collaboration with coalition forces; and discuss the interoperability issues with these collaborative efforts. Provide a roadmap of DEW to improve the effectiveness for future Navy ships. (Langford, SEA-19B Directed Energy Weapons 2012)

The key points in this tasking statement are to:

- Address a broad spectrum of missions commensurate with the needs of the U.S. Navy
- Consider current fleet structure and funded programs
- Develop the concept(s) of operations
- Consider the potential technology gaps for both DEW and integrating DEW into current and future Naval forces
- Identify and characterize the gap fillers
- Produce a coherent vision of U.S. Navy missions that incorporate DEW
- Provide a roadmap of DEW to improve the effectiveness for future Navy ships

This statement was further refined by the project team with assistance from our project faculty advisor, Dr. Gary Langford. These refinements, incorporating external restraints and internal constraints, are further discussed in the next section.

C. PROBLEM DEVELOPMENT

The problem statement developed by SEA-19B to address the tasking statement was driven by two factors. The first is any potential solution must be fielded in the short term. While short term was not a defined period of time, the project team specified the period to four years. This timeframe capitalized on current DE technology while still allowing some time for improvements and modifications prior to deployment. The second factor supported the four year period in that only DEW technologies with operationally tested prototypes were considered. Testing was required in real-world environments against possible targets, vice a laboratory setting. A technology that has not advanced beyond the laboratory stage would not be ready to be fielded in four years due to inevitable “improvements” coupled with the requirement for extensive operational test and evaluation. Additionally, the funding required for system and platform integration as part of the progression from a laboratory to an operational testing environment is considerable adding typically 60% of the total costs (National Institute of Standards & Technology 2002). The Airborne LASER (ABL) and Tactical High-Energy LASER (THEL) are two examples of the time and funding required to make an operational (or at least ready to be fielded for additional testing) DEW. The ABL program started in 1996, had the prototype fully constructed and ready to fly in 2003, with testing conducted from 2008 to 2010 (FAS 2010). For seven aircraft, including all development and testing, the total cost was expected to be 1.6 billion dollars in fiscal year 2005 dollars (Lockridge 2001). Similarly, the THEL program started in 1996, was ready for testing in 1998, with several tests conducted starting in 2002 (Pike 2011), at a cost of between 150 to 200 million dollars (Sirak 1999). The two driving factors of conforming to a four year timeframe and using operationally tested prototypes shaped the problem statement for the SEA-19B Capstone Project.

1. Problem Statement

In order to focus the work of the project team, it was necessary to identify the problems facing the U.S. Navy with respect to DEW and produce a clear and concise problem statement to guide the team. Among the problems facing the Navy are that conventional weapons are nearing their peak technical capability, DEW technologies have been paralyzed by runaway budgets and sub optimal performance without the emergence of an operational system, as well as the fact that DEWs are currently being pursued by other countries throughout the world.

Conventional gun systems have not changed significantly since World War II. They have become smaller with less range but have greater accuracy and a higher rate of fire. The largest guns on current U.S. ships are 5 inch guns with a range of 13 nautical miles (United States Navy 2012) compared to the 16 inch guns on the Iowa Class battleships with a range of nearly 21 nautical miles (Fischer, et al. 2006). Several programs have attempted to improve conventional guns further, specifically the Extended Range Guided Munition (ERGM) but that program failed to field an operational round.

Missile systems have similarly reached their pinnacle. Missiles can be made faster than bullets or more agile, but are still be limited by the laws of physics and properties of the materials used in the manufacture of the missile (not to mention engineering and manufacturing limitations). Eventually, using a missile will be a question of economics as it is not financially sustainable to engage a relatively inexpensive rocket propelled grenade (RPG) with a multimillion dollar missile (although the need to defend the potentially multi-billion dollar unit from the RPG does exist). The Standard Missile family continues to be modified and improved from the original SM-1MR put into service in 1967. These missiles have been the main air defense weapon on surface ships since their development and are now used for ballistic missile defense and anti-satellite missions in addition to the traditional air defense mission. The newest Standard Missile, SM-6, has a unit cost of 3.64 million dollars in fiscal year 2012 dollars (Oestergaard 2012).

DEWs offer advantages over conventional weapons by providing attack at the speed of light, precise targeting, rapid engagement of multiple targets, adjustable damage capacity, low operational cost, reduced logistic support, a nearly unlimited magazine, and wide area coverage for offensive and defensive purposes. DEW also seem to be at the forefront of the next revolution in military weapons (Deveci 2012). Unlike conventional kinetic energy weapons, DEWs are minimally affected by the effects of wind and gravity. Because the evolution of conventional weapons has essentially plateaued, there is the potential for our adversaries to close the capability gap and therefore pose a greater threat. The United States must pursue improved technologies to maintain the military edge that it has enjoyed and depended on over the years.

Another problem with DEW is that they are expensive to research and develop. Sunk costs associated with current weapons and ways of thinking, bureaucratic inflexibility, and an inability to institutionally embrace disruptive change could stand in the way of the development and fielding of these highly promising weapons (McGrath, Directed Energy and Electric Weapons Systems (Serial 1) 2012). While these DEW technologies offer tremendous promise, funding spread across multiple programs may threaten the emergence of those that may provide a return on investment of these sunk costs. Navy leadership must make cohesive decisions to focus funding during these budgetary constrained times into only those areas that will provide the greatest benefit. The project will seek out these areas and make recommendations to funnel future funding into producing effective weapons that provided added capability to the warfighter.

The United States is not the only country pursuing DEWs. China, Russia, India, Iran, South Korea, France, Israel, and Germany all have made commitments to and technical progress in DEWs research and development programs (McGrath, Directed Energy and Electric Weapon Systems (DEEWS) Serial 3: China 2012). With these countries actively pursuing DEW technology, the United States may be at risk of suffering technological surprise form the very technologies it originally developed (McGrath, Directed Energy and Electric Weapons Systems (Serial 1) 2012). If the United States is going to continue their global military preeminence, it must continue to seek the military advantage offered by DEWs.

A concise problem statement was formed considering the limitations for conventional weapon improvement, the military potential of DE, and the two aforementioned factors from the tasking statement. The problem is:

> Conventional weapons are nearing their peak technical capability. As a result, Directed Energy Weapons (DEWs) are the next logical step. In the past, DEW technologies have been paralyzed by runaway budgets and sub-optimal performance. Several countries are pursuing DEWs, therefore, it is important for the United States Navy to maintain the upper hand by continuing to research and develop these weapons. However, given the increasing budgetary restraints, U.S. Navy leadership must identify viable short-term DEW technologies that offer an immediate return on investment and the potential for continued development and improvement. DEWs offer the U.S. Navy an avenue to maintain a technological advantage to help defend maritime platforms.

2. Scope

For decades, research has been conducted on the feasibility of employing directed energy in the form of weaponry with hopes of achieving both the potential of “deep magazines,” as well as the prospect for enhanced “force continuum” options. However, the challenges associated with weaponizing directed energy are numerous. They include overcoming atmospheric attenuation, power requirements beyond current shipboard generating and cooling limits, and R&D roadblocks such as beam director quality, energy storage materials (batteries), and cycle time. Since much of the DEW research is very broad in nature, and there are dozens of technologies with various maturity levels. It was necessary for the project team to limit the scope of the project to a manageable level. In the briefest of terms, the scope is to determine the requirements, the concept for operations, and characterize the fielding and operations of a DEW within the next four years.

Like most aspects of the Systems Engineering (SE) Process, the project scope was molded through an iterative process that determined what aspects of DE would be included in the project, as well as those that would not be addressed. Based on initial tasking, we focused on the capability gap faced by unit commanders to address the fast paced nature of force protection scenarios that both limit the amount of time to make informed decisions, and determining the actual intent of a potential adversary. It was the intent of the project sponsor and the NPS faculty to provide an initial tasking that would focus on a specific warfare area that DEWs could potentially improve, thus reducing the overlap from the countless studies that have already been conducted of these weapons. The project team determined the scope of their research was too broad for the timeline of the project, and that Navy specific recommendations were not necessarily explored with adequate depth.

Another feature common across much of the contemporary research is it focuses on what DE could be opposed to what it actually is. Therefore, we decided to focus on a short term perspective, and concentrate on only those technologies that have reached a relevant level of maturity. We achieve this short term perspective by closely examining only those systems that have a built and operationally tested prototype. Our goal is to offer added value to the warfare commander, as well as a return on investment by providing a net result for federal dollars already spent. By added value we mean that a chosen technology must offer a comparative advantage over what already exists, or that it can provide an additional capability to augment how current systems are employed. Instead of focusing on the potential capabilities of future DEWs, we were interested in determining what, if anything, the existing DEW prototypes could accomplish in an operational environment in the near term.

a. In Scope

Since the project was scoped to fielding potential DEWs in the near term, it was necessary to define a notional timeline to guide the DEW from concept of operations to the validation of operational capability. Therefore, the following timeline was considered in selecting those technologies that would be selected for further analysis.

- 12 months to the development of concept of operations
  - Includes a platform specific integration plan, the co-uses, training, logistics, and support
- 24 months to the demonstration of operational utility
- 36 months to initial operational capability
- 48 months to validation of operational capability

This compressed timeline was the driving force behind identifying only those technologies that could potentially be fielded relatively quickly. The project team conducted extensive background research through open source documents to identify the directed energy technologies that have achieved a Technology Readiness Level (TRL) of 6 or higher, which represents a system or prototype that has been demonstrated in a relevant environment. A TRL of 7 represents a system that has been successfully tested in an operational environment. The minimum TRL 6 requirement was essential to ensure that the chosen technologies were able to meet the strict four year timeline.

b. Out of Scope

There are several limitations and constraints with respect to DEW that have influenced what has been scoped out of the project. The limitations of DEWs that were discovered during the background research assisted in further scoping the potential mission areas described. For example, DEWs were not assessed for their potential capability of supporting the Anti-Submarine Warfare (ASW) mission due to high attenuation of the electromagnetic spectrum in an underwater environment as shown in Figure 1 compared to the atmosphere shown in Figure 2.

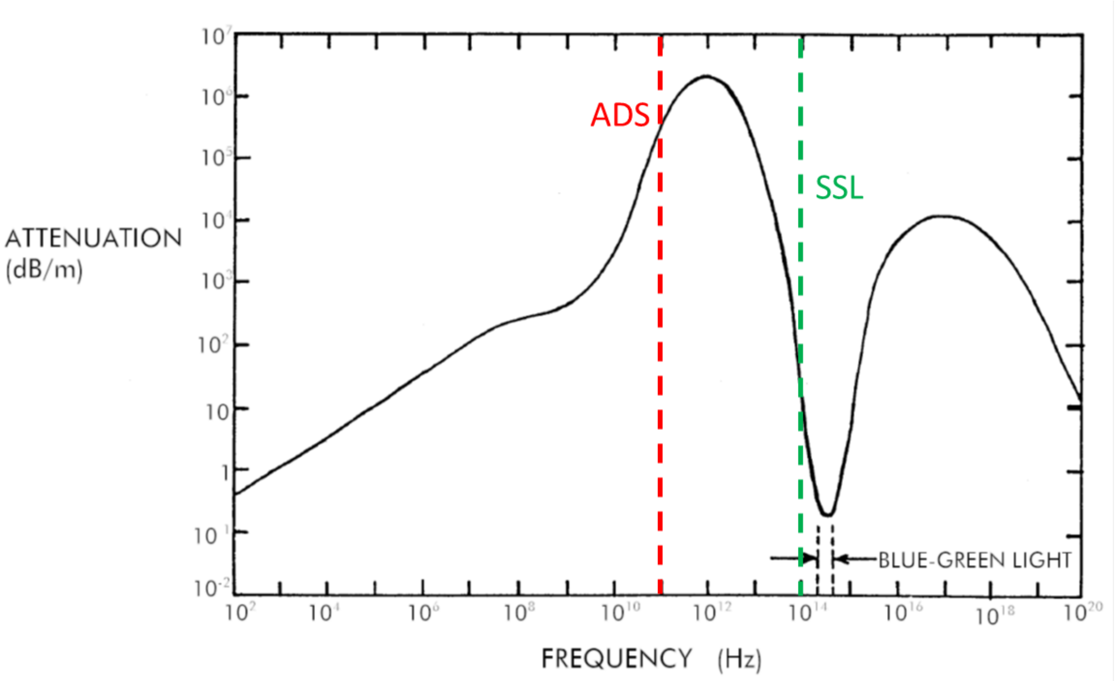

Figure 1. Attenuation of electromagnetic radiation in sea water (after Harney, Combat Systems Volume 1 2004)

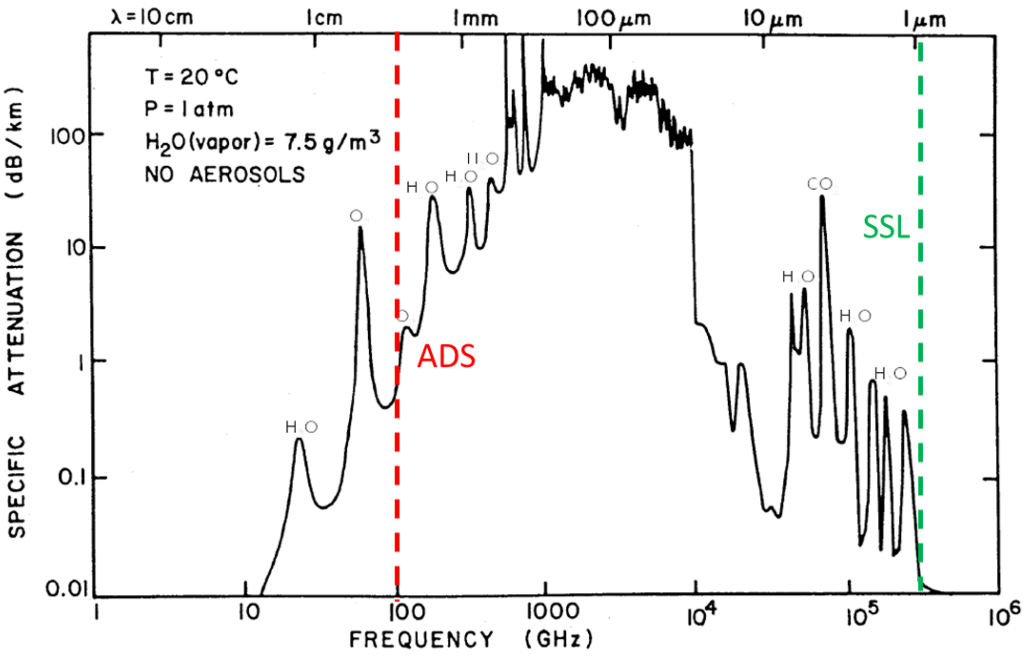

Figure 2. Molecular absorption of the atmosphere (after Harney, Combat Systems Volume 1 2004)

Unlike some conventional weapons, DEWs are limited to line of sight (LOS) operations, thus over-the-horizon firing scenarios were not considered. Due to the design power characteristics of currently fielded DEW prototypes, the technologies designed to provide a Ballistic Missile Defense (BMD) capability were excluded. Similarly, we excluded the evaluation of space-based weapons, in this case largely due to limitations associated with LASER system optics. Through discussions with the project sponsor, the project focus was placed on beams not bombs, and therefore we did not consider Electromagnetic Pulse (EMP) bombs or any variant of this technology.

There are also a number of constraints that have contributed to the scoping of the project. Since the project was a multi-national effort, the obtainment of classified or proprietary data for these systems fell outside the scope of the project. The project group found an acceptable level of open source data to carry out the project.

From a political perspective, DEW technologies whose primary purpose is to blind, or were designed to cause suffering and/or superfluous injuries to enemy combatants were excluded to ensure compliance with Protocol IV of Convention on Certain Conventional Weapons of 1980 (International Committee of the Red Cross 2012). In addition, our project assessment did not concern itself with the politics surrounding the use and/or employment of DEW in the field; however, due diligence will be given to ensure proposed solutions do not violate U.S. or international commitments and treaties.

Due to the inherent size, power, cooling requirements, and limited implementation time of the DEW prototypes only surface combatants were considered with respect to systems integration. Since directed energy weapons operate LOS, all technologies were evaluated and assessed primarily on their ability to provide a defensive capability, and each technology’s offensive capability (as applicable) was not excluded from the analysis, but was given secondary consideration.

We determined that several of the current ships in the fleet could potentially support directed energy weapons, however, by focusing on the mission areas of each platform we narrowed our focus to three platforms. We investigated Cruisers, Destroyers, and the Littoral Combat Ship. The Cruisers were scoped out of the project because they are approaching the end of their life cycle amid talks to decommission those remaining in the fleet in the near term. The Littoral Combat Ship was scoped out of the project since we determined that any system which could operate on a DDG could also operate on a LCS. LCS has four 750 kW generators, two of which will be online at any given time for normal operations (Potts 2013). With 1500 kW of excess power generation capability, there is sufficient excess power to operate any of the potential DEW systems analyzed for this paper, and if required, the mission bay of the LCS could be configured to hold the DEW equipment. DDGs will still make up the bulk of the surface fleet in the next four years, so focusing on installing a DEW on a DDG would have a larger impact Navy wide. Once more LCS get introduced into the fleet and their CONOPS is tested, LCS would be a potential candidate in the future. Therefore, we focused our attention on the integration of these technologies on the Arleigh Burke (DDG-51) Class Destroyer as this appears to be the most probable choice to implement these weapons in the fleet in the near term.

3. Project Approach

The burden of progress implies that new systems should provide either increased capability, or achieve it through more efficient means. Sometimes certain unique capabilities within a mission capability set are gapped. These gaps need to be identified and equipment or doctrine needs to be developed to fill the gap. This project addresses both completing mission areas currently fulfilled by conventional weapons as well as mission areas which do not have a current conventional solution and are therefore gapped.

The lack of standoff non-lethal options within the use of force continuum, particularly applicable to the force protection mission, is one such gap. Current forces have numerous lethal weapons with long (greater than 100m) standoff range such as rifles and crew-served weapons, and several non-lethal options with either short (less than 30m) or no standoff range. Rubber bullets and beanbags fired from pistols and shotguns respectively are the non-lethal option with a short standoff range, while chemical sprays and batons have no appreciable standoff range. Fire hoses can be used in a force protection situation, but greatly lose effectiveness beyond the range of the rubber bullets and beanbags. It should be noted that these weapons are usable against individuals or small groups of people while no non-lethal weapon is in the U.S. Navy arsenal effective against vehicles.

In this non-lethal case, a “gap” exists in the proportional list of responses available to the combatant commander since there are no alternatives options between “warn” and “kill.” Combatant commanders are forced to either do without, or improvise with respect to these gapped capabilities. As a result, the goal for our research project is mission oriented, and more specifically, to ensure that mission capability gaps are adequately evaluated.

With respect to directed energy weapons procurement, Hollywood fiction has biased many individuals by ingraining in them unreasonable expectations. *Iron Man* is a recent example. Developing game-changing technologies would be ideal, but should never be expected in a short period of time. When game-changing technologies are evolutionary, they must be built upon from seemingly less significant technologies. Evolutionary development is the same approach many successful civilian corporations are taking with respect to product development. Staying competitive means not only having the foresight to anticipate trends, but also possessing the ability to evolve current technological capability over time (Burrus 2012). With regards to DE, it is important to remember that directed energy “is what it is,” and more importantly it “is not what it is not.”

Through our research we have identified a short list of technologies with already constructed and operationally tested prototypes. This list was determined by broadly researching numerous DE technologies from chemical LASERs like ABL and THEL, to Microwave Amplification by Stimulated Emission of Radiation (MASERs), to plasma beams and Electromagnetic Pulse (EMP) weapons. Using this large list, the team removed items that fell outside the scope of the project like EMP and sonic weapons. The team then further researched remaining technologies to determine what prototypes have been built and operationally tested at least to some extent. The four technologies which remained were Chemical LASERs (CL), Solid State LASERs (SSL), Free Electron LASERs (FEL), and High Powered Microwaves (HPM). Our objective is to analyze each of the technologies on our short list to determine if they can provide the combatant commander with some sort of advantage.

II. BACKGROUND

A. STATE OF CONVENTIONAL WEAPONS

The concept of skilled aimed fire remains a treasured ability on the modern battlefield. Every new weapon when first introduced must be trained on to hone the skill needed to be employed in battle (Eshel 2012). Precision fire has long been the underlying principle to the exploitation of gunpowder. The Chinese standardized the formula for gunpowder in 1044 CE. However, many innovations were implemented before simple muskets could be used as the standard weapon for most armies. Over the course of six centuries, innovations such as tapered projectiles, advances in the gunpowder formula, and rifling made gunpowder a necessity in every armory (Needham 1986).

Guns continued to advance in terms of accuracy, range, rate of fire, and destructive potential. Increasing the caliber generally increased both the range and destructive potential of a round, while more technological approaches were required for improving the accuracy and rate of fire. Cannons used on land and ships both had to develop before becoming weapons of choice and many of the same innovations that worked to forge muskets into rifles by rifling the barrels greatly improving accuracy and interrupted screw which dramatically improved rate of fire. These upgrades were integrated into their large projectile brethren and made artillery the focus of many land armies and dreadnaughts the prized ship in any fleet throughout most of the 20th century. The pure destructive potential and ability to turn the tide of battle led many historians to regard artillery as the “King of Battle” (McKenney 2007).

Missiles were the next major evolution in trying to create a more destructive weapon. Early missiles in development during World War II helped to add a new dimension to the battlefield (Zaloga 2003). The one major use of rockets was in bombarding London with V-1 and V-2 rockets with limited success. The rocket attacks killed 6,184 people compared to the bomber raids during ‘The Blitz’ which killed over 43,000 (Cleary 2011). Due to the unreliability of the technology, both Axis and Allied forces continued the more dangerous (from the point of view of the attacker) practice of bombing from aircraft vice long range rocket attacks. Using aircraft risked not only bombers, but fighter escorts and the crews for all the planes as well. At that time, aircraft were a much more dependable method compared to long range rocket attacks of delivering the massive amounts of ordnance needed (Corvisier 1994). Leveraging technology from the space program, missile technology greatly improved in terms of speed, payload, and accuracy, making missiles the preferred method of long distance ordnance delivery for current forces (North 2001).

B. STATE OF DIRECTED ENERGY WEAPONS

There are numerous examples of functional DEW projects in that have been built and "operate as designed." Although some of the technologies have achieved significant milestones such as having prototypes built and achieving operational demonstrations such as the ABL and THEL, DE has never been able to attain priority status with respect to conventional weapons in their designated roles in military operations. It would appear decision makers do not want to invest in a system unless it replaces an existing system or fulfills a capability gap. ABL and THEL are examples of this of systems which had traction due to the ballistic missile defense (BMD) gap. From the perspective of plug and play, a lack of mission needs, misguided expectations, or conventional systems that just perform better have stood in the way of successful DE programs. For example in the 1980s, President Ronald Reagan's Strategic Defense Initiative, more commonly referred to as "Star Wars," nearly brought directed energy technology to the forefront of weaponry research. Legal complications coupled with a diminishing Soviet threat caused the program to be canceled and resources diverted to other priorities (Correll 2012). Unfortunately, "Reagan did not understand the science of missile defense and the quality of advice he was getting as spotty" (Correll 2012). Concurrently, the U.S. Air Force had been working on a revolutionary ABL Laboratory project, putting a chemical type LASER aboard a wide-body airframe with the objective of shooting down enemy missiles. "It had to face numerous operational challenges, such as the need to fly above hostile territory waiting for target missiles to be launched and to focus its LASER at a single point on a moving missile" (Collina and Davenport 2012). Appropriations shortfalls, poor test results, and significant doubts as to Star Wars' operational viability resulted in significant concerns over the program’s future. Eventually, the 16-year and $5 Billion effort was cancelled (Collina and Davenport 2012).

The lesson learned from numerous failed DEW programs is that both a clearly identified need and reasonable expectations based on credible scientific knowledge are necessary precursors required to generate momentum for DEW projects. In addition, technologies must be relevant to the current trends prevalent throughout the services, the Navy in the case of this project. After initial background research was conducted on various DE programs, four technologies were deemed as plausible for shipboard use by the project team. Solid State LASERs (SSL), Chemical LASERs (CL), High Powered Microwaves (HPM), and Free Electron LASERs (FEL) were identified as either having current prototypes in testing (several SSLs and HPM), programs which were successfully tested but canceled (several CL), or programs which are nearing the operational prototype phase (FEL). These four technologies and specific programs are detailed below.

1. Solid State LASER (SSL)

a. Technology History

Solid state LASERs have evolved over the years and several uses have been found for military application. The first LASER was built in 1960 by T. Maiman and utilized a synthetic ruby rod with mirrors on both ends (one semitransparent) pumped with a helical xenon flash lamp surrounding the rod. The result was an intense pulse of coherent red light at 694nm. This early ruby LASER system output contained irregular spikes that stretched over the duration of the pump pulse. This problem was improved in 1961 by R.W. Hellwarth with a method called Q-switching which concentrated the output of the ruby LASER into a single pulse. However, the Q-switch consisted of a cell filled with nitrobenzene and required very high voltages. The Q-switch was soon replaced by spinning one of the resonator mirrors, and a further refinement was the insertion of a spinning prism between the fixed mirrors of the resonator. One of the earliest applications was in LASER range finding, which operated by measuring the time-of-flight of LASER pulse reflected from a target and calculating the distance (Koechner and Bass 2003).

In 1964 the best choice of a host for neodymium ions (Nd), namely yttrium aluminum garnet (YAG), was discovered by J. Geusic. Nd:YAG has a low threshold of excitation which permits continuous operation, and the host crystal has good thermal, mechanical, and optical properties. High Purity Nd can be grown with relative ease (Koechner and Bass 2003). Since its discovery, Nd:YAG remains the most versatile and widely used active material for solid-state LASERs and immediately replaced the ruby in the military rangefinder application (Koechner and Bass 2003).

During the 1970s, efforts were concentrated on engineering improvements, such as an increase in component and system lifetime and reliability. The early LASERs often worked poorly and had severe reliability problems. At the component level, damage resistant optical coatings and high-quality LASER crystals had to be developed; and the lifetime of flash lamps and arc lamps had to be drastically improved (Koechner and Bass 2003). On the system side, the problems requiring solutions were associated with water leaks, corrosion of metal parts by the cooling fluid, deterioration of seals and other parts in the pump cavity due to the ultraviolet radiation of the flashlamps, arcing within the high-voltage section of the LASER, and contamination of optical surfaces caused by the environment (Koechner and Bass 2003). Also during this time, improvements were made in the performance of diode LASERs. Solid State LASERs started moving out from being research tools in laboratory settings into industrial use as machining tools and medical instruments (Koechner and Bass 2003).

During the 1980s with the discovery of alexandrite, titanium-doped sapphire, some solid state LASERs became tunable between 660 and 980 nm. Improvements to diode LASERs provided devices with longer lifetimes, lower threshold currents and higher output powers, and were capable of continuous operations at room temperatures. Since the early LASER diodes were very expensive, their use as pump sources could only be justified where diode pumping provided an enabling technology. Therefore, the first applications for diode-pumped Nd:YAG LASERs were for space and airborne platforms, where compactness and power consumption is of particular importance (Koechner and Bass 2003). The evolution of diode pumping solid state LASERs offers significant improvements in overall systems efficiency, reliability, and compactness (Koechner and Bass 2003).

The evolution of the solid state LASERs over the past several decades has resulted in the design and weaponization of these LASERs for military use. A SSL DEW contains four major components: a tracking subsystem, a LASER subsystem to contain the medium which generates the LASER beam, a beam director with stabilizer through which the LASER is fired, and a fire control computer interface. While some programs have been cancelled for various reasons, several still exist and possess the potential to change how the United States fights and wins our Nation's wars.

b. Programs

(1) LASER Weapon System (LaWS). The LASER Weapon System (LaWS) was built by Raytheon and has reached a technology readiness level (TRL) of 6 and has been operationally tested (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2012). A 33kW continuous wave (CW) operational prototype shown in Figure 3 is currently installed on the USS Dewey (DDG-105) and has achieved a near perfect record in shooting down UAV's and stopping small boats. The Navy stated the following regarding tests of LaWS:

> In June 2009, LaWS successfully engaged five threat-representative UAVs in five attempts in tests in combat-representative scenarios in a desert setting at the Naval Air Weapons Station at China Lake, in southern California (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2012).
>
> In May 2010, LaWS successfully engaged four threat-representative UAVs in four attempts in combat-representative scenarios at a range of about one nautical mile in an over-the-water setting conducted from San Nicholas Island, off the coast of southern California. LaWS during these tests also demonstrated an ability to destroy materials used in rigid-hull inflatable boats (RHIBs) at a range of about half a nautical mile, and to reversibly jam and disrupt electro-optical/infrared sensors (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2012).

Figure 3. Photograph of LASER Weapon System (LaWS) Prototype (from O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2012)

While there is discussion that the LASER may be capable of conducting ASCM, the capability has yet to be proven. The Navy has envisioned LaWS being used for operations such as disabling or reversibly jamming electro-optical (EO) sensors, countering Unmanned Aerial Vehicles (UAVs) and EO guided missiles, and augmenting radar tracking (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2012). The system’s unclassified operating characteristics are 5 sec on/5 sec off for 4 minutes followed by a 16 minute recharge down time and uses the ship’s electrical plant to charge in normal underway power configuration of two generators (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2012). The 33kW prototype currently utilizes lead acid batteries, although the goal is to go to lithium ion which will reduce the overall battery size by 2/3 making shipboard integration easier (Chernesky 2012).

According to the Deputy Program Manager of the Naval Directed Energy Program Office PMS-405, this program has been given the green light by

NAVSEA 05 and a 125–150 KW LASER has been determined to be technically feasible to be fitted onto a DDG-51 class ship, and integrated into LCS-4 and LCS-5 classes (Chernesky 2012). All blueprints and technical drawings currently exist to facilitate this installation with both lead acid and lithium ion batteries. The system is comprised of 95% Commercial off the Shelf (COTS) technology (Chernesky 2012).

(2) Maritime LASER Demonstration (MLD). The Maritime LASER Demonstration (MLD) (Figure 4) is the marine variant of Northrop Grumman's Joint High Power Solid State LASER (JHPSSL) the "Firestrike." The JHPSSL was funded in 2006 for Phase 3 of the project by the Office of the Assistant Secretary of the Army for Acquisition, Logistics, and Technology, Office of the Secretary of Defense – High Energy LASER Joint Technology Office, Air Force Research Laboratory, and the Office of Naval Research. Program execution was conducted by the U.S. Army Space and Missile Defense Command / Army Forces Strategic Command. The U.S. Navy awarded Northrop Grumman with a $98 million contract for the Maritime LASER Demonstration and it has reached a technology readiness level (TRL) of 7 (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2012).

Figure 4. Photograph of the Maritime LASER Demonstration (MLD) (from Angell 2012)

The MLD combines the electric LASER module technology from the JHPSSL with a purpose designed beam-control and fire-control system. The MLD module technology consists of stackable 15kW units that can be phase controlled and combined into a single beam to increase the output power. In 2009, Northrop Grumman became the first U.S. company to reach the 100kW power level threshold with this LASER, which measured at more than 105kW by stacking seven 15kW units. Although mission dependent, many consider power requirements of 100kW or greater to classify the LASER as weapons grade (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2012). There is no open source data detailing the maximum number of 15kW LASERs that can be stacked, but this could affect the scalability of the system. The following are the test and evaluation milestones of the Maritime LASER Demonstration.

- In July 2010, the ability of MLD to track small boats in a marine environment was tested at NSWC Port Hueneme, CA (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2012).
- In late August and early September 2010, MLD was tested in an over-the-water setting at the Navy's Potomac River Test Range against stationary targets, including representative small boat sections (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2012).
- In November 2010, an at-sea test of the system against small boat targets reportedly was stopped midway because one of the system's components needed to be replaced. The test was resumed in April 2011 (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2012).
- On April 6, 2011, the system successfully engaged a small target vessel. According to the Navy, this was the first time that a LASER of that energy level had been put on a Navy ship, powered from that ship, and used to counter a target at range in a maritime environment (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2012).
- In May 2011, Northrop stated that it could build the first unit of a full-power engineering and manufacturing development (EMD) version of the weapon within four years, if the Navy could find the resources to fund the effort (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2012).

The MLD test platform for the April, 2011 testing was accomplished from the former USS PAUL FOSTER, a decommissioned Spruance Class Destroyer where it was integrated into the ship's radar and navigation systems, as well as the ship's electrical system. The MLD demonstrated the ability the disable a small boat in actual maritime conditions of 8 ft. waves, 25kt winds in both rain and fog (Northrop Grumman 2012).

(3) Tactical LASER System (TLS). The Tactical LASER System (TLS) has a beam power of 10kW and is designed to be added to the Mk 38 25 mm machine guns installed on the decks of many Navy surface ships. A rendering of the TLS mounted system is shown in Figure 5. TLS would augment the Mk 38 machine gun in countering targets such as small boats and could also assist in providing precise tracking of targets (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2012). The TLS program is a collaborative effort between Boeing and BAE where full system testing was expected to take place in the summer of 2012. This test was intended to target surface and air targets but permission was not granted in time for the targeting of UAVs. The test resulted in successful engagements of the surface targets at "several thousands of meters" but was not tested against air targets (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013).

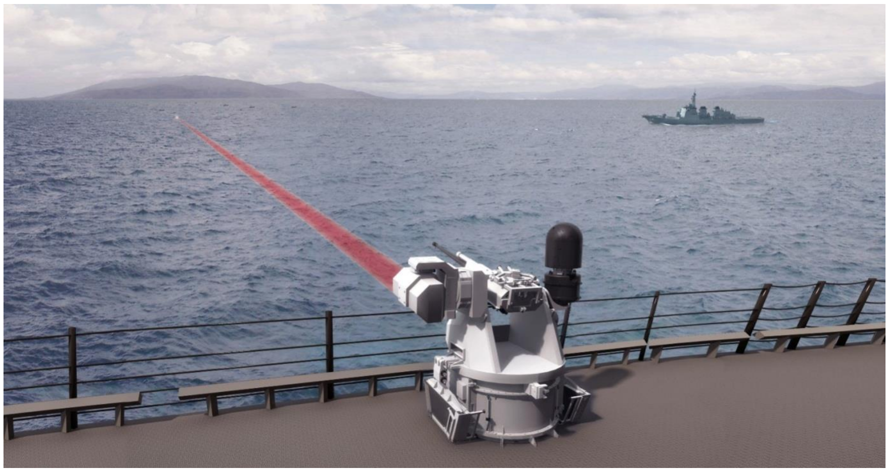

Figure 5. Rendering of Tactical LASER System (TLS) Integrated on Mk 38 Machine Gun Mount (from O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2012)

2. Chemical LASER (CL)

a. Technology History

Chemical LASERs were first conceived over fifty years ago. Canadian chemist J.C. Polanyi (Superstars of Science 2011) first proposed the idea of chemical based LASERs in 1961 (Lin 1983). The hypothesis was that a chemical reaction of excited elements would create an infrared LASER. The chemicals could be excited by light, heat, or electricity. A reaction of hydrogen atoms with ozone or chlorine could be used to create an infrared LASER. Then that LASER could be amplified to create a useable beam (Lin 1983).

The first chemical LASER demonstration would come 3 years later in 1964. Jerome Kasper and George Pimentel were able to optically pump Hydrogen Chloride (HCl) to create a suitable LASER. Pimentel and others continued their experiments throughout the 1960s to expand the chemicals that could produce a LASER. Hydrogen Fluoride (HF) and Deuterium Fluoride (DF) were quickly demonstrated as viable as well (Pimentel 1965).

Through continued experimentation other elements were found to be able to produce LASERs such as the Chemical Oxide Iodine LASER (COIL). The following chemicals also produced LASER: Cyanide (CN), Nitric Oxide (NO), Carbon Monoxide (CO), and Hydrogen Bromide [Deuterium Bromide] (HBr [DBr]) (Lin 1983). The most reliable forms for chemical LASERs are HF, DF and COIL (Kopp 2008). There are three types of initiation for a chemical LASER:

- Vibrational: The oldest and most established method of making a LASER. Mixing the elements in a cavity to create a reaction. Sometimes using a pump to vibrate the elements. Then focusing that reaction to create the LASER (Lin 1983).
- Rotational: Here the elements are in a chamber that rotates to mix them. Just like with vibrational, the mixing creates a reaction. And the reaction is focused to make a LASER (Cohen, et al. 1986).
- Electronic: The newest method of creating a LASER. Elements are bombarded by electrical impulses. The product of the electrical reaction creates the LASER (Basov, et al. 1989).

Chemical LASERs currently have the capability to deliver kilowatts of power over long ranges. There is potential for delivering megawatts, but is unrealized at this time. The weapons focus has been achieving kilowatts of power that will destroy targets at a distance. The one major difference between a SSL and a CL DEW is the medium in which the beam is generated, the other major components remain the same.

b. Programs

(1) Mid-Infrared Advanced Chemical LASER (MIRACL). Mid-Infrared Advanced Chemical LASER (MIRACL) is a DF LASER that was developed by the U.S. Navy and has been operational since 1980. It was cancelled by the Navy in 1983, but since 1990, U.S. Army Space and Strategic Defense Command has maintained the MIRACL (Sherman 1998).

The MIRACL has a very strong beam quality to be used against target in flight. It operates at a wavelength of 3.8 microns and can lase for 70 seconds continuous on a single target. It has been tested against both flying drones including the BQM34 and missiles such as the VANDAL missile (Sherman 1998).

(2) Airborne LASER (ABL). Airborne LASER (ABL) is a COIL in a 747 developed for the Air Force by Boeing in 1996. The first flights were conducted in 2003 with the entire systems configured. From 2008 to 2010; Boeing conducted testing using the system (FAS 2010).

The ABL was created to be used against missiles. It operates at 1.315 microns wavelength (FAS 2010). It can lase its target for three to five seconds on the target after a solid state LASER acquires the target. The COIL has been tested against an NC-135E (Grill 2007). It has also been tested against missiles with great success (Cadena and Selinger 2009) (MDANews 2010).

(3) Airborne Tactical LASER (ATL). Advanced Tactical LASER (ATL) is a COIL in an AC-130 aircraft developed for the Air Force by Boeing in 1996. The first flight testing was conducted in 2005. In 2009, it was adapted to fit into a MV-22 aircraft as well. The testing for the ATL was conducted from 2005 -2010 (Global Security 2011).

The ATL was created to attack ground targets. It operates at 1.315 microns wavelength (Alexander 2003). The ATL can generate between 100–300 kW for five seconds (Global Security 2011). When there is not excessive attenuation, the range can increase to 20 kilometers (Hambling, New Scientist 2008). ATL has been used to defeat ground targets (Wallace 2009).

(4) Tactical High Energy LASER (THEL). Tactical High Energy LASER (THEL) is a truck and trailer based weapon developed for the U.S. and Israel by TRW (now part of Northrop Grumman) in 1996. The THEL was ready for use in 1998. It was tested in 2002 (Pike 2011).

The THEL was created to defend against missiles, rockets, artillery shells, and aircraft. The THEL operates at 3.8 microns wavelength. The THEL has lased long enough to destroy Katyusha rockets, artillery shells, and mortar shells (Kopp 2008).

3. High-Power Microwave (HPM)

a. Technology History

Research into the use of microwaves began with studies of radio frequency technology, specifically for communication purposes (Morrison 2008). Microwaves were artificially created by Heinrich Hertz in 1888. The invention of gridded tubes brought about the use of radios in the early twentieth century. Using resonant cavities connected to electrical circuits, researchers discovered how to create higher frequencies (Benford, Swegle and Schamliglu 2007). Higher frequencies were sought after once it was discovered that they are more advantageous in terms of the amount of information they could carry (T. Williams 2011). Assuming amplitude modulation to carry the data, the bandwidth (amount of data able to be carried) is increases at twice the rate of the frequency (Harney, Combat Systems Volume 1 2004).

Early physicists believed that electromagnetic waves could be powerful sources used to take down aircraft. Research in this field led to the creation of radar systems in the 1930s (Guoqi, Benqing and Lu 2005). During World War II, several developments such as extrapolation of the magnetron, invention of the traveling wave tube, and invention of the backward wave oscillator (BWO) spurred growth in the field.

Moreover, significant developments in regards to High-Powered Microwaves (HPM) occurred from the investigation of nuclear power effects, specifically in regards to the interaction of waves and particles.

Part of the future generation of abundant nuclear power involves controlling the nuclear fusion (as opposed to fission) process. Research into how electromagnetic wave stimulation could support the fusion process fostered a better understanding of how waves and particles interact in the production of thermonuclear power (Benford, Swegle and Schamliglu 2007). This fusion research coincided with developments of pulse power technology with focus on generating and emitting strong electronic beams (Guoqi, Benqing and Lu 2005).

In terms of weaponry, HPM roots are traced back to the technology race between the Soviet Union and the West. Development has gone from first electromagnetic bomb testing in 1962 to more recent developments in crowd control technology (Weinberger, High-Power Microwave Weapon Systems Start to Look Like Deadend 2012).

HPM weapons are designed to exploit parts of the electromagnetic spectrum in order to neutralize targets. Through concentrated radio waves, HPM weapons transmit high amounts of energy which can be used to disrupt electronic equipment or produce devastating biological effects. HPM weapons consist of three main components. These components are a pulse power source, a high power microwave source, and an antenna (Benford, Swegle and Schamliglu 2007).

The pulse power source drives the HPM weapon by generating a highly amplified electronic pulse. There is a variety of pulsed power types which include modulators, Marx-generators, pulse forming lines (PFL), pulse forming networks (PFN), and inductive energy storage in combination with opening switches. Normally, the pulse components are connected in series with other pulse components, i.e., a Marx-generator in series with a PFL (Benford, Swegle and Schamliglu 2007).

The HPM source acts as the heart of the weapon converting the energy of the electronic pulse into electromagnetic form, specifically into microwaves. The interface between the pulse power source and the HPM is extremely important because if the impedances of the pulse source and HPM are not properly matched then power losses could occur. As a result, this interface determines the size and mass of the overall system (Benford, Swegle and Schamliglu 2007). The HPM source has other components designed for support, such as vacuum pump, magnet, a collector for capturing the beam, and cooling system. Finally, the antenna is the physical interface between the atmosphere and the microwaves. The antenna directs the beam at targets. Source parameters influence the connection to the antenna, most notably the waveguide mode (Benford, Swegle and Schamliglu 2007). The waveguide mode is responsible for transmitting the electromagnetic waves. Characteristics of the antenna such as frequency, power, directivity, and gain influence the output beam propagation. These characteristics determine the bandwidth, signal strength, power efficiency, and the amount of beam spreading (antenna-theory.com 2011).

These components come together to produce a system that uses directed energy to produce weaponry capable of engaging targets in a non-lethal manner. Traditional non-lethal weapons use kinetic energy (rubber rounds or bean bags for example) which still have chance to kill or permanently injure the target if hit in specific areas (eyes or throat for example). HPM poses a lower risk of accidental lethal exposure compared to kinetic non-lethal weapons. However, HPM weapons affect personnel in the same manner and have a greater range than most small arms which can be useful in open areas (DOD Non-lethal Weapons Program 2007).

b. Programs

The Active Denial System (ADS) is designed as a nonlethal crowd dispersal weapon. The system works by focusing wave energy in the form of a beam. This beam produces a powerful heat sensation when directed at targets causing them to move away instinctively. The beam is composed of millimeter waves at a frequency of 95GHz. These waves are able to penetrate human skin up to 1/64 of an inch which is roughly about three sheets of paper. Due to this shallow penetration, there is minimal risk of severe permanent injury (although lasting minor injuries to nerves, fat cells, and ducts are possible). In addition, the effects of the weapon cease when a target moves out of the way of the beam (Air Force Research Laboratory 2006).

Operational testing of ADS involved a series of Joint Military Utility Assessments (JMUA) conducted over an 8 month period beginning in 2005 (LeVine 2009). The first JMUA tested the system 1 version of the technology which is composed of the HPM weapon system attached to a Humvee. Personnel from the Marines, Air Force, Coast Guard, Army, and Border Patrol operated the system in a series of urban terrain and entry control point scenarios in order to evaluate its performance (LeVine 2009). The first test was conducted at Creech Air Force Base in August 2005 and resulted in the ADS system achieving 914 hits off of 657 shots due to the use of beams.

The second JMUA test was conducted in Fort Benning, GA and included testing the system in search and rescue, entry control point, and perimeter security scenarios. This JMUA test resulted in 1473 hits off of 979 shots (LeVine 2009). And, the third JMUA conducted tests of the system in port and harbor environments. JMUA 3 was conducted in 2006 at Santa Rosa Island, Eglin AFB FL and focused on force protection missions in port. Scenarios included boat-on-water iterations and pier side security demonstrations. JMUA 3 was the first time the ADS system carried out live fire scenarios over water. JMUA 3 resulted in 474 hits off of 305 shots.

In all three assessments, the consensus by operators and test evaluators was ADS has military utility and is highly effective as a non-lethal counter personnel weapon (LeVine 2009). Following these assessments the ADS system was certified for deployment with hopes of it being used against insurgents in Iraq. Eventually, it was deployed to Afghanistan in 2010; however, the weapon was not used due to potential public scrutiny issues (Fortin 2012).

4. Free Electron LASER (FEL)

a. Technology History

In 1971, John Madey invented and developed the Free Electron LASER (FEL) that generates a relativistic electron beam in an open optical cavity resonator. Madey, at Stanford University, measured gain from an FEL configured as an amplifier at 10-µm wavelength, which was an important step in FEL development. This experiment, and the successful operation of the same FEL configured as an oscillator in 1977 at 3-µm wavelength, created a large interest in FEL research. Two important FEL attributes, tunability and design flexibility, were demonstrated by these two experiments at significantly different wavelengths using the same apparatus (National Research Council 1994). FEL's differ from conventional LASERs in that they use an electron beam as the lasing medium rather than a gas or a solid. The FELs are usually based on the combination of a linear electron accelerator followed by a high-precision insertion device, which may also be placed in an optical cavity formed by mirrors. Under certain circumstances, the accelerated electrons in the insertion device bunch together more tightly than usual (also known as microbunching). Over the length of the insertion device or during multiple passes back and forth through the optical cavity, the electrons in the microbunches begin to oscillate in step, thereby giving rise to light with properties characteristic of conventional LASERs. Because the microbunches are so spatially small, the light generated presents as in ultrashort pulses that can be used for strobe-like investigations of extremely rapid processes. Current FEL's cover wavelengths from millimeter through infrared and are nudging into the visible (Jefferson Lab 2005).

b. Programs

FEL currently has a technology readiness level (TRL) of 4 which is defined as component and/or breadboard validation in a laboratory environment (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2012). There are numerous FEL facilities across the U.S., with the Thomas Jefferson National Accelerator Facility having the most advanced FEL technology. The Office of Naval Research (ONR) is currently overseeing the development of FEL technology.

C. DIRECTED ENERGY AND CONVENTIONAL WEAPON COMPARISON

Dating back to the 1950s, science fiction films captivated audiences with tales of futuristic weapons that had unlimited capability. These weapons could project beams of light capable of disintegrating intended targets as in 1951's *The Day the Earth Stood Still*. Soon after when Charles Townes and Arthur Schawlow published designs for a LASER in 1957 with the first one built three years later, this Hollywood fantasy became real, although unweaponized (Salisbury 1999). Past fantasies of futuristic weapons are soon becoming reality due to advancements in DE technology namely increased power levels, tracking abilities, and miniaturization. These advancements along with advantageous aspects of DEWs make them attractive alternatives to current conventional weapon systems.

DEWs can provide multiple benefits to the warfighter. Speed of light engagements and deep magazines are the two most eye catching capabilities of DEWs. DEWs have the potential to equip the U.S. military with the ability to have a high depth-of-fire with speed of light delivery, allowing a more powerful means of self-defense. Moreover, the variability of the energy level provides graduated lethality with minimum collateral damage and a low cost-per-engagement when compared to the projectile and logistics support costs of conventional explosive or kinetic munitions. Against specific low-value, light-armored targets (UAVs or small boats for example) DEWs have the potential to be an effective alternative to the use of expensive missile systems. Ultimately, DE weapons can provide speed-of-light and precision engagements against high speed vessels, complex ASCMs, swarm attacks, and slow speed aircraft.

Despite the benefits of DE weapons, there are some drawbacks to their employment. Due to the technology being relatively new, there are still concerns over the reliability of DE weapons in an operational environment. Conventional gunpowder weapons have been reliable since the advent of percussion caps in the mid-1800s. For this reason, many military decision makers are hesitant to replace current conventional systems with unproven DEWs. In addition, conventional weapons currently have a greater range than directed energy weapons due to not being constrained by line-of-sight and do not require nearly the power levels of DEWs. Due to atmospheric attenuation, the range of directed energy weapons can be considerably degraded, especially in poor weather conditions. Although weather affects current radar and targeting systems, kinetic rounds are not hampered by rain. As a result of atmospheric attenuation, there is no guarantee that the DE impinging on the target will be of sufficient intensity to cause expected damage despite being projected at the speed of light. Furthermore, many DEW must be charged prior to use (SSL or the cooling requirement of HPM for example) which requires a significant power source compared to conventional weapons which must be loaded but then can generally remain ready to fire for extended periods of time.

Despite the aforementioned drawbacks to DEWs, it is worthwhile to the U.S. military to achieve DEW superiority on the battlefield. The capability of having a near limitless magazine and the ability to conduct speed of light engagements are very enticing. Additionally, since DEWs are still in their infancy, there are considerable opportunities for improvement. On the other hand, conventional weapons have reached their peak capability and any major performance breakthroughs are not expected.

Table 2 shows many of the advantages and disadvantages of the various LASER technologies considered for this project. Additionally, power efficiency can be a problem with large scale DEWs. SSLs have power efficiencies between 20–30% with LaWS at ~ 25. For LaWS to achieve the current output of 33kW, 130kW would have to be provided.

Table 2. Comparison of LASER Types (from Deveci 2012)

Type of Laser	Wavelength	Advantages	Disadvantages
HF	2.7 - 3.3 µm	Most Developed Megawatt level	Size and Weight Safety requirements Sophisticated logistics
DF	3.3 - 4.2 µm		
COIL	1.3 µm		
SSL	1.06 µm	Less complex Compact Less sensitive to shock Low electric energy requirements High efficiency	Cooling problem Kilowatt level
FEL	Tunable	Selectable wavelength	Most complex Kilowatt-level limits Large Systems

III. SYSTEMS ENGINEERING PROCESS

A. APPROACH

The approach to solving the problem of defending maritime platforms with DEW previously identified in Chapter I started with identifying what the U.S. Navy is required to do. We used the Universal Naval Task List (UNTL) as a way to identify key needs at a general level for the Navy. The UNTL is a functional decomposition of warfare areas, which can be mapped back to the Department of Defense-wide Universal Joint Task List (UJTL). In order to determine the Naval Tasks that might be applicable to DEWs, the assumption was made that the only limiting factors for DEWs at this phase was the laws of physics (restricting the missions by available prototypes came later and were being researched concurrently). By only considering the theoretical physical limitations of DEWs, a list was made of the UNTL mission area requirements where DEWs could have some role (even if that role was very small or better fulfilled by conventional weapons).

B. METHOD

Specific mission requirements that rolled up into the warfare area requirements also had to be determined. For example: the UNTL lists “attack air targets” as a requirement, which includes shooting down missiles and aircraft. This UNTL requirement is the Navy’s Air Warfare area under which many specific missions reside. To determine the specific mission requirements, an evaluation similar to that of the UNTL was made of the Navy’s Required Operational Capabilities (ROC) and Projected Operating Environments (POE) document as well as the Surface Force Training Manual (SFTM) for Anti-Terrorism/Force Protection (AT/FP) Critical Capability Requirements (CCRs), where the ROC/POE was silent in that regard. Like was done with the UNTL, a determination of which missions had potential DEW applicability (only based on the laws of physics, the specific abilities of current DEW prototypes would come later) was made and then those specific missions were mapped back to the UNTL requirements.

Figure 6 describes the process of mapping needs to tasks to missions. This process was an iterative process due to revisions to the continued scoping of the problem statement, continued project team research on available DEW prototypes, and the eventual selection of specific prototypes to be analyzed. These iterations in scoping the project required several re-evaluations of the described mapping process in order to ensure that the mapping process continued to match the problem statement and project goals.

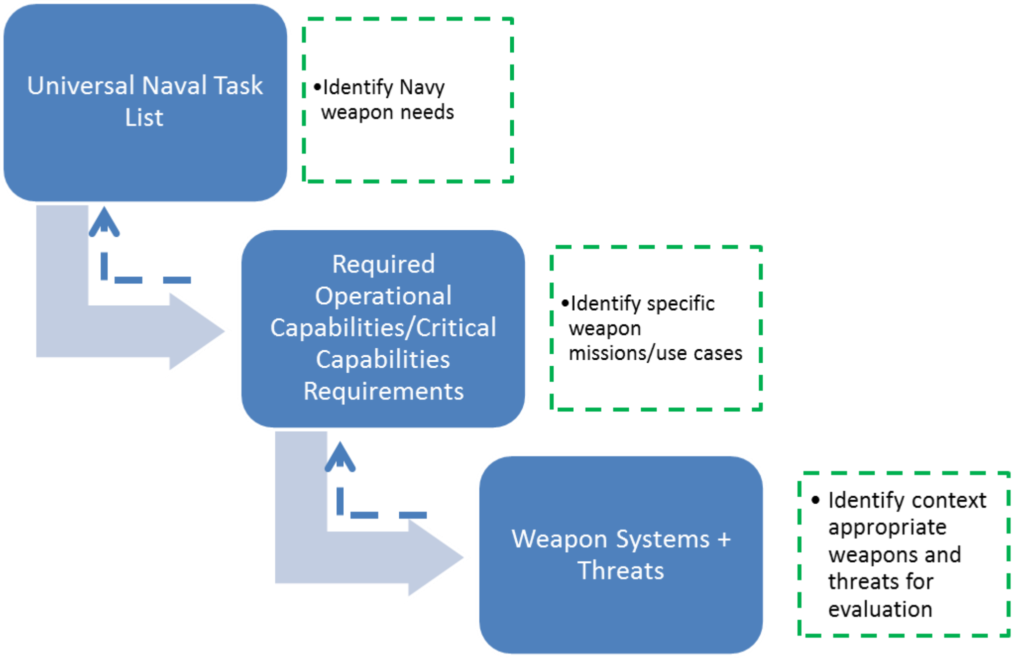

Figure 6. Navy Needs to Weapon Mapping Concept

Following our mapping process, the mission areas where DEW can have a theoretical impact (based on the laws of physics) is shown in the following mapping:

- NTA 3: Employ Firepower
    - NTA 3.2.1 Attack Enemy Maritime Target
        - NTA 3.2.1.1 Attack Surface Targets
            - SUW 1.6 Engage surface ships with DEW
            - SUW 1.10 Conduct close–in surface self-defense using crew operated DEW
            - SUW 2.2 Conduct SUW to support surface forces

        - SUW 2.3 Engage surface targets with assigned anti-surface sector
- NTA 3.2.2 Attack Enemy Land Targets
    - AMW 14.3 Conduct direct fire
- NTA 3.2.3 Attack Enemy Aircraft and Missiles
    - AW 1.1 Provide area defense for a strike group
    - AW 1.2 Conduct air self-defense using DEW
    - AW 1.4 Provide area defense for a convoy or underway replenishment group
    - AW 1.5 Provide area defense for amphibious forces in transit and in the amphibious objective area
    - AW 1.6 Provide area defense for a surface action group
    - AW 1.7 Engage air targets during joint/group operations
    - AW 1.10 Provide sea-based theater BMD for Navy area
    - AW 1.12 Provide air defense for non-combatant evacuations operations
    - AW 1.13 Provide air defense for naval/joint/combined TF operations
    - AW 2.1 Provide air defense of a geographic area (zone)
    - AW 9.1 Engage medium/high altitude, high-speed airborne threats with DEW
    - AW 9.3 Engage low altitude threats with DEW
    - AW 9.4 Engage low/medium altitude airborne threats with DEW
    - AW 9.5 Engage airborne threats using installed anti-air weapons
    - AW 9.6 Engage airborne threats utilizing soft-kill weapons systems (e.g., chaff/decoys)

    - NTA 3.2.4 Suppress Enemy Air Defenses
        - AMW 14.3 Conduct direct fire
        - IO 2.2 Conduct electronic jamming of target acquisition/target tracking/fire control/missile seeker radars
        - IO 2.3 Conduct electronic jamming of communications/data link/ identification systems
    - NTA 3.2.5 Conduct Electronic Attack
        - NTA 3.2.5.1 Conduct C2 Attack
            - IO 2.2 Conduct electronic jamming of target acquisition/target tracking/fire control/missile seeker radars
            - IO 2.3 Conduct electronic jamming of communications/data link/ identification systems
    - NTA 3.2.9 Conduct Non-Lethal Engagement
        - ATFP CCR 12 Pier Demonstration/Passive Protest Exercise
        - NCO 19.6 Conduct seizure of noncombatant vessels
        - NCO 19.9 Conduct drug traffic suppression and interdiction operations
        - NCO 19.13 Support enforcement of fisheries law and treaties
        - NCO 19.15 Support drug traffic suppression and interdiction operations
        - NCO 19.16 Support illegal entry suppression operations
        - NCO 33.1 Operate as chokepoint patrol unit
- NTA 6: Protect The Force
    - NTA 6.1 Enhance Survivability
        - NTA 6.1.1 Protect against combat area hazards

- NTA 6.1.1.1 Protect Individuals and Systems
- NTA 6.1.1.2 Remove Hazards
  - NTA 6.1.1.2.1 Conduct Explosive Ordinance Disposal
- NTA 6.2 Rescue and Recover
  - NTA 6.2.2 Conduct Personnel Recovery
    - NTA 6.2.2.2 Perform Combat Search and Rescue
      - FSO 6.1 Support/conduct combat/noncombat SAR operations by fixed or rotary wing aircraft
      - FSO 6.2 Conduct combat/noncombat SAR operations by surface ships
    - NTA 6.2.2.3 Conduct Tactical Recovery of Aircraft and Personnel
      - FSO 6.1 Support/conduct combat/noncombat SAR operations by fixed or rotary wing aircraft
      - FSO 6.2 Conduct combat/noncombat SAR operations by surface ships
- NTA 6.3 Provide Security for Operational Forces and Means
  - NTA 6.3.1 Protect and Secure Area of Operations
    - NTA 6.3.1.1 Establish and Maintain Rear Area Security
    - NTA 6.3.1.2 Protect/Secure Installations, Facilities and Personnel
    - NTA 6.3.1.3 Provide Harbor Defense and Port Security
      - NCO 33.1 Operate as chokepoint patrol unit
    - NTA 6.3.1.4 Protect Lines of Communication
    - NTA 6.3.1.5 Establish and Enforce Protection Perimeter

        - NTA 6.3.1.6 Conduct Surveillance Detection Operations
            - NCO 45.8 Conduct surveillance and interdiction operations of swimmers/swimmer delivery vehicles
    - NTA 6.3.2 Conduct Military Law Enforcement Support (Afloat and Ashore)
        - NTA 6.3.2.2 Maintain Law and Order
            - NCO 19.6 Conduct seizure of noncombatant vessels
            - NCO 19.9 Conduct drug traffic suppression and interdiction operations
            - NCO 19.13 Support enforcement of fisheries law and treaties
            - NCO 19.15 Support drug traffic suppression and interdiction operations
            - NCO 19.16 Support illegal entry suppression operations
            - NCO 33.1 Operate as chokepoint patrol unit
        - NTA 6.3.3 Combat Terrorism
            - ATFP CCR 2 Deter, detect, defend against, and mitigate Terrorist Activities
            - ATFP CCR 4 Entry Control Point (ECP)Threat
            - ATFP CCR 8 Pier side Small Boat Attack Exercise
            - ATFP CCR 9 Terrorist A/C Attack Exercise
            - ATFP CCR 12 Pier Demonstration/Passive Protest Exercise
            - ATFP CCR 14 Swimmer Attack

            - ATFP CCR 15 Nighttime Small Boat Attack at Anchor

A second mapping of potential mission areas appropriate for a DEW was conducted after the problem statement had been refined. This revision of the missions appropriate for a DEW was based on what was thought to be implementable within four years. This revision also incorporated technologies which had been operationally tested and were still funded:

- NTA 3: Employ Firepower
    - NTA 3.2.1 Attack Enemy Maritime Target
        - NTA 3.2.1.1 Attack Surface Targets
            - SUW 1.6 Engage surface ships with SUW weapons
            - SUW 1.10 Conduct close–in surface self-defense using crew operated weapons
            - SUW 2.3 Engage surface targets with assigned anti-surface sector
    - NTA 3.2.3 Attack Enemy Aircraft and Missiles
        - AW 1.1 Provide area defense for a strike group
        - AW 1.2 Conduct air self-defense using DEW
        - AW 1.4 Provide area defense for a convoy or underway replenishment group
        - AW 1.5 Provide area defense for amphibious forces in transit and in the amphibious objective area
        - AW 1.6 Provide area defense for a surface action group
        - AW 1.12 Provide air defense for non-combatant evacuations operations
        - AW 1.13 Provide air defense for naval/joint/combined TF operations

        - AW 9.1 Engage medium/high altitude, high-speed airborne threats with DEW
        - AW 9.3 Engage low altitude threats with DEW
        - AW 9.4 Engage low/medium altitude airborne threats with DEW
    - NTA 3.2.9 Conduct Non-Lethal Engagement
        - ATFP CCR 12 Pier Demonstration/Passive Protest Exercise
        - NCO 19.6 Conduct seizure of noncombatant vessels
        - NCO 19.9 Conduct drug traffic suppression and interdiction operations
- NTA 6: Protect The Force
    - NTA 6.3 Provide Security for Operational Forces and Means
        - NTA 6.3.3 Combat Terrorism
            - ATFP CCR 4 Entry Control Point (ECP)Threat
            - ATFP CCR 8 Pier side Small Boat Attack Exercise
            - ATFP CCR 9 Terrorist A/C Attack Exercise
            - ATFP CCR 12 Pier Demonstration/Passive Protest Exercise
            - ATFP CCR 15 Nighttime Small Boat Attack at Anchor

This second evaluation of the needs to mission mapping also scoped out anything that was not shipboard. Although the tasking statement directed the project team to "integrat[e] DEW into Naval forces" (Langford, SEA-19B Directed Energy Weapons 2012), the team further scoped the project to strictly naval ships (and eventually solely the DDG-51 class) for several reasons, chief among them being that at the time that this mapping had been done, the prototypes to be evaluated had been selected and none of the selected prototypes were deemed able to fit on existing ship-borne aircraft. Shipboard platforms seemed to be the only suitable platform for short term fleet integration. This was determined due to the current space and excess power available on many classes of ships in the fleet. Analyzing the integration of DEW onto other naval platforms (LCS and

CVN for example) would provide additional insights to an appropriate fleet wide procurement strategy (in terms of systems purchased), but would not change the effectiveness of DEW systems in a maritime environment (if a given DEW is effective onboard a DDG-51, it will be effective onboard another class assuming the other ship can support the DEW logistical requirements in terms of power, space, and cooling). Additionally, further background research by the project team and preliminary analysis of the selected DEW prototypes revealed that missions related to theater-wide missile defense or ballistic missile defense (BMD) was unrealistic for the systems available for analysis. The only system to have successfully engaged a ballistic missile was ABL was not selected as a potential shipborne prototype as discussed in the technology selection section of this chapter. Finally, several missions that were similar or duplicates were eliminated (an example being SUW 1.6-Engage surface ships with SUW Weapons and SUW 2.2-Conduct SUW to support surface forces). SUW 2.2 was eliminate as the core task of engaging a surface ship is covered under SUW 1.6. With the final list of missions applicable for the use of DEW determined, it was possible to map missions to threats and weapons (see Appendix A).

C. TAILORED SYSTEMS ENGINEERING PROCESS

We evaluated the relative net worth of a DEW by developing a unique systems engineering (SE) process with emphasis on needs, mission, weapon, performance, cost, and integration mapping. This tailored SE process was created to provide context to the analysis comparing potential DEW to current conventional weapons. A context driven approach is critically important to avoid the failures of the ABL program. The ABL program, which had a hefty price tag and spent a long time in development, was changed from an acquisition program to a research and development (R&D) program and the second aircraft cancelled in 2009. Then Defense Secretary Robert Gates made this change to the ABL program due to “significant affordability and technology problems, and the program’s proposed operational role is highly questionable” (Gates 2009) before it was ultimately canceled in 2012. According to the operational concept for the ABL, the aircraft would have to loiter in or near enemy airspace waiting for a ballistic missile to be fired and then attempt an intercept. Although the ABL was effective at shooting down missiles throughout several tests, the operational concept was not viable.

Conversely, our process required that in order for a weapon to be effective, it must fill some mission gap or improve upon current capabilities using an appropriate concept of operations. The utilization of the UNTL to map weapons to missions was extended as shown in Figure 7. The larger systems engineering process for the project evolved out of the approach of ensuring a need was being fulfilled while using the method of mapping needs to missions to weapons and threats described above. A strongly iterative waterfall process with feedback loops was tailored to accommodate the mission mapping process, the extrapolation from various sources of data for DEWs, and the consolidated analysis using several modeling and simulation tools.

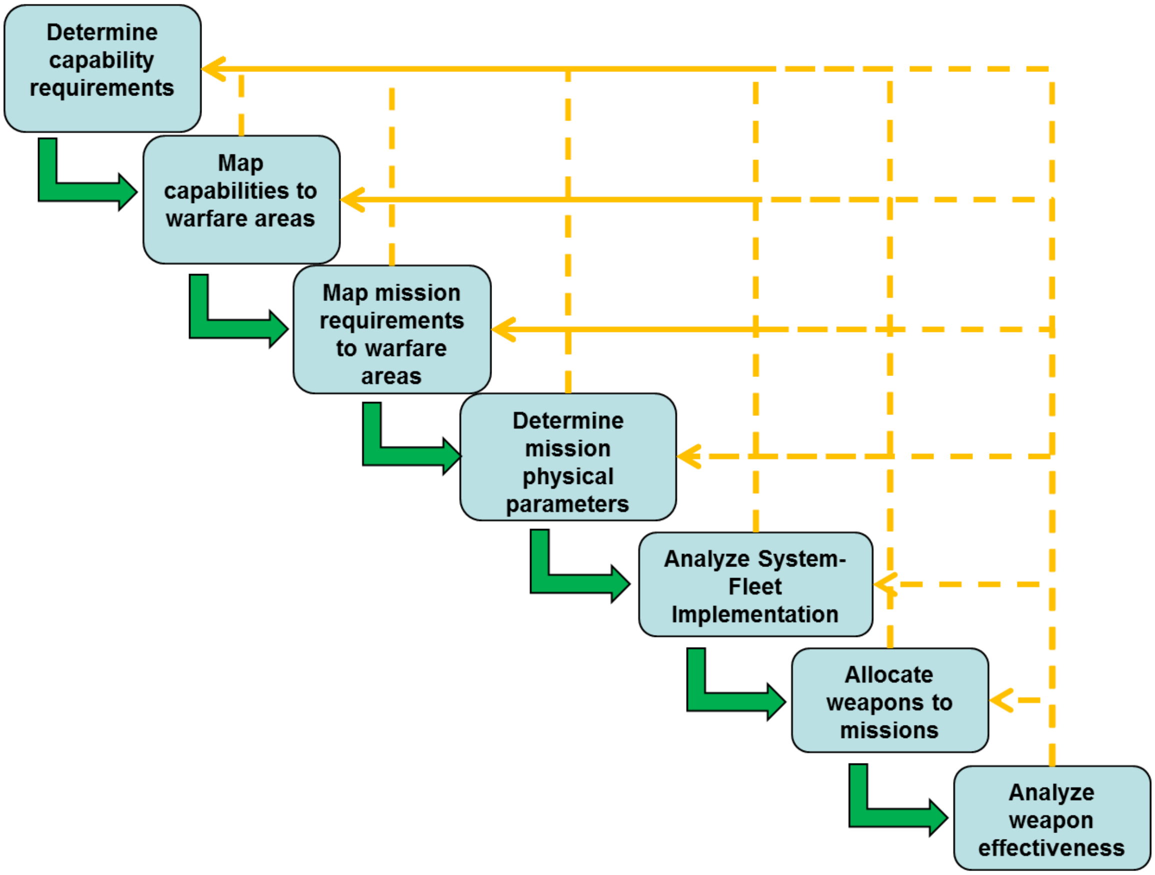

Figure 7. Tailored Systems Engineering Process (Tailored Waterfall)

D. STAKEHOLDER ANALYSIS

With this project carried out at the unclassified level and with the inclusion of foreign nationals, many potential stakeholders chose not to be involved, specifically those companies developing the prototypes that we analyzed. The decisions by these companies to acknowledge our work but not participate limited the stakeholders of this project to a select few as shown in Table 3. This table represents the different stakeholders along with their needs, goals, and concerns. Stakeholders are those individuals or entities that have a vital interest in the outcome of the project. Primitive needs are the basic necessities expressed by the stakeholders while effective needs are the needs of the stakeholder in the context of DE and this project. Concerns are issues the stakeholders view as being critical to their needs. Goals are the outcomes stakeholders desire pertaining to the DE.

Table 3. Stakeholders

Stakeholder	Primitive Needs	Effective Needs	Concerns	Goals	Type
NPS	Provide high quality education for Armed Forces and government civilians	Foster research that supports development of DE	Potential roadblocks of research and education	Increase combat effectiveness of Armed Forces through research and development of DE	Educational Institution
N9I	Enhance naval warfare capability	Ensure development of integrated DEW for Naval Forces	Integrated warfare requirements of DEW	Successful integration of DEW on naval platform	Naval Division
Operator	Accomplish mission	Use DEW System to accomplish mission objectives	System performs as intended and is user friendly	Fulfill mission requirements using DEW system	User

Naval Postgraduate School (NPS) is a higher learning institution responsible for educating graduate-level personnel across not just DoD, other U.S. governmental agencies and defense industry professionals, but members of Allied nations' corresponding agencies as well. Part of providing an education is fostering the intellectual growth of students and faculty through research. This research is invaluable to the increase of combat effectiveness throughout the Armed Forces. As a stakeholder of this project, NPS desires to advance the combat effectiveness of the Navy through supporting the study of DEW and its integration onto a naval vessel. Concerns of NPS include any potential roadblocks that may impede this study.

N9I is the Warfare Integration Division of the Navy and the sponsor of the project. The purpose of the division is to integrate warfare goals and objectives with force requirements, resulting in enhanced warfare capability. N9I is therefore concerned with the successful integration of DEWs on naval platforms and that this integration fulfills battle force requirements.

Operators are the individuals (Sailors) who will utilize the system. Users have requirements to meet and employ the system in order to fulfill a given mission. For this reason, it's important that the system performs as intended or the mission could be jeopardized.

Although interests in the outcome of this project involve many other agencies and businesses, the unclassified nature of the project has led to little acceptance among those entities as previously discussed. The project team has spent a considerable amount of time formulating workarounds to this reluctance to cooperate. This workaround led to a gap in the amount of data received which the project team augmented by utilizing open source information, applying the physics based solutions to the characteristics of the weapons, and using analogist information in cost and integration issues where possible. No classified or distribution limited data is included in this analysis, but the process could be used with such data if it were to become available.

E. SELECTED SOURCES OF INFORMATION (SSOI)

DEWs are produced and studied by a host of businesses, agencies, and research facilities all of which could have served as potential sources of information. However, due scoping the project to those systems which could feasibly be integrated onto naval platforms within a four year timeframe, sources of information were narrowed to those entities that supplied DEW technologies at TRL 6 or above.

The SSOI Distribution shown in Figure 8 represents the various selected sources of information (SSOIs) that are associated with the project. SSOIs are those individuals and entities that can provide information that pertains to the project. The SSOIs are mainly contractors that supplied DEW prototypes for testing. Raytheon supplied the LASER Weapon System (LaWS) and the Active Denial System (ADS). Northrop Grumman supplied the Maritime LASER Demonstration (MLD). Boeing and BAE developed the Tactical LASER System (TLS). Some other SSOIs include PMS-405, the Navy’s Directed Energy Program Office, 129th Rescue Wing who has used GINA in several search and rescue exercises, and the USS DEWEY which currently is being used as the test bed for LaWS.

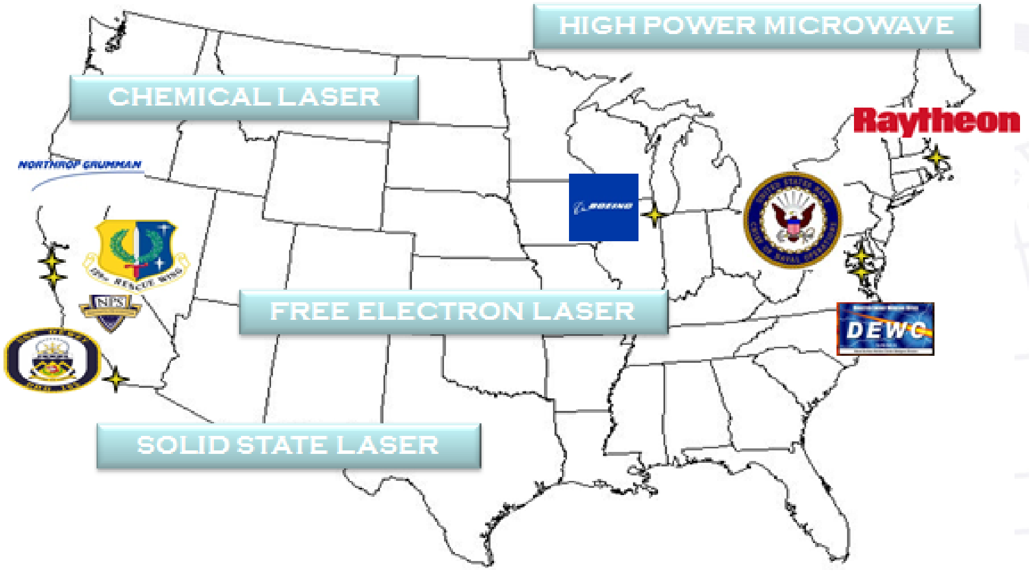

Figure 8. Selected Sources of Information (SSOI) Distribution

As with the stakeholders previously, the SSOI as potential stakeholders have the same categorical needs, concerns, and goals. These needs, concerns, and goals are fundamentally different than the stakeholders as any public company is responsible to be profitable for their respective stockholders. Also, as these SSOIs are all contractors, their needs (both primitive and effective), concerns, and goals are all similar and apply to them all. The SSOIs are detailed in Table 4.

Table 4. Selected Sources of Information (SSOIs)

SSOI	Primitive Needs	Effective Needs	Concerns	Goals	Type
Boeing, BAE, Northrop Grumman, Raytheon	Gain substantial market share	Sell their DEW System	Customers deeming systems worth purchasing	Obtain contract for producing DEW	Contractor
	Brand recognition	Build cadre of experts	DEW is sufficiently tested	Obtain contract for supporting DEW	
	Attract new employees	Employ premier workforce	Sufficient systems are sold to recoup R&D money and make profit	Obtain contract to develop next DEW	
	Attract new shareholders				
	Secure future R&D money				

Contractors are businesses, and businesses need to make revenues and profits. In order to gain a substantial portion of the market, the above contractors desire to sell their respective DEW to the government or any other entity which desires them and can legally buy the DEW. Gaining market share is accomplished through gaining contracts, having their brand recognized by potential users, and having a high quality workforce that will allow them to manufacture, supply, and potentially maintain units. In general, contractors are focused on providing systems that meet the requirements of their customers, with the expectation that the customer provides clear requirements (which accurately address the needs of the customer preventing requirement creep during development) and then purchases the system assuming the requirements are met.

F. TECHNOLOGY SELECTION PROCESS

There are numerous challenges to developing directed energy technology including R&D roadblocks, high power requirements, and mission effectiveness. As might be expected, the potential benefits are significant as well. The possibility of “deep magazines” and expanded “use of force continuum” opportunities has long been sought out by military commanders; literally dozens of potential technologies and permutations exist. Our tasking called for a thorough analysis of issues that address a broad spectrum of missions commensurate with the needs of the U.S. Navy. We then factored in current fleet structures, as well as currently funded programs. Next we developed the associated concepts of operation. From here we were able to evaluate the potential technology gaps for not only directed energy weapons, but also for their integration into U.S. Naval forces. This process for formulating a technology gap resulted in our conclusion to only consider DEW technologies that currently have an operationally tested prototype. The technology must be both feasible and applicable to the current U.S. Navy mission. In addition, deployment of a DEW must have the ability to comply with the four year timeline previously discussed.

In determining which of the four technologies identified in the background section (Solid State LASERs (SSL), High-Powered Microwaves (HPM), Free-Electron LASERs (FEL), and Chemical LASERs (CL)) deserve further analysis, each technology was measured against three criteria. The technology has to be capable of working successfully in the established four-year timeframe, has to improve the mission effectiveness of the ship, and has the ability to be integrated onto a ship. Based on these criteria, FEL and CL were removed from further consideration in the project.

Although a FEL has tremendous potential as a DEW with the ability to modify the wavelength as required and the high power output, the drawbacks of the technology are prohibitive of a shipboard environment and do not have the potential to be implemented in four years. These drawbacks include large size, radiation hazard, high power requirement, and large weight. CL were also eliminated from further consideration. Although CL are the most technologically mature of any of the potential DEWs as shown with the ABL and THEL programs, the requirement of a logistics train providing (and removing after firing) toxic chemicals does not reduce (and would likely increase) the reliance on the logistics train. This elimination of FEL and CL from further consideration constrains the project to two technologies, HPM and SSL. Each of the remaining two technologies provides a different capability and will be analyzed separately.

IV. MODELING AND SIMULATION

A. MODELING METHODOLOGY AND BACKGROUND

In order to accomplish our goal of evaluating each weapon in a specific engagement, in the context of a mission, we built a meta-model and two simulations. The meta-model aggregated different engagements into a single, searchable database and provided an interactive mapping of that engagement to weapons, threats, missions, warfare areas, environments, and weapon platforms. The simulations would help to gain insights in what combination of weapons would be best, how DEWs could affect ship survivability, and what the CONOPS of a potential DEW employment might look like.

With the mission requirements evaluated for applicability and mapped from the top down, starting with the UNLT and ending with a ROC/POE or CCR defined mission, the next step was to define the context for evaluation within a model to evaluate each weapon's effectiveness within those mission contexts. We chose an engagement centric view around which to construct the model. A visual representation of the model of the model parameters for an engagement between a ship and its target are depicted in Figure 9. An engagement centric view was chosen because a directed energy weapon is not equally effective against all threats and in all environments. Therefore, we needed to place a weapon into a specific context, evaluate its performance in that context and environment, and then aggregate all of the weapon's engagements. Weapon performance would be aggregated in a database, with meta-tags embedded in the engagement file to link that engagement to all of the objects that are represented in that specific engagement's context. The aggregated engagement results for all weapons can then be compared on a one-to-one basis, comparing conventional, LASER, and microwave weapons in equivalent, quantifiable terms, to determine the exact advantages and niches for each weapon.

The model is based on the following assumptions. For each engagement we assumed that the earth was flat, that the weapon platform was the center of the universe, that all threat motion was relative and direct towards the weapon platform, and that weapon and threat speeds remained constant (no acceleration, no drag). Assuming a flat world negated the need to know the exact weapon height and all engagements were entered such that the slant range to the threat was within a line of sight to the weapon (assumed to be at an altitude of 0 meters relative to mean sea level). Assuming no drag or acceleration was necessary because unclassified weapon and threat cross-sectional areas were unavailable and provided a counter weight for conventional weapons against DEWs being able to instantaneously move to the next target without delay. Upon the intercept of a threat by a weapon, we then accounted for some weapon effect delay, during which the threat is not killed until the end of that delay (i.e., no instantaneous kill or damage). We also assumed an infinite number of successive threats that can only be engaged one at a time, which allows us to get a rough order of magnitude of how many kills a weapon can achieve against a specific threat type in each specific context. Finally, we assumed that the vital area radius was mission specific and that the threat detection slant range was engagement specific. Each vital area radius represents that distance by which a threat must be successfully engaged or the model assumes that the engagement is a failure. This was based on the expertise of the team members to account for situations such as an inbound ASCM, where if it is engaged at less than a certain distance, it will still impact the ship, causing high amounts of damage regardless of a successful intercept. Also, this was done because even very low powered DEWs can produce a very high power density on a target if it is extremely close (i.e,, within a few meters) and allowing threats to get that close to the weapon in the model would result in an unrealistically high number of successful engagements.

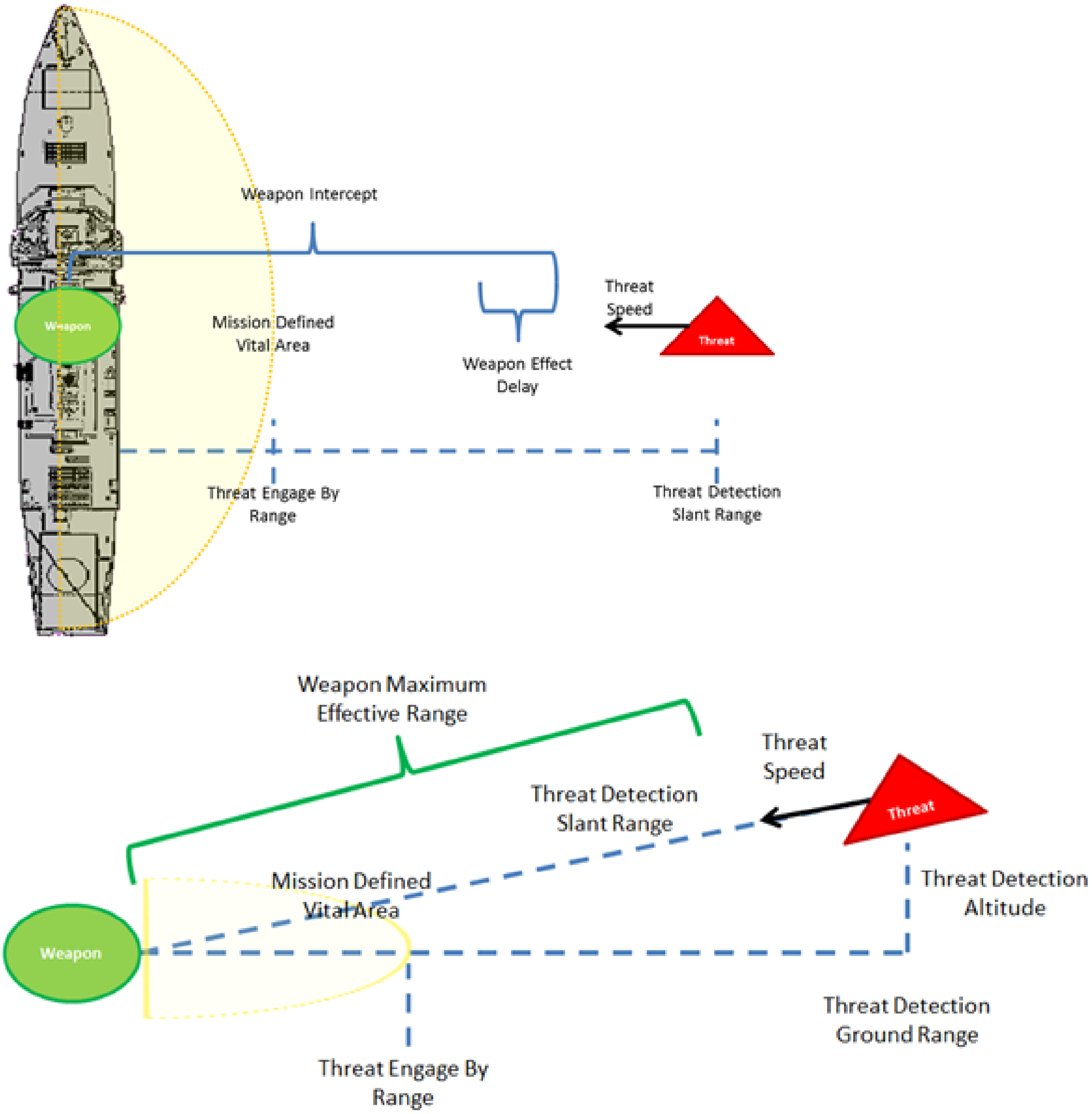

Figure 9. Model Engagement Diagram

B. GLOBAL INFORMATION NETWORK ARCHITECTURE (GINA)

In order to realize the true potential of the output of the Systems Engineering Process for this project, it was determined that Global Information Network Architecture (GINA) was the best tool available for complex meta-modeling. Team members interviewed the Chief Technology Officer of Big Kahuna Technologies, LLC, Mr. Frank Busalacchi, who developed GINA and the U.S. Army Corps of Engineers, Engineer Research and Development Center (ERDC) liaison officer (LNO) to TRAC

Monterey, Dr. Thomas Anderson who has multi-domain experience working with the architecture including the network certification of the architecture for the U.S. Army. In addition, the project team researched several official reports and articles about GINA modeling to help make the decision to use GINA. We determined that the GINA environment allow both integration and interoperation behavior of system components to be specified, not programmed (Dolk, et al. 2012) (Anderson, Dolk and Busalacchi 2012).

GINA is a natural extension of object oriented software engineering that recognizes that a finite number of relationship types (in GINA called vectors) exist between data objects (X-Types) in the enterprise architecture, and that a great majority of object oriented coding is spent defining these relationships in brittle code. In GINA the relationships, or vectors, are objects themselves. Additionally, GINA is implemented with the ethos that to build a model of the software's functionality is superior in time savings and errors over physically coding and compiling traditional software (Dolk, et al. 2012). GINA also allows variables (called elements), X-Types, and vectors to be assigned a Globally Unique Identifier (GUID), which means that a GINA model and all of its components can be globally accessible and identifiable, and version control (such as with a spreadsheet) is effectively mitigated against.

Inherently defined vectors are the key difference in programing with GINA's Vector Relational Data Modeling (VRDM) compared to an object oriented language like Java or C++. Inherently defined means that the constructs for the different relationship types are pre-configured in GINA, whereas in the C++ or Java APLs, there are no pre-configured or pre-defined relationship keywords, objects, or methods: they must be created by the programmer. VRDM is the "language" of GINA in software engineering terms and it is the building blocks and connections of and between objects in modeling terms. VRDM is the GINA mode or engine that GINA applications are built with underneath the user interface. When building an object model using conventional object oriented software engineering techniques, a programmer or engineer will spend a significant amount of time writing code to define relationships between objects, whereas in GINA those relationship constructs have already been defined and are immediately available to be implemented within the model, allowing the model design team to focus their efforts on the model's functions and characteristics rather than its mechanics (Dolk, et al. 2012, 4). In GINA a vector is a relationship object and there are four base types of relationships: collection, derivation, declaration, and union. In our project, these vector relationships represent the results of our tailored Systems Engineering process. A collection is a relationship based on proximity. This proximity could be based on time, distance, or association. For example, two students at NPS have a proximity relationship based on attending NPS. A derivation is a second-order relationship which means that for example: two people have a relationship due to a third person they know in common. A declaration is a relationship that exists because a party says it does. For example, a man and woman could have a relationship that is declared by an official marriage license. A union is a collection of relationships all treated in the same manner. These four relationship types are configured into GINA allowing the user to apply them without doing any traditional programming. These relationships are implemented as vectors in GINA.

Figure 10 shows the composition of GINA objects. It should be noted that the diamond indicates that the item is (or can be) made up of several of the objects that the arrow is pointing to (an X-Type consists of several elements and services but a vector consists of only one X-Type). As shown in Figure 10, a Service (such as "Save") is invoked by an Event (such as "User clicks save button"). The "Save" Service is invoked by a Directive that (such as "On user form *x*, give the user the option to 'Save' form inputs"), which is then part of a larger collection of Directives housed in a Content Manger. A Content manager might then also contain Directives, for example to download new data, update user forms, or perform arithmetic operations on data (Busalacchi, Tinsley, et al. 2010). Using a Content Manager, Elements perform their various functions such as storing, displaying, or manipulating data for example.

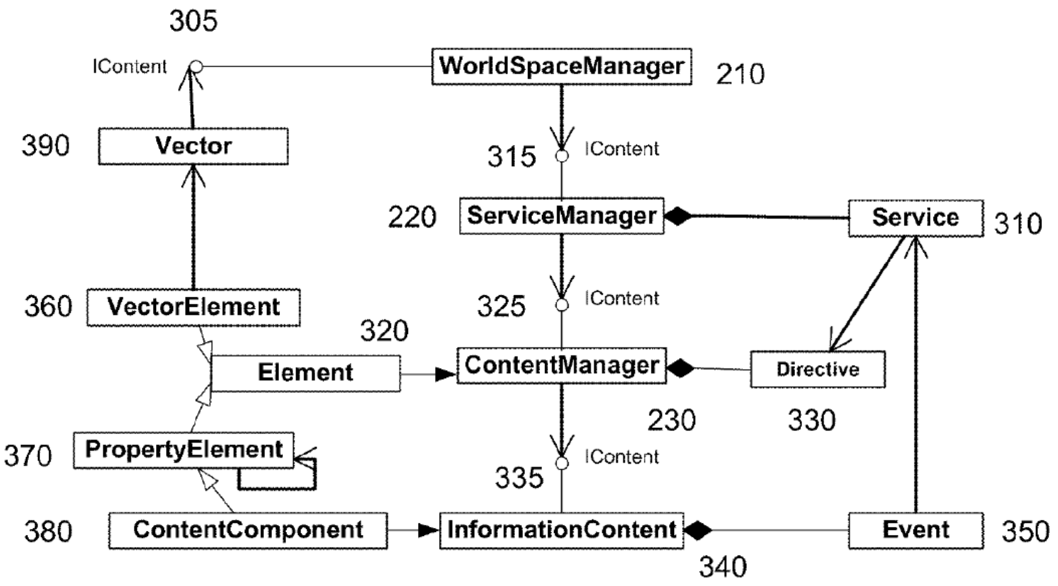

Figure 10. Global Information Network Architecture (GINA) Information Object Structure (from Busalacchi, Tinsley, et al. 2010)

There are two basic object types in GINA, X-Types and Vectors. X-Types are the objects in traditional programming languages. Vectors are the relationships between X-Types. As the relationship has data associated with it, the vector is also an X-Type. The fact that a Vector is a specialized X-Type allows for the relationship to be easily implemented because of the supermetadata tagging attributes inherent in an X-Type provide the necessary constructs to hold relationship specific and unique identifying data tags necessary to implement a relationship between two objects. At its most basic level of coding, in the GINA bootstrapped process that compiles and runs GINA, an X-Type is comprised of three primitives, an element, an X-Type, and a directive. The element contains the information. The element can store the information and output the information when queried. A directive allows for changing the information stored in the element (such as user entered data or data from an online database via an external connection). A vector is made up of a single primitive defining what object or objects it is related to. These relationships are shown in Figure 11.

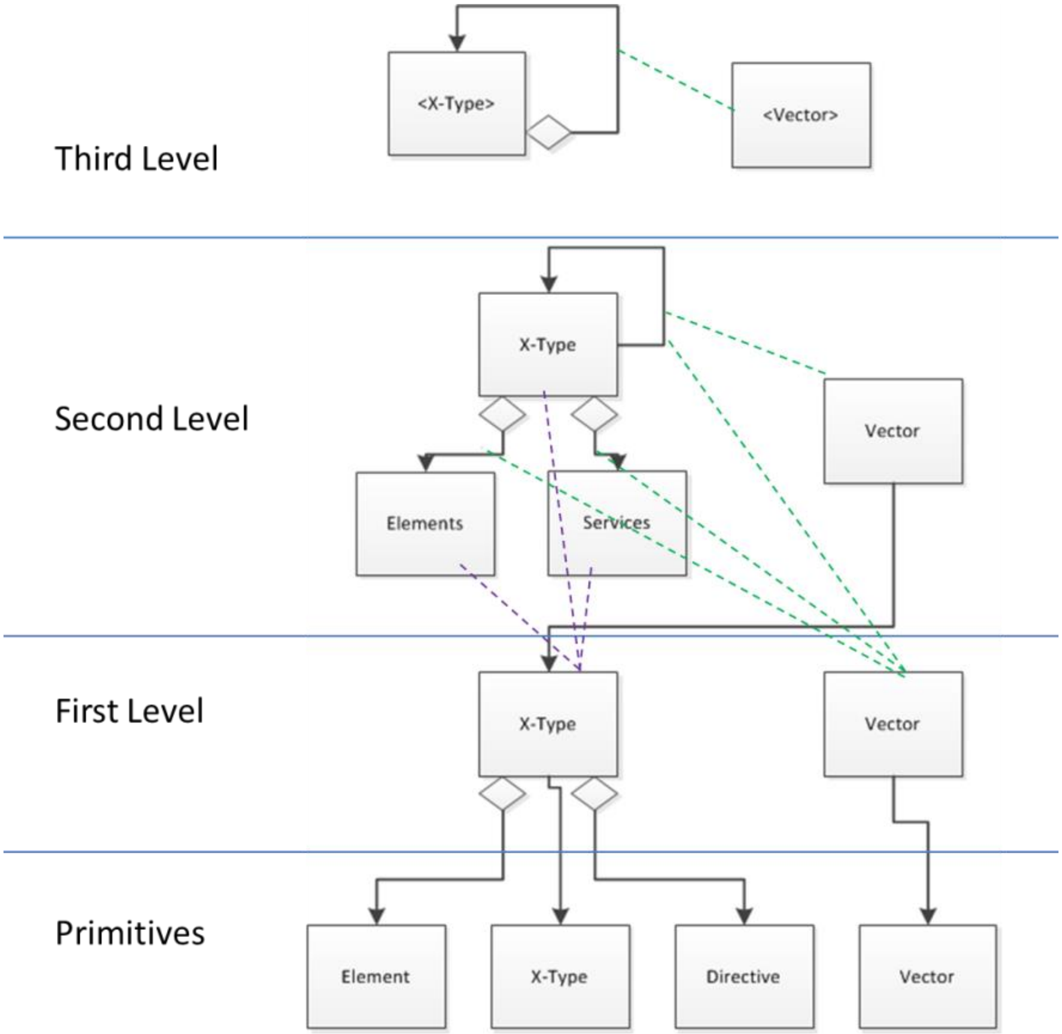

Figure 11. Universal Modeling Language (UML) Model of Global Information Network Architecture (GINA)

These levels are interpreted in the terms of written language. The third level (which is actually a subset of the second level) can be thought of as a collection of several documents. The second level would be an individual document. The document is made up of a collection of ideas all expressed in words. The first level represents these words that describe the ideas. Each word contains a little bit of information, but when the words are combined, the document as a whole represents the interaction between the defined objects and vectors. The words are made up of a finite selection of letters, these letters are the primitives. Each letter serves a specific purpose, as does each primitive. This recursive form of building allows for describing GINA as a GINA model a key aspect of GINA. The recursive nature and simple yet well-defined building blocks allows for straightforward implementation of a GINA model.

In Java, an object is a subroutine that would be called by another program. There are some that are programed into Java, but these libraries must be imported to give access. One example is the math functions library. There is not an innate way to do a square root in Java, but the math library has one. Once everything is coded, the program must be compiled in order to become an executable. Assuming there are no syntax errors, this compiled code can be run and tested. This debugging takes the majority of time for any program, especially if compiling time is counted as well. Once the code is as correct as possible, it is compiled to be used. The compiled code cannot be altered in any way and there is not an easy way to go from the compiled code to the source code again if anything must be changed. This reliance on compiling is perhaps the greatest drawback of object oriented languages.

GINA gets around this major issue as the compiled code never needs to be changed. GINA consists of the relationships and the workings of the X-Types and vectors, but the actual X-Types and relationships are defined with the compiled code. Each entity is given a globally unique identifier (GUID) allowing for easy traceability. GINA is accessible through a web browser to the GINA database, facilitated by the correct permissions and the Internet. The user interface, referred to as “Task Oriented,” and outputs can also be customized to fit the needs of the users. The linked databases can be changed readily and the vector X-Types only need to be updated to reflect the units of the new database. For example, if linking a new database to the existing model, you might need to add additional elements with the target X-Type to store data types from the new database that were not present in the previous databases that were linked to the model. Unlike the need for applying traditional programming to customize the user interface, GINA allows unskilled programmers to implement complicated models with minimal training. The benefit of GINA is these modifications and customizations can be accomplished without having knowledge of the details of the model (Busalacchi, Chief Technology Officer, Big Kahuna Technologies, LLC 2012).

The ability to build a complex metamodel without intensive software coding, the ability to define a project specific language and framework within which to evaluate and visualize model data from multiple disjoined sources, and the ability to easily extend and upgrade the model with new or more accurate data at a later date provided the basis for determining GINA's appropriateness for SEA-19B's project. Additionally, since GINA is a software modeling language, its outputs are 100% traceable to their source X-Types, Directives, and data. In other words, the GINA model is not a black box (where the user has no knowledge of and no ability to discover the processes or functions that translate data from input to output), and any validation of the model's results can be easily and visually explained and can be shown to map back to a logical systems engineering process. From an analytical perspective, a GINA model provides a means of comparison between weapons in the context of various missions. A most important aspect of GINA is that we were able to make a direct comparison of seemingly unrelated data and systems. An example of this ability to make direct comparisons is shown in Figure 12 below. Many different data inputs (such as Threat Parameters or Weapon Parameters) are pulled from unrelated sources (such as SQL database tables) and are read into objects (Threat X-Type or Weapon X-Type). Then those objects, based on their relationships with all of the other objects in the model (including X-Types such as Environment and Weapon Platform) are able to be analyzed in a multidimensional fashion, meaning the data can be explored through the paradigm of a specific X-Type or a collection of X-Types via a user-defined GINA form or set of hyperlinked forms for a web interface, allowing for a model of the system to be built. Before knowing exactly what questions are to be answered, the allowable relationships are characterized in GINA and made available for exploration and evaluation with minimal to no rework required to modify the model. Consequently, the GINA model can be structured around a problem domain and context and reused with higher levels of fidelity without reword. However, the same cannot be said for spreadsheet analysis. One way to think about a GINA model is like a building with many doors. Each door represents an X-Type and each hallway represents a vector. The same building is expressed and described, no matter which door you enter through, but depending on the chosen door, your perspective of the building will look different and provide a unique view that may not be available from any other entrance. This changing of perspective without changing the model is the GINA advantage over typical model representations. The object intersection, created by hyper planes of metadata in Figure 12 illustrates this concept.

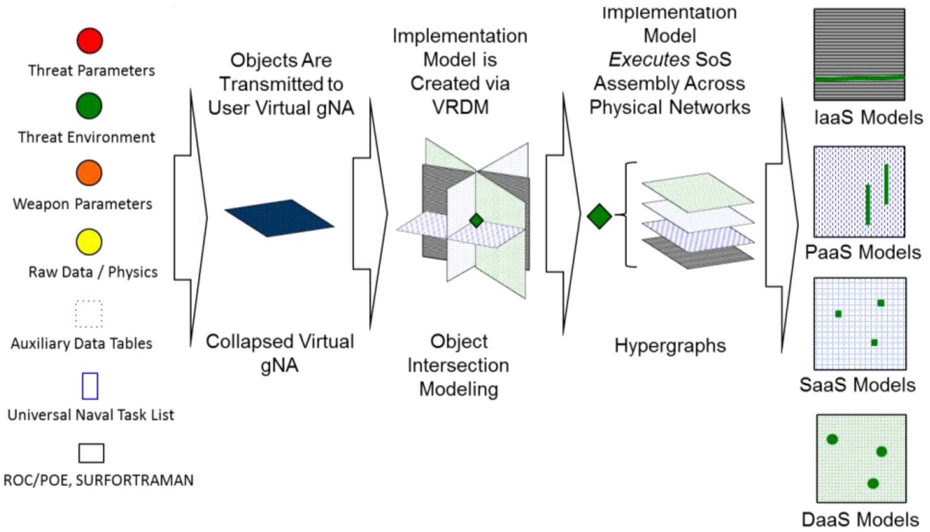

Figure 12. Inputs to Objects to Model to Analysis in Global Information Network Architecture (GINA)

While GINA excels at meta meta modeling, it is not a practical method for explicit advanced mathematical operations beyond basic arithmetic operations. In order to provide for this capability, Big Kahuna Technologies, LLC (the GINA inventor) has developed a custom content manager to take variable data and perform complex mathematical operations on them. Through the content manager, SEA-19B was able to carry out our analysis of weapon effectiveness with respect to a threat, mission, and environment. The content manager code is shown in Appendix B.

SEA-19B's GINA model is depicted in Universal Modeling Language syntax in Figure 13. Each box with text that is underlined represents an X-Type object. By tracing each X-Type's relationship to the other X-Types, the tailored systems engineering process described in Chapter 3 is apparent. For ease of implementation, each X-Type was built initially using MySQLServer Manager which defined a database for each X-Type, listing all of the columns in each X-Type. Once completed, the database was exported to the GINA server to build vectors and populate the column elements. The two X-Types surrounded with red-dashed lines were part of the original model design, but were not used in the final implementation. These two X-Types originally intended functions were absorbed by the Engagement X-Type because an attenuation would need to be recalculated for each engagement based on that engagement's slant range to the threat and the value added by saving those attenuation calculations for global reuse later was jointly assessed by the project team and Mr. Frank Busalacchi as being greatly outweighed by the additional time and complexity associated with implementing that feature into the model. The enumeration X-Type can be used to add more complexity to environmental variables and the attenuation X-Type can be used to save previous attenuation calculations in order to reduce processing time by reusing previously calculated values.

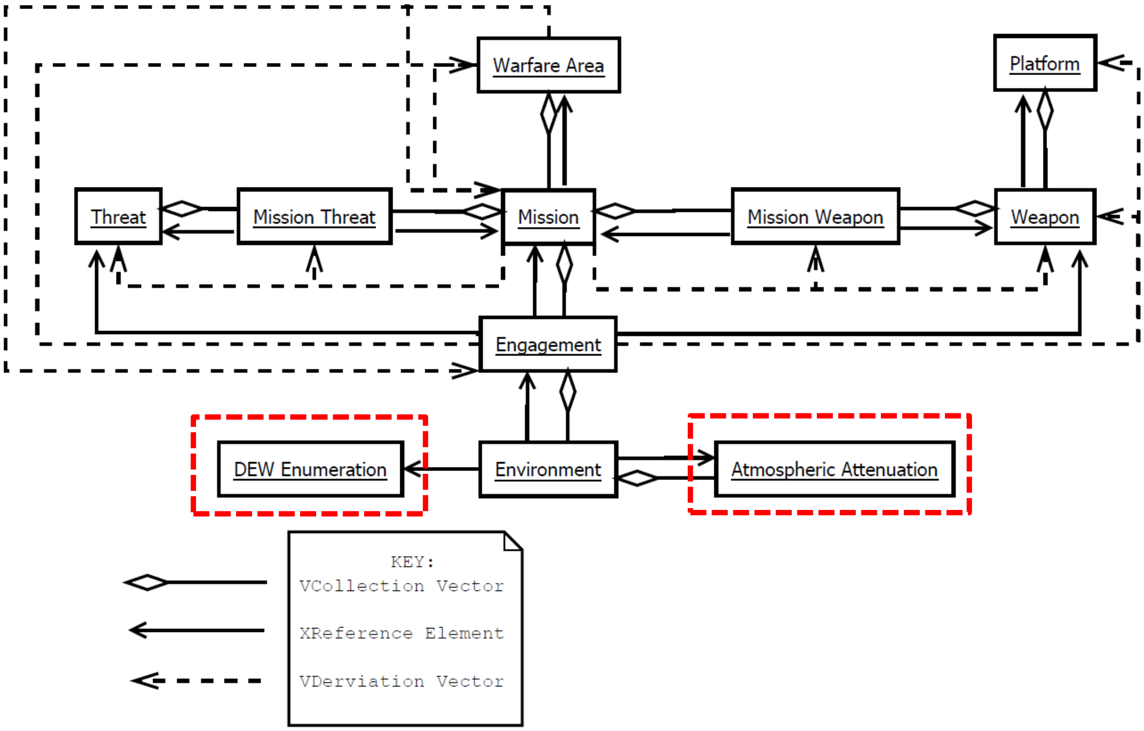

Figure 13. SEA-19B Global Information Network Architecture (GINA) Model Universal Modeling Language (UML) Diagram

The GINA model allows the user to complete many engagements, and then query the whole model for results, meaning that each Engagement instance pulls data from every X-Type in the model and that combined Engagement data, for all engagements, can be aggregated in an SQL query to a spreadsheet for external statistical analysis. Several

X-Types stand alone in the sense that they are independent of engagements in the real world: Platform (such as DDG-51), Environment (such as marine with 2 mm/hr rainfall), Atmospheric Attenuation (such as 0.8 dB/km), and DEW Enumeration (such as Environment Characteristic). Each naval combatant has differences such as combat systems, maneuvering ability, and damage control features, from other combatants that allow it to accomplish certain missions. However, because the Navy must be able to respond on short notice and with the time to reconfigure ships and platforms while forward deployed, most combatants cover the same missions (at least to some extent). When called to respond to a crisis, the nearest ships (regardless of class) will be capable of responding. Therefore, this analysis presumes that platforms are independent from engagements and are only related to engagements and missions by installed weaponry. That presumption is why there is a derived relationship from Engagement to Platform via Weapon. Similarly, the Environment is not dictated by the objects that find themselves in a specific environment; rather, objects exist in an environment that is variable (i.e., changes). Therefore, Environment is linked to Engagement by characterizing Engagements as a collection of N Environments—whether those Engagements are successful or not. Related to Environment is Atmospheric Attenuation. For each Environment, there is an infinite number of Atmospheric Attenuations: one for each specific wavelength and propagation path. DEW Enumeration is an X-Type that allows multiple environmental variables to be selected easily. Originally, DEW Enumeration would have allowed the project team to have multivariate environments available; however, due to time constraints and complexity only rain rate was used to differentiate environments since the largest source of scattering is water particles in the atmosphere (Harney, Combat Systems Volume 1 2004) and DEW Enumeration was not used. DEW Enumeration is available and accessible in the model should a future project wish to expand the number of Environments available for modeling.

The remaining X-Types in the GINA model are directly related to Missions and each Mission has a collection of possible Engagements. Each Mission has a collection of

Mission Threats and a collection of Mission Weapons. Each Mission Threat has a collection of Threats. Each Mission Weapon has a collection of Weapons. Therefore, each Mission has a finite set of Threats and Weapons that change based on the Mission selected. This configuration of X-Types makes sense because a threat defines a mission, which necessitates a weapon. Each Mission then has a collection of Engagements consisting of a specified Threat, Weapon, and Environment. From our analysis of the UNTL, each Warfare Area has a collection of Missions. The Xreferences in the model allow each X-Type to "know" its uniquely identifiable instance of an X-Type. For example, an Engagement has some Mission and the Xreference specifies that *this* Engagement's Mission is AW 1.1. The referencing system in GINA, based on Global Unique Identifiers ensures that regardless of the number of objects that are instantiated in the model, each object will be identifiable and uniquely traceable[1]. A full listing of X-Types, Vectors, and Elements can be found in Appendix C.

C. MODELING DIRECTED ENERGY WEAPON (DEW) PERFORMANCE

GINA is well suited for modeling the complex contextual relationships between weapons, missions, warfare areas, environments, platforms, and atmospheric attenuation. Using the content manager, GINA facilitates sophisticated mathematical tools to apply principles of fundamental physics to drive DEWs. In addition, GINA incorporates some innovative ways to address what a DEW means in a tactical sense by qualifying the data and relationships in GINA and quantifying a weapon's full range of performance with math.

To develop our model, we considered the current state of the art in weapons modeling. Currently, weapons effectiveness models consider effectiveness in binary terms: hit or miss. More specifically, a hit equals kill. In a 2012 report by Naval Surface Warfare Center, Dahlgren, VA, the Navy concluded that "conventional air-to-air warfare

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[1] The project GINA model is hosted at p4ie.nps.edu. For access, contact NPS Information Technology and Communications Services.

(AAW) models…are not well suited for showcasing current or near-term laser-weapon capabilities" (Staton and Pawlak 2012). When evaluating DEWs, degraded performance (after "hit") must take into account the accumulation of energy required for a "kill" over a period of time. This deposit of energy on the target over time is especially relevant when evaluating the current continuous wave operations of the latest prototypes. The prototypes have been operationally tested at relatively low output power levels whose effects are observed to be cumulative over time.

Separate mathematical models were developed to model LASER and microwave weapon effectiveness. Separate models were chosen because the ADS is used against human targets (Ackerman 2012) and the LaWS, MLD, and TLS LASER weapons are primarily intended to be used against non-human targets (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013). Good analytical models exist for calculating the effects of electromagnetic radiation against non-human materials (Harney, Combat Systems Volume 3 2004); however, due to ethical implications of intentionally subjecting humans to electromagnetic radiation, our research did not result in finding any analytical models for human radiation effects. Therefore, empirically derived data was used to develop a human effects model for microwave radiation.

In order to make a one-to-one comparison between the LASER and the Microwave devices to conventional weapons, it was necessary to define exactly what the outcome of an engagement was, which may not necessarily be lethal. Therefore, we assumed all engagement end states were be broadly categorized as either a *Type I Engagement* or a *Type II Engagement* as shown in Table 5.

Table 5. Engagement End State Definitions

Weapon/Engagement End State	Type I Engagement	Type II Engagement
LASER	Burn though threat armor before the threat breaches the vital area	Threat armor failure under stress due to structural weakening
Microwave	Probability of death from exposure > 1% before the threat breaches the vital area	Exposure causes the pain threshold to be reached before the threat breaches the vital area
Conventional	Ability to intercept a threat before the threat breaches the vital area	Not applicable

1. LASER Model Development

In developing a mathematical model for LASER performance the textbook *Combat Systems*, Volumes 1–6 by Dr. Robert C. Harney, Senior Lecturer, Naval Postgraduate School, Systems Engineering Department, was predominately used. Additionally, subject matter expert input was received from Dr. Gary O. Langford, capstone advisor.

Two methods were considered as defeating a threat using a LASER: burn through and structural weakening. Burn through involves transmitting enough radiant energy such to melt and/or vaporize the target. The damage mechanism is to cause the threat material properties to degrade through erosion, evaporation, or melting. Structural weakening involves the buildup of energy on a target such that when the target is placed under dynamic stress (e.g., from moving very fast as in a missile or withstanding waves/wake as in a speedboat) the target structure fails before the point of melting or vaporization has been met. The process of calculating what it means to “kill” a threat with a LASER is outlined in Chapter 17 of Combat Systems Volume 3. It involves calculating the amount of fluence, measured in Joules per square-centimeter, required to melt a threat material, and then calculating the amount of fluence over time (the intensity in Watts per square-centimeter) that can be applied to a target via a LASER. A method of calculating that fluence is given in *Combat Systems Volume 3*, equation 17.8.

$$F = \rho * h * \left(C_p * (T_{melt} - T_{ambient}) + \Delta H_{fusion}\right) * \left(\frac{1}{1 - R_f}\right)$$

Equation 2. Target LASER Fluence for Type I Engagement

In order to calculate fluence, the threat's density (g/cm^3) ρ, thickness (cm) h, specific heat (J/g-K) Cp, melting temperature (K), ambient temperature (K), reflectivity (%) R_f, and heat of fusion (J/g) ΔH are determined. For all analysis, ambient temperature was assumed to be 15° C. The fluence for a Type II Engagement was estimated by dividing by 6. This factor of one-sixth is an estimate for all LASER between 0.6 to 10.6 microns (based on an interview with Dr. Gary Langford, citing empirical data from gasdynamic and chemical laser fluences on military hardened targets in the marine environment). The effects of the atmospheric absorption, thermal blooming, turbulence fostered beam wander, beam jitter, and beam divergence, and beam width and quality factors (profile and astigmatism) contributed to this factor of 6 reduction in fluence.

In order to simplify the GINA model inputs and make use of the data available for evaluation, the following assumptions were made for LASER analysis. In order to combine multiple beams into a single beam, we assumed that the adaptive optics in the beam director perform as advertised and that the individual beams are combined in phase to form a single coherent beam, spherical, Gaussian beam. The radiation was assumed to be continuous wave, not pulsed. Aerodynamic induce erosion of the surface material of the threat was incorporated into the factor of one-sixth use to calculate fluence. The ambient temperature of the threat material was assumed equal to the ambient temperature of the environment. And, atmospheric attenuation included scattering and absorption, but not turbulence (issues also incorporated into the factor of one-sixth used to calculate fluence).

The minimum LASER inputs for engagement modeling were determined to be peak output power (Watts), aperture/lens diameter (meters), wavelength (meters), and the Gaussian beam matching factor (unitless). Additionally, the total atmospheric attenuation (dB/km) (scattering + absorption) and the target range (meters) are necessary model inputs. Using these inputs, the following parameters can be calculated: Gaussian beam waist, Rayleigh range, beam half angle, beam divergence, spot size at range, peak intensity at range, and average intensity at range. These parameters can describe a Gaussian beam as shown below.

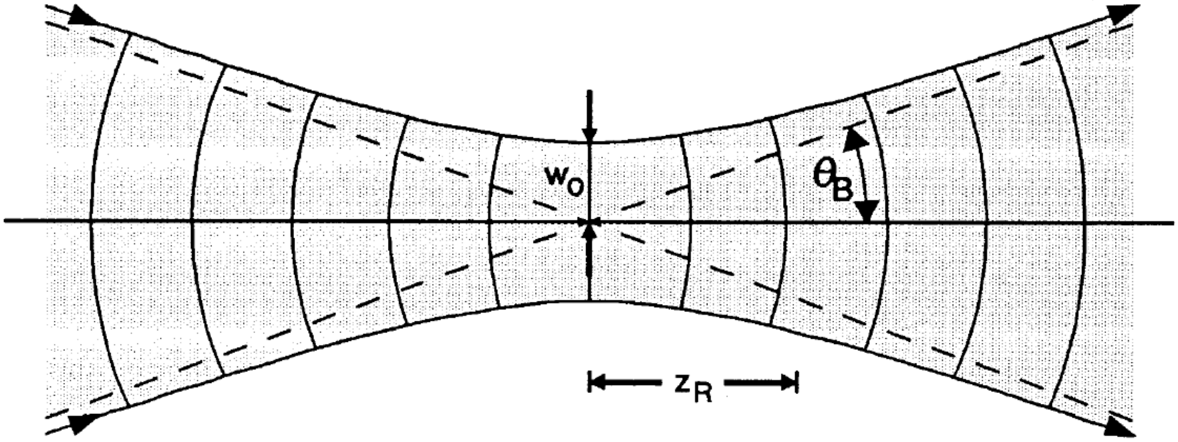


Figure 14. Gaussian Beam Profile Characteristics (from Harney, Combat Systems Volume 2 2004, 1004)

From *Combat Systems Volume 2,* equation 3.7, the beam waist is calculated as:

$$W_0 = \frac{D}{\sqrt{M}}$$

Equation 3. Beam Waist

D is the aperture diameter and M is the Gaussian beam matching factor. The square root of M is “the number of beam waist distances that can fit across the aperture diameter. *M* is typically between 5 and 8" (Harney, Combat Systems Volume 2 2004, 1026). Unless provided by the manufacturer, our model assumed M = 6.5.

From *Combat Systems Volume 2*, equation 3.37, the Rayleigh range is calculated as:

$$Z_R = (\pi D^2)/(M\lambda)$$

Equation 4. Rayleigh Range

From *Combat Systems Volume 2*, equation G.69, the beam half angle divergence is calculated as:

$$\theta_B = \frac{\lambda}{\pi * W_0}$$

Equation 5. Half Angle Beam Divergence

From *Combat Systems Volume 6*, equation M.6, the beam full angle divergence at the 1/e power points is calculated as:

$$\varphi = \sqrt{2} * \theta_B$$

Equation 6. Full Angle Beam Divergence (1/e power point)

With these values, you can then calculate the peak intensity on the target at range R (meters) from Combat Systems Volume 6, equation M.5.

$$I_{pk} = \frac{4 * P * e^{-\alpha * (\frac{R}{1000})}}{\pi * ({W_0}^2 + R^2 * \varphi^2)}$$

Equation 7. Peak Intensity at Range

α is the total atmospheric attenuation coefficient in km^{-1} and P is power in Watts. Intensity is given in Watts per square meter. To convert to Watts per square centimeter, you must divide by 10,000. As part of the GINA model, in order to calculate atmospheric attenuation, a MODTRAN 5 integration program was written. The output from MODTRAN 5 is transmittance through the slant range, which replaces the $e^{-\alpha(R/1000)}$ term with T, which is the percentage of total Intensity output from the LASER that is received on the threat. Due to the factor of one-sixth used to calculate fluence, this is a very conservative estimate for intensity received by the target.

Peak intensity is at the very center of the LASER beam and falls off with a Gaussian profile. This profile is shown in Figure 16 from Combat Systems Volume 6, Appendix M. Jitter, which is the random movement of the LASER beam in space, normally measured in micro-radians per second, will slew and break up the point of peak intensity on the target, sometimes creating “hotspots” that are displaced from the geometric center of the beam. A nominal value for jitter is about 10 µRad/s (Harney, Combat Systems Volume 3 2004). Over several kilometers jitter has the potential to reduce significantly the ability to focus the LASER beam at the target. Therefore, jitter must be accounted for in some manner. Figure 15 shows a sample error analysis for factors affecting total energy on target. In this example the total intensity is reduced by about 30% due to jitter. However, the project team did not have access to weapon control metrics, jitter values, or beam quality definitions (which vary widely across the LASER community (Harney, Associate Professor, NPS Systems Engineering Department 2013)).

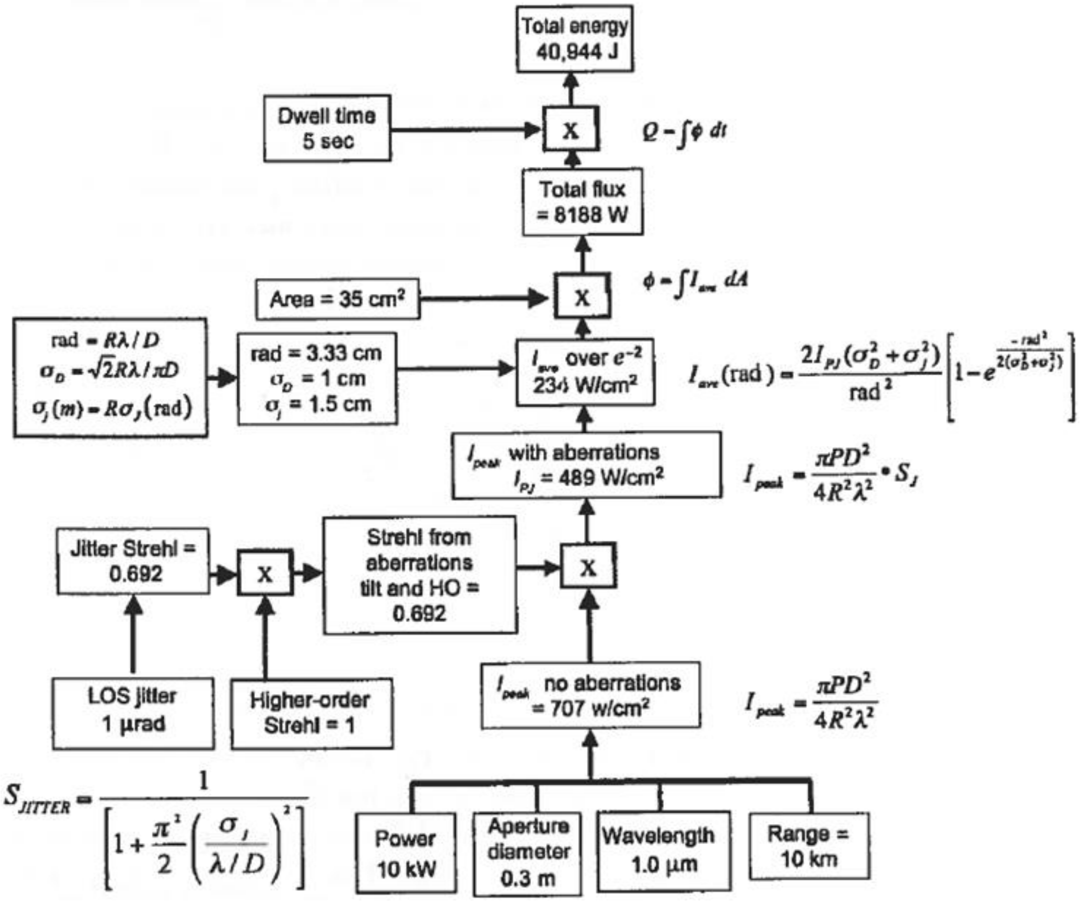


Figure 15. Sample LASER Beam Error Budget (from Merritt 2011)

Since the project team did not have access to the data required for a full LASER beam quality analysis, it was the recommendation of Dr. Robert Harney and Dr. Gary Langford to include jitter in the fluence calculation, by assuming that suitable control systems have been developed, as evidenced by the fact that each of these systems has successfully engaged targets in operational testing. Therefore, we accounted for jitter by using average intensity over the beam spot size. That being said, without confirmation of the specific beam control parameters associated with each system, it is possible that the intensity predicted using this method was overestimated by as much as 30%. However, we attempted to correct for that by adjusting our assumed target reflectance to match actual tests results that have been reported in open sources. We recommend that further analysis be done with the actual data to confirm these results.

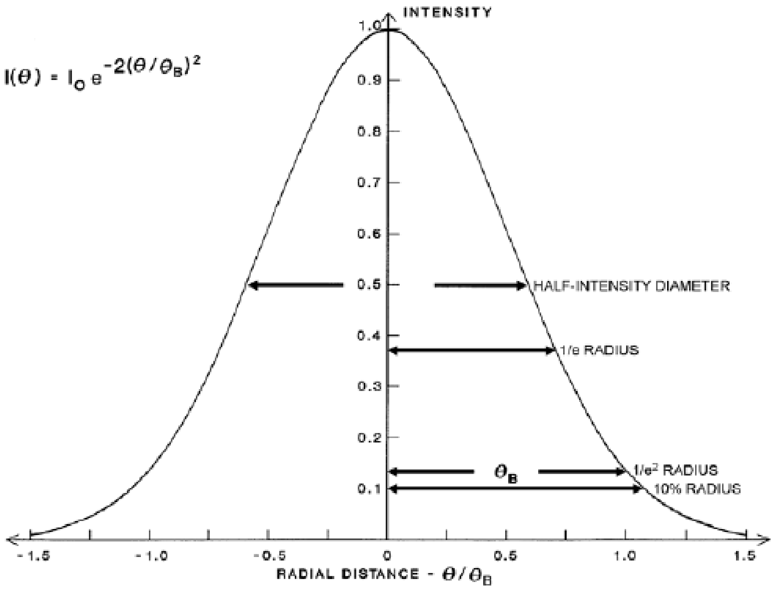


Figure 16. Gaussian Beam Intensity Profile (from Harney, Combat Systems Volume 6 2011)

To account for the fact that jitter reduces the peak intensity and will move the beam such that point of peak intensity will not necessarily be held on the same point on the threat body throughout the engagement, we first assumed that instead of the 3-dimensional Gaussian profile, that the beam intensity profile is conical (Figure 17), which is much simpler to calculate as a triangular distribution rather than a truncated normal distribution. If the peak intensity is the height of the cone and the jitter-expanded beam spot size is the base of the cone, then the volume of the cone is the total intensity at range R in the LASER beam. This triangular geometry makes analysis fast and less error prone by eliminating the integral and truncating the intensity to the relevant area around the target. To calculate spot size, accounting for jitter with a triangular geometry, we used the following parameters: beam waist without jitter at the target (calculated with Equation 8), the range to the target, the wavelength and the sine of the angle of jitter multiplied by the range to the target as shown in Figure 17.

$$W_R = W_0 * \left(1 + \left[\frac{R}{Z_R}\right]^2\right)^{1/2}$$

Equation 8. Gaussian Beam Spot Size at Range (from Svelto 2010, 153-155)

Using the spot size W_R as a baseline, we then expanded that spot size to account for jitter by using the sine of the jitter angle multiplied by the range to the target and added that value to the original spot size to calculate an expanded spot size as shown in Figure 17.

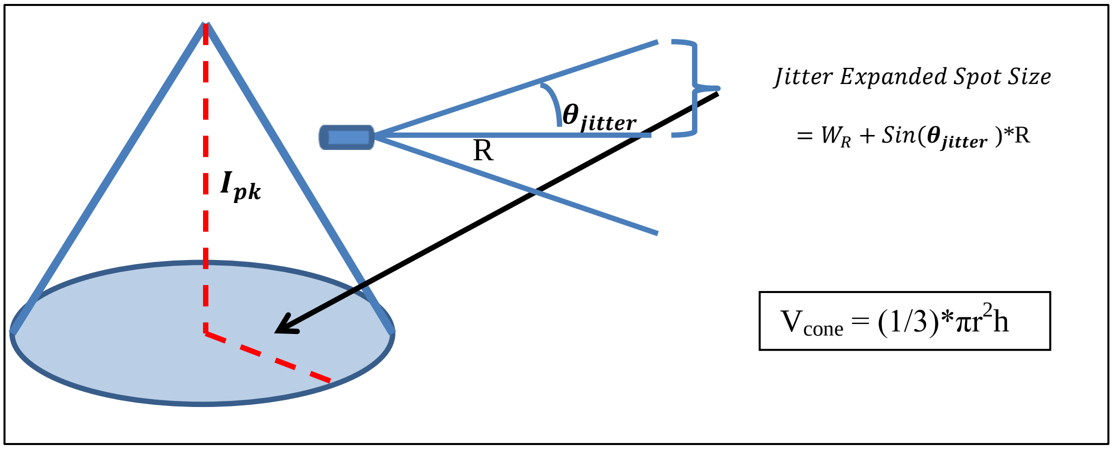


Figure 17. Conical Intensity Profile Approximation of Gaussian Profile

The total intensity in the beam at the range of the target distance was computed as volume of the cone (integrate over the jitter expanded spot size). Dividing the total intensity by the area of the spot size gives the average intensity in the beam in the spot on the target. Then we take the average power in the beam spot at any range to be one-third of the peak intensity at that range. The average intensity is a good, conservative estimate and it does not rely on testing to get the actual jitter value. The factor of one-third accounts for targeting/slewing system contributions to jitter and eliminates the need for detailing the beam intensity fluctuating over the target.

Calculating the average intensity at a given range, facilitates the summing up of the beam the intensity over time (e.g., per second, in units of Joules per square-centimeter on target in 1 second) over the entire engagement range. This formulation of beam intensity on target can then be used to solve for the number of Type I and Type II Engagements possible against a given threat over a specific range. Fluence for a Type I Engagement is calculated using Equation 2.

$$Number\ of\ Type\ I\ Engagements = \frac{Total\ Fluence\ Over\ Range}{Fluence\ for\ Type\ I\ Engagement}$$

Equation 9. Number of LASER Type I Engagements Possible

$$Number\ of\ Type\ II\ Engagements = \frac{Total\ Fluence\ Over\ Range}{\frac{Fluence\ for\ Type\ I\ Engagement}{6}} = \frac{Total\ Fluence\ Over\ Range}{Fluence\ for\ Type\ II\ Engagment}$$

Equation 10. Number of LASER Type II Engagements Possible

This method of calculating kills by a LASER weapon is superior to the conventional models of evaluating kills when applied to LASERs because it allows for the gradual deposit of energy onto a target over time in an engagement unlike current combat models that would evaluate a LASER kill as instantaneous (just like an exploding bomb would be modeled) which is more comparable to predicted Mega Watt class LASER weapon performance (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2012). In order to incorporate this method of calculating kills, an analysis class was written in Visual Basic .NET to be integrated with the GINA model, enabling on-the-fly calculations. The code is available in Appendix D.

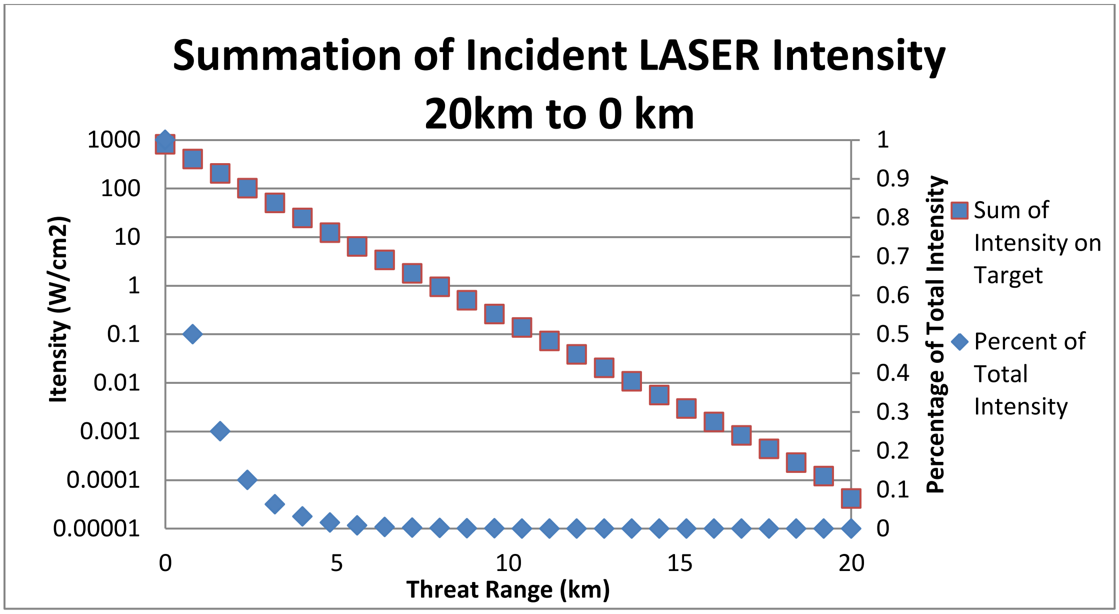


Figure 18. Sample Maritime LASER Demonstration (MLD) Intensity Profile over 20km Against a Mach 1.8 Threat

A simple spreadsheet analysis of this method of integrating intensity over range was performed in order to verify the project code used with GINA. The intensity received versus range was calculated and summed over all range increments during the engagement. Figure 18 shows intensity per range based on the 105 kW MLD LASER and a threat closing at 800 m/s. We chose to use an integral approximation of the total intensity on the threat by using a 1 second time increment for the numerical summation. By evaluating the Rayleigh Range of the LASER and the amount of intensity at the target range, it was clear that the Rayleigh Range represents a maximum tactical range because the intensity level at the Rayleigh Range, as a percentage of the total fluence required for a Type I or II Engagement, is so miniscule that to attempt to engage a target at or beyond that range would be a waste of power for the weapon platform as it would not produce any relevant damage effects against a non-human target at that range. Therefore, it is necessary to evaluate what the actual maximum effective range of the weapon is against military equipment, hardware, and structures. By inspection of sample LASER data presented in Figure 18, we decided to assume that the maximum effective range of a

LASER weapon is the range at which the total intensity of the LASER accumulated on the target equals 1% of that required for a Type I Engagement. The threshold of 1% was an arbitrary choice, but it is justified because the range at which 1% of the fluence necessary for a Type I Engagement is accumulated can be thought of as the "trigger range," at which the weapon can begin to effectively (having measurable and noticeable damage effects) engage a given threat which is shown by the knee in the curve in Figure 18. This calculated maximum effective range will be unique to different threat types/materials and speeds for the same LASER weapon. Another way to think of this definition of maximum effective range is that any potential engagements attempted beyond this range are wasting power and cooling resources on the weapon platform due to a miniscule amount of intensity being received at the target due to normal range loss as well as atmospheric attenuation. As the range to the target increases beyond the Rayleigh Range, the triangular factor of one-third is insufficient to account for the effects of jitter (due to larger spot size and lower peak power) and a factor of one-sixth is more appropriate (at 2 to 3 times the Rayleigh Range) (Langford, Senior Lecturer, SE Department, Naval Postgraduate School 2013). Therefore, the GINA model specified all detection ranges to be less than or equal to the Rayleigh Range for LASER weapon engagements.

$$
\begin{aligned}
&Total\ Fluence\ on\ Target \\
&\quad = \int_{Vital\ Area\ Radius}^{Detection\ Range} \frac{1}{3} * PeakIntensity(Range)\ dRange \\
&\quad \approx \sum_{Time\ Finish}^{Time\ Start} \frac{1}{3} * PeakIntenstiy(R(t))
\end{aligned}
$$

Equation 11. Threat Kill Fluence Integral Approximation

2. Microwave Model Development

When considering what it means to have a Type I Engagement and Type II Engagement with a microwave weapon, it becomes difficult to define clear metrics. There is little if any research in this area due to obvious ethical concerns of exposing humans to microwave radiation and then measuring the damage effects. Safety limits provide some insight, but most limits are orders of magnitude away from actual lethal/weapon's grade limits of exposure and are difficult to apply to weapon metrics.

Damage can be caused by a microwave weapon in two ways: thermal heating and electrical inductance. Electrical inductance was scoped out of the project because background research showed that microwave weapon interest was primarily as a non-lethal weapon against humans (Department of Defense Unkown). Thermal heating, as with a LASER, involves the accumulation of Joules over the threat surface area and some capacity for energy absorption leading to an increase in temperature. Unlike LASER weapons, microwave weapons, such as ADS, have been designed primarily as anti-personnel weapons with purposely less-than-lethal effects. One source that our research uncovered is a collection of empirical data published by the Institution of Chemical Engineers called *Thermal Radiation: Physiological and Pathological Effects*. This reference provides detailed analysis of thermal burns caused by radiation, explosions, and laboratory experiments over the past several decades. The empirical data shown allowed a relationship between intensity and time to reach the threshold of pain in addition to an average time to achieve a lethal dose.

To determine the intensity on target produced by a microwave weapon, peak output power, frequency, attenuation, threat range and antenna area were considered.

$$G = \frac{4\pi\rho A}{k^2\lambda^2}$$

Equation 12. Microwave Weapon Antenna Gain (Payne 2012, 35)

Microwave antenna gain is dependent on: antenna efficiency (%) ρ, antenna physical area (m^2) A, antenna constant of proportionality (assumed to be $4/\pi$) k (Payne 2012, 33), and microwave wavelength (m) λ. The antenna proportionality constant assumption is based on "an intermediate or typical pattern" because although the project team has pictures of the antenna, the actual antenna array configuration for ADS was unavailable (Payne 2012, 33). The antenna gain is then used to calculate intensity (normally referred to as irradiance for microwaves, but we used intensity to keep the same terms throughout the project as the units are the same). The equation used to calculate microwave intensity is a combination of a simplified microwave propagation equation from the text book *Principles of Naval Weapon Systems 2nd Ed.* and an atmospheric transmittance term from *Combat Systems Volume 3*. Although simplified, in that the propagation equation's gain component does not include detailed terms that might take into account factors such as electronics temperature during operations, and a more specific mathematical description of the antenna array's properties, the other terms remain the same with the addition of the attenuation term to the equation. Therefore, the intensity equation used is a valid way of calculating the intensity that can be adjusted in future studies with the simple addition of correction factors to account for more specific information that might then be available to study. To account for atmospheric attenuation, the intensity equation is multiplied by percent atmospheric transmittance (T) to calculate the actual intensity at the target.

$$I = \frac{P_{peak} * G * T}{4 * \pi * R^2}$$

Equation 13. Microwave Intensity on Target (Payne 2012, 39)

Table 6. Irradiance and Pain Threshold for Microwave Radiation on Humans (from Hymes, Boydell and Prescott, Thermal Radiation: Physiological and Pathological Effects 1996, Table 4.3 & 4.4)

Irradiance (kW/m2)	Time to Pain Threshold (S)
3.7	20
4.2	13
5.2	10
6.2	10
6.3	8
8.4	5.5
9.7	5
14.5	3
18	2

Table 6 shows various amounts of irradiance (intensity) incident on humans and the average time in seconds to reach their threshold for pain. Using power regression, a relationship between intensity and pain can be constructed as shown in Figure 19.

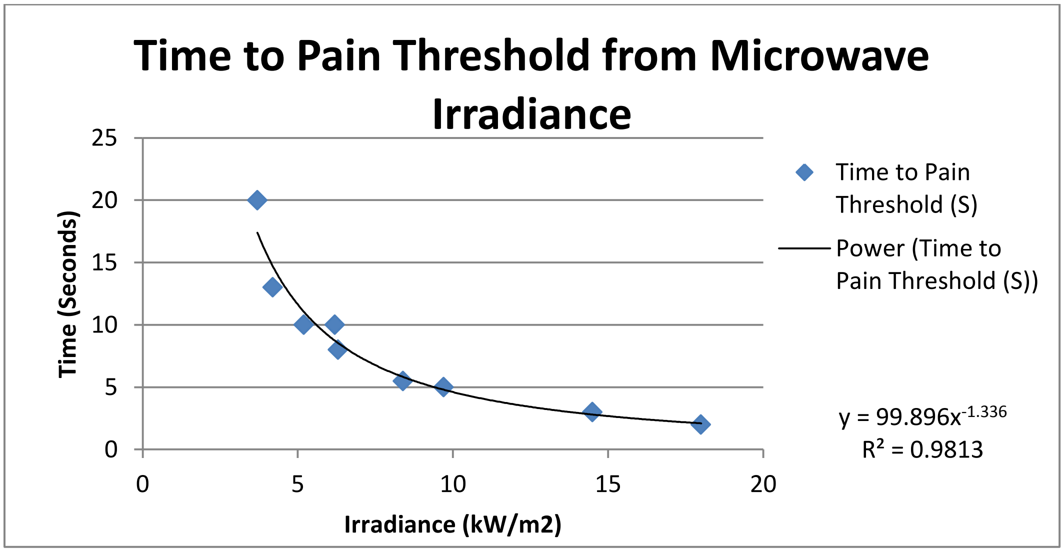


Figure 19. Time to Pain Threshold Regression

Additionally, *Thermal Radiation* provides a method of calculating radiation dose units, based on the intensity and the exposure time. This method provides a unitless and relative measure of radiation based on empirical data.

$$RadDose = t * I^{\frac{4}{3}} * 10^{-4}$$

Equation 14. Microwave Dose Calculation (from Hymes, Boydell and Prescott, Thermal Radiation: Physiological and Pathological Effects 1996, 21)

Time (t) is in seconds and intensity (I) is in kW/m^2. When the radiation doses are calculated for pain thresholds, the average dose is approximately unitless 92 ((Hymes, Boydell and Prescott, Thermal Radiation: Physiological and Pathological Effects 1996, 21).

To reach a lethal exposure limit, the dose must exceed unitless 1050, which corresponds to a 1% chance of death from exposure. It is important to note for the purpose of interpreting this analysis that a 1% chance of death essentially corresponds to the beginning of 2rd degree burns (which can be fatal depending on the percentage of the body that has been burned) (Hymes, Boydell and Prescott, Thermal Radiation: Physiological and Pathological Effects 1996, 2). This lower limit was chosen because microwave weapons, specifically ADS, have been sought out as a less-than-lethal options (LeVine, The Active Denial System: A Revolutionary, Non-lethal Weapon for Today’s Battlefield 2009), and it is important to understand when to turn off the weapon, how long to radiate for, or whether some variable power option is needed. At unitless 2300, the probability of death increases to 50% (Hymes, Boydell and Prescott, Thermal Radiation: Physiological and Pathological Effects 1996, 2). The dose level for a lethal dose is approximately one order of magnitude greater than required to reach the pain threshold. This lethal dose corresponds to the rule of thumb that safety exposure limits for electromagnetic radiation are about one order of magnitude less than the actual lethal limit (Harney, Associate Professor, NPS Systems Engineering Department 2013). For follow-on research, it should be noted that the four thirds exponent is based on data that was derived from many sources of burns, not just radio-frequency burns, and can (and should) be adjusted to correspond to actual test data.

$$P(death) = 2.56 * \log\left(I^{\frac{4}{3}} * t\right) - 14.9$$

Equation 15. Lethality Probability from Radiation Exposure (from Hymes, Boydell and Prescott, Thermal Radiation: Physiological and Pathological Effects 1996, 36)

We constructed a spreadsheet model of the source data to confirm (that by dividing the intensity by 10 (1 order of magnitude), and substituting that value into the regression equation for pain) the resultant time to reach the lethal limit. This lethal limit was confirmed by using the original intensity, and the calculated lethal exposure time back into the radiation dose formula, which consistently produced a radiation dose between the 1% and 50% probability of death limits. Therefore, an accurate method of calculating microwave weapon Type I and Type II Engagements was derived and validated.

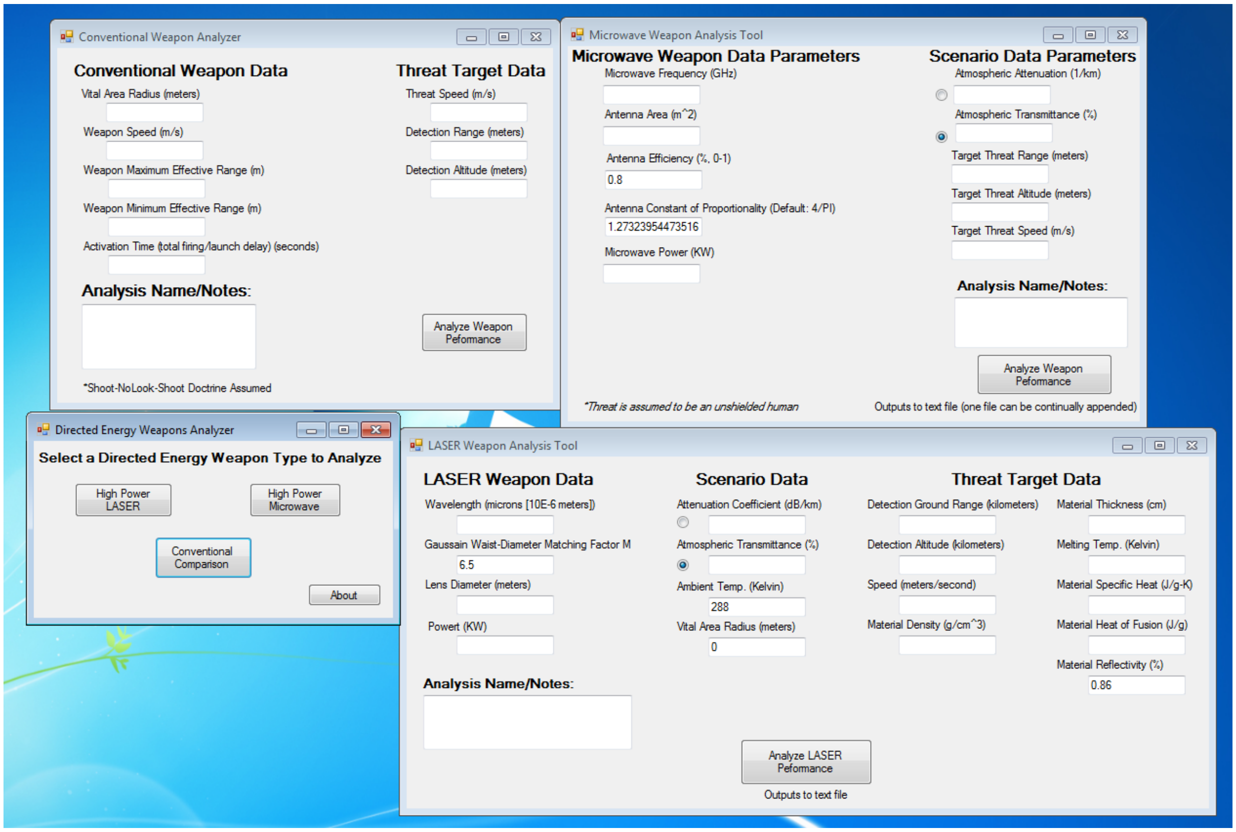
$$Number\ of\ Type\ II\ Engagements = \frac{99.896 * I^{-1.336}}{Total\ Engagement\ Time}$$

Equation 16. Microwave Type II Engagements Possible

$$Number\ of\ Type\ I\ Engagements = \frac{99.896 * \left(\frac{I}{10}\right)^{-1.336}}{Total\ Engagement\ Time}$$

Equation 17. Microwave Type I Engagements Possible

For both LASERs and microwaves, the total engagement time is equal to the detection range of the threat divided by the threat speed. The equations for calculating microwave Type I and II Engagements were translated into Visual Basic .NET code and incorporated into the DEWAnalysisSEA19B class, see Appendix D.



Antenna Efficiency (%, 0-1): 0.8

Antenna Constant of Proportionality (Default: 4/PI): 1.27323954473516

○ Atmospheric Attenuation (1/km)

● Atmospheric Transmittance (%)

Gaussain Waist-Diameter Matching Factor M: 6.5

○ Attenuation Coefficient (dB/km)

● Atmospheric Transmittance (%)

Ambient Temp. (Kelvin): 288

Vital Area Radius (meters): 0

Material Reflectivity (%): 0.86

Figure 20. Directed Energy Weapon (DEW) Analyzer Software Screen Shot

For testing the model during development (to ensure the equations were calculating properly) and in order to provide a quick analysis tool, a simple user interface was built into a DEW Analyzer application (Figure 20). This application allows the user to input the weapon and threat characteristics and export to text file (with an optional CSV file for easy import into Excel) the engagement effectiveness in terms of Type I and Type II Engagements possible.

3. Conventional Weapon Comparison

In order to make a usable comparison of DEWs to existing weapons, a method of calculating the effectiveness of conventional weapons must be made in the same terms as DEWs. For the purposes of the GINA model, and in accordance with the current modeling paradigms which express conventional weapon success as a binomial process, and do not account for a gradual accumulation of damage to a target (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2012), we assumed that conventional weapons were not capable of Type II Engagements. Therefore, in order to calculate the number of Type I Engagements possible, a linear engagement model was used with a designated boundary between Type I and Type II engagements. The GINA model assumes that if a conventional weapon can reach the threat before the threat has breached the vital area, then the weapon will achieve a Type I Engagement. We consider conventional weapons and DEWs on the same terms in order to attempt to achieve an accurate comparison.

This type of engagement analysis is based on missile engagement analysis in *Combat Systems Volume 6*, chapter 7. A depiction of this type of analysis is show in Figure 21.

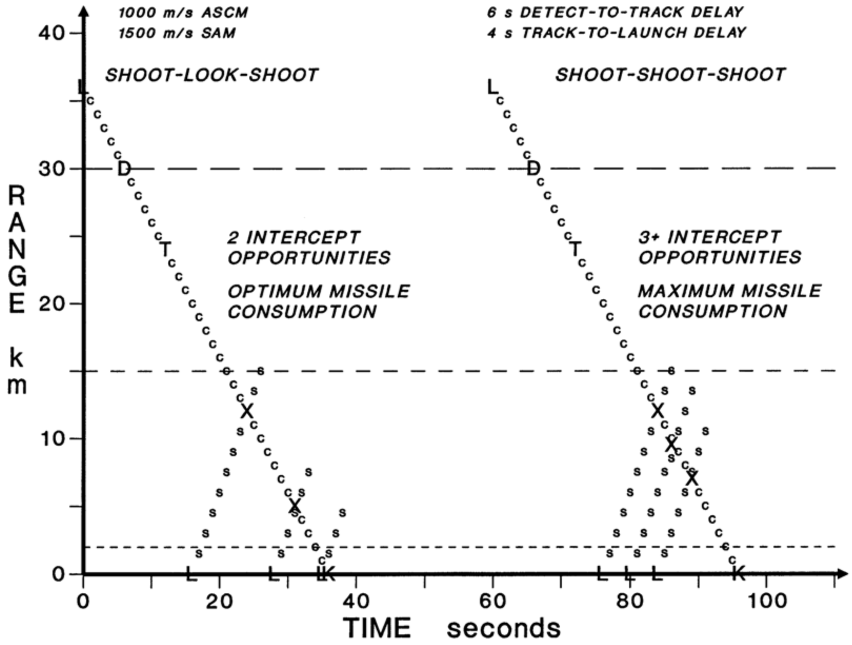


Figure 21. Simple Missile Engagement Analysis (from Harney, Combat Systems Volume 6 2011, 323)

The number of Type I Engagements possible is based on the threat detection range, threat speed, weapon launch delay, and weapon speed. The assumption is made that the engagement will not begin beyond the weapon's maximum range. By launch delay, we mean the total time between successive launches or firings (as we are extending this analysis to bursts of bullets, such as from the CIWS). This delay includes tracking, firing solution, launch preparation, and possibly re-targeting. Threat and weapon data used for this portion of the model is shown in Appendix E.

$$\mathit{Number\ of\ Type\ I\ Engagments} = \mathit{Truncate}\left[\frac{\mathit{ThreatSlantRange}/\mathit{ThreatSpeed}}{\mathit{WeaponLaunchDelay}} - \frac{\mathit{VitalAreaRadius}/\mathit{ThreatSpeed}}{\mathit{WeaponLaunchDelay}}\right]$$

Equation 18. Number of Conventional Type I Engagements Possible

4. Modeling Atmospheric Attenuation

For this project, MODTRAN 5 was chosen to model atmospheric attenuation for ship-based DEWs. While other radiative transfer programs have been written that give more precise results for the LASER region, MODTRAN 5 was acceptable and readily available for use by the project team. Also, there existed a wealth of knowledge in operating MODTRAN in the form of faculty at NPS. Finally, MODTRAN 5 is an "extensively validated…narrow band model" for use by the U.S. Department of Defense to calculate atmospheric attenuation over both the microwave and LASER wavelength regions of the electromagnetic spectrum (Spectral Sciences, Inc. 2012).

In setting up MODTRAN for use by the project team it was necessary to make several input assumptions for MODTRAN. The default Tape 5 input file format used is the Navy Maritime model (see Appendix F) which includes atmospheric data specified by the U.S. Navy. Table 7 outlines the specific assumptions that were made. All model values used were picked from the default MODTRAN 5 options, both of which (values and options) have been validated.

Table 7. MODTRAN Default Variable Options Selections (LASER Spectral Region) (from Berk, et al. 2011)

MODTRAN Model Variable	**SEA 19B Model Set Assumption**
Base Tape 5 File	NavyMaritime.tp5 (U.S. Navy base MODTRAN model)
Slant Path Option	Between 2 Altitudes, of which the weapon (H1) is always at 0
Model	1976 U.S. Standard Atmosphere
Season	Spring-Summer
Extinction	Maritime Extinction (23 km visibility)
Clouds	None
Rain Rate	Variable based on GINA Model: 0, 2, 5, or 10 mm/hr
Wind	7.2 m/s (from NavyMaritime option)
Wavelength DV	0.005 micrometers
Full Width Half Maximum (for slit function)	0.01 micrometers
Slit Function	Rectangular
Output	NavyMaritime.tp6: Average transmittance percent over center wavelength +/- 0.005 microns

For calculating microwave attenuation in MODTRAN 5, several adjustments were made to the input from the standard form used for the LASER spectrum. MODTRAN only accepts lower wavelength inputs in the form of wavenumbers in units of cm^{-1}. Therefore, prior to being executed the following conversion was made:

$$Wavenumber = 1/(\lambda * 100)$$

Equation 19. Wavelength to Wavenumber for Microwave in MODTRAN5 (from French 1971, 214)

Then in Card4, Flags1 and Flags2 must both be set to null (a blank space) and FWHM must be set to 0.1. This allowed MODTRAN to compute microwave attenuation accurately.

5. Atmospheric Model Global Information Network Architecture (GINA) Integration

In order to make an application accessible to GINA, it must have a well-defined application programing interface (API). MODTRAN is a fully compiled program with no such API available. Therefore, a “class wrapper” was needed to access MODTRAN through GINA. A class wrapper is used to “[marshal] data between managed and unmanaged code, on behalf of the wrapped object” (Microsoft 2013). In this case with our GINA model, the object is MODTRAN and we need to be able to define variables corresponding to the values that make up the input Tape 5 file that MODTRAN reads in order to compute atmospheric attenuation. The Tape 5 file would normally be edited in a text editor by the user. By defining variables for each file parameter, GINA can be used to pass the relevant data to the class wrapper, which then translates that data into the MODTRAN file format, executes the MODTRAN console application, reads the MODTRAN Tape 6 output file, translates that output value into a model relevant format, and then passes that value back to GINA for use in the GINA model. The process of data flow from user input to, to MODTRAN, and back to an output that the user can interpret is shown in Figure 22. The class wrapper code is available in Appendix G.

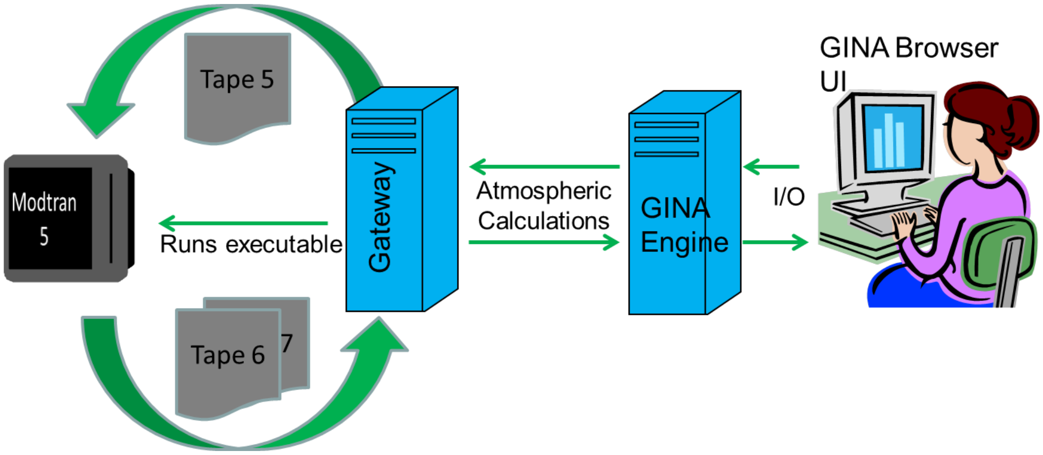


Figure 22. MODTRAN Class Wrapper Gateway for Global Information Network Architecture (GINA) Integration

The benefit of writing this class wrapper and placing it in the GINA context is that future variations of the model can take advantage of the class wrapper and context, and then incorporate any of the variables that have been hardcoded as predefined values and make them model inputs. Additionally, the class wrapper can be used by anyone else who needs to more easily access the input-output parameters of MODTRAN. A detailed software development process for the MODTRAN5 class wrapper can be found in Appendix H.

D. DIRECTED ENERGY WEAPON (DEW) MODEL VALIDATION AND ATMOSPHERIC EFFECTS

1. Model Data Collection

The only data available for analysis was unclassified, open-source data. If a parameter was missing that was necessary for carrying out analysis, we based our GINA model inputs on reference material and subject matter expert advice as shown in Table 8 (values in red italics). Table 8 represents the consolidated data available to the project team for DEW analysis. The model was built around the figures shown in Table 8. Conventional Weapon data used for comparative analysis is listed in Table 9.

Table 8. Directed Energy Weapon (DEW) Model Data Assumptions

System	Power	Wavelength/ Frequency	Aperture Diameter/ Area	Gaussian Beam Waist Matching Factor/ Antenna Constant	Antenna Efficiency	Power Efficiency
ADS	100kW (Miller and Svitak, NATO NAVAL ARMAMENTS GROUP Workshop on Counter Piracy Equipment and Technologies 2009, 5)	95 GHz (Department of Defense Unkown)	4.772 m^2 (Miller and Svitak, NATO NAVAL ARMAMENTS GROUP Workshop on Counter Piracy Equipment and Technologies 2009, 5)[2]	***4/π*** (Payne 2012, 33)	***0.8*** (Payne 2012, 35)	0.5 (LeVine, The Active Denial System: A Revolutionary, Non-lethal Weapon for Today's Battlefield 2009)
LaWS	33kW (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013)	1.064 µm (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013)	***0.66 m*** (Tressler 2010)[3]	***6.5*** (Harney, Combat Systems Volume 2 2004, 1026)	N/A	0.25 (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013)
LaWS+	150kW (Chernesky 2012)	1.064 µm (O'Rourke, Navy Shipboard LASERs for	***0.66 m*** (Tressler 2010)[2]	***6.5*** (Harney, Combat Systems	N/A	0.25 (O'Rourke, Navy Shipboard

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[2] Assuming a perfectly square array

[3] Estimated from CIWS installation diagram by counting 7.25 beam director's able to fit across 188 inches

		Surface, Air, and Missile Defense: Background and Issues for Congress 2013)		Volume 2 2004, 1026)		LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013)
MLD	105kW (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013)	1.064 μm (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013)	***0.49 m*** (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013)[4]	**6.5** (Harney, Combat Systems Volume 2 2004, 1026)	N/A	0.225 (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013)
TLS	10kW (Keller 2009)	1.6 μm (Keller 2009)	***0.3 m*** (Department of Defense 2010)[5]	**6.5** (Harney, Combat Systems Volume 2 2004, 1026)	N/A	0.30 (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013)

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[4] 1ft*2ft = A = π*(D/2)^2, ∴ D≈0.49m

[5] Based on an analogous system because the Air Force LASER is also small and low powered

Table 9. Conventional Model Data Assumptions

Weapon Designator	**Weapon Name**	**Weapon Speed (m/s)**	**Weapon Max Effective Range (m)**	**Weapon Type**
MK 15	Close-In Weapon System	1113	1490	CONV
MK 38 Mod 2	25mm Bushmaster	1100	2460	CONV
MK 54	5 Inch/54 Cal. Deck Gun	808	15000	CONV
RIM-116	Rolling Airframe Missile	681	9000	CONV
RIM-66 MR	SM-2 Block III Medium Range	1191	166680	CONV

Threat material data used to represent the armor that a DEW would affect to produce damage and thereby measure success in the GINA model also needed to be collected and input into the GINA model. Aluminum, Stainless Steel, Titanium, and Wood stood out in our research as those that would encompass most threats to be evaluated. Since melting temperature is not applicable for wood, the ignition temperature was substituted. During an engagement, the reflectivity of the threat will change due to oxidation, carbonization, and other thermal induced processes. Also, specific threat reflectivity values were not available (if known at all). Therefore, for all targets, reflectivity was assumed to be 86% (Langford, Senior Lecturer, SE Department, Naval Postgraduate School 2013). The specific data used in our analysis is consolidated in Table 10.

Table 10. Threat Material Thermal Properties Assumptions (after Stanmech Technologies, Inc. n.d.)[6]

Material	Density (g/cm^3)	Specific Heat (J/g-K)	Melting Temperature (K)	Latent Heat of Fusion (J/g)
Aluminum 1100–0	2.71264	1.00416	916.4833	393.094
Stainless Steel 430	7.7504	0.46024	1699.8167	452 (MATWEB.com n.d.)[7]
Titanium 99%	4.51184	0.54392	1933.15	434.962
Wood (Oak)	0.74736	1.2 (Massachusetts Institute of Technology 2009)[8]	755.3722 (HandyFacts.com n.d.)[9]	115.2 (Electronics Cooling 2008)
Fiberglass	0.026 (National Institute of Standards & Technology n.d.)[10]	0.844 (Massachusetts Institute of Technology 2009)	1394.15 (BFG Industries, Inc. 2004)	38 (Lux 2000)[11]

Prior to integration in the GINA model, the selected mathematical equations were validated using sample data that was assumed before the complete GINA model threat list had been finalized and actual GINA model threat data collected. The threat data used for validation (Table 11) was generated based on the project team's experience to represent some different, generic threats that might be representative of actual threats.

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[6] Unless otherwise notated in the table

[7] Approximated using ASTM A514 Steel, grade P

[8] Approximated as hard wood

[9] Ignition temperature

[10] R-15 blown fiberglass

[11] Approximated using Sulfur

The purpose of validating the model was to provide a range of generalized threat data to get an estimate of DEW performance, test the model assumptions, equations, and software, and draw some inferences about the DEWs selected for analysis.

Table 11. Validation Threat Data

Threat	Threat Material	Material Thickness (cm)	Threat Speed (m/s)
Low Slow Flyer (LSF)	Aluminum	0.5	77.17 (150 kts)
Fast Attack Craft/Fast Inshore Attack Craft (FAC/FIAC)	Aluminum	2.0	23.15 (45 kts)
Anti-ship Cruise Missile (ASCM)	Titanium	0.1	600 (Mach 1.8)
Hostile Person	Human Skin	N/A	4.5 (10 MPH)

2. Directed Energy Weapon (DEW) Model Validation

As part of the GINA model equation validation process, an analysis of the relevant atmospheric windows was conducted. An early concern was that ADS would be rendered completely ineffective by attenuation in the marine environment caused by scattering from aerosols such as sea spray and evaporation. Following an analysis of the atmospheric attenuation and by substituting realistic attenuation values into the GINA model equations for validation, it was determined that the attenuation effects on microwave radiation out to the maximum effective range of the ADS (about 700 yards as reported by the Air Force) did not result in a significant degradation in performance in the maritime environment as discussed below in the next section and shown in Figure 24.

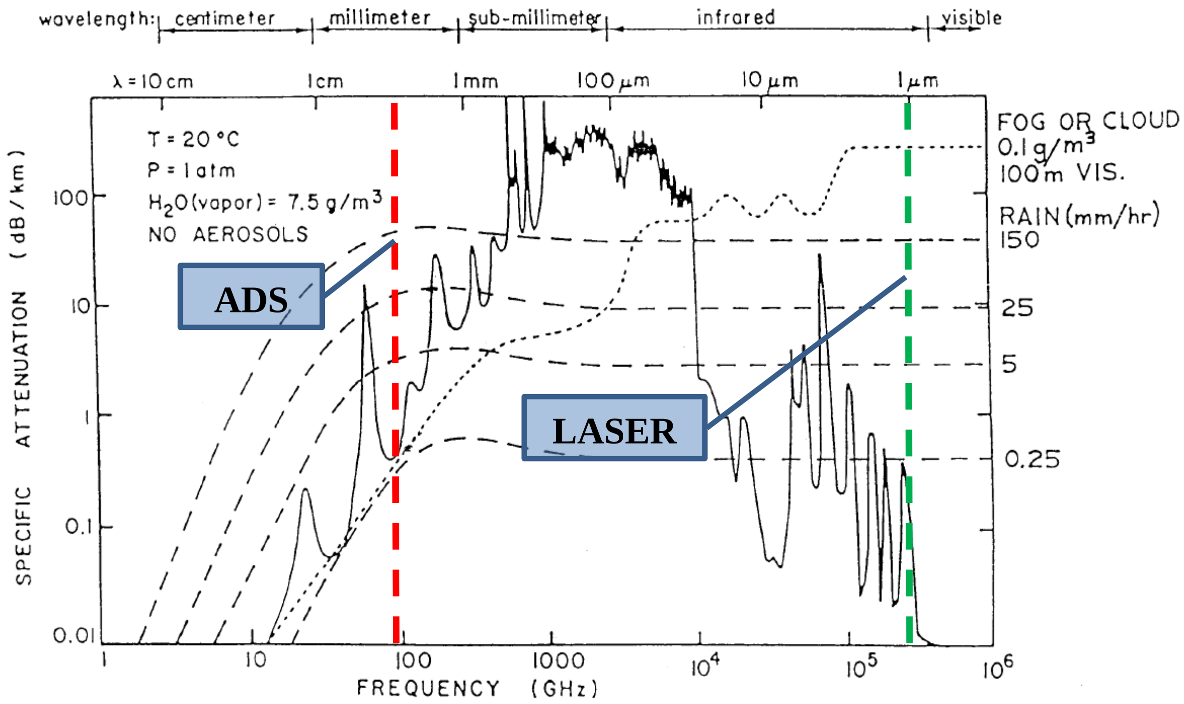

Figure 23. Microwave and LASER Attenuation (after Harney, Combat Systems Volume 1 2004)

Figure 23 above shows the effects of weather on wave propagation in the electromagnetic regions from microwaves to visible light, based on MODTRAN data. On the graph, the ADS and the approximate LASER frequencies/wavelengths are shown. When compared to RADAR systems which typically operate below 10 GHz, the 95 GHz ADS incurs significantly more attenuation, which only increases as humidity and other particulate matter is introduced. Comparing the ADS to a surface search RADAR, which can experience significant clutter in the maritime environment, lead to the early assumption by the project team that the ADS would not be an effective naval weapon.

3. Microwave Model Validation

In order to make an initial assessment of ADS's relevance in the marine environment prior to full GINA model implementation, we chose to evaluate the ADS under 3 atmospheric attenuation conditions: Clear (2 dB/km), Light Rain (3 dB/km), and

Heavy Rain (10 dB/km). The threat selected was a human approaching at 10 mph, presumably in a boat moving toward a pierside ship. The threat would begin approaching at 1,000 meters and close to 0 meters from the ADS on a completely horizontal path. The three weather conditions were evaluated to determine the relationship between the time to achieve a Type II Engagement and the type of weather. Surprisingly, the ADS performed much better than expected as seen in Figure 24. Even in heavy rain, the ADS performed well out to 350 meters.

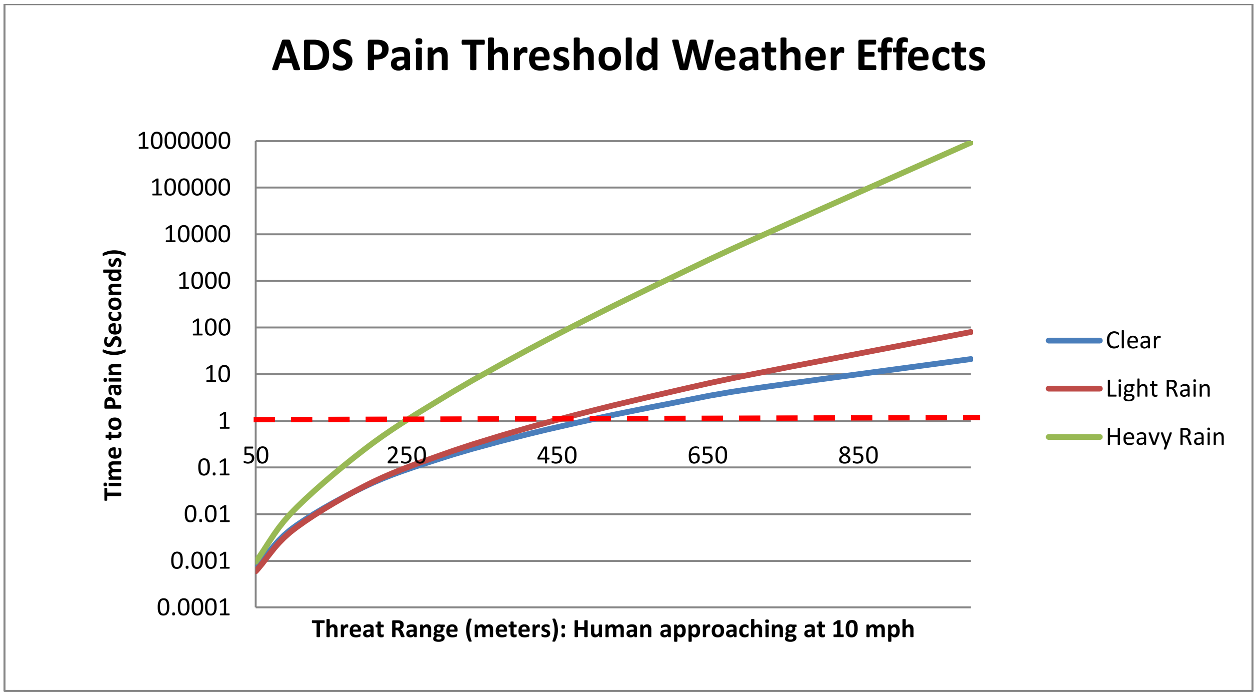

Figure 24. Active Denial System (ADS) Performance in Weather

The red line at 1 second in the ADS weather performance graph shows where the weapon is most effective. Any longer than 1 second to achieve a Type II Engagement means that the threat is not being heated quickly enough to cause the type of near-instantaneous pain necessary to force the threat to stop. Under heavy rain that range is about 250 meters and under light rain and clear conditions that range is about 450 meters. Light rain can be thought of as simulating sea spray during a small boat threat attack.

Therefore, based on this limited analysis, the offers added benefits to offer the Navy. During testing, most subjects were able to tolerate the microwave radiation for a few seconds at 700 yards (640 meters) (Ackerman 2012). If you look at the clear weather line, at 650 meters, it shows time to pain as about 2 seconds. Also, at 700 yards it has been reported that the ADS transmits 12 J/cm^2 (Ackerman 2012). The predicted intensity for a threat at 600 meters (656 yards) is approximately 16 J/cm^2, which is very close to the expected value based on Ackerman's data. Therefore, this analysis supports the use of the microwave mathematical model within the GINA model for predicting the real-world effects of high power microwave weapons.

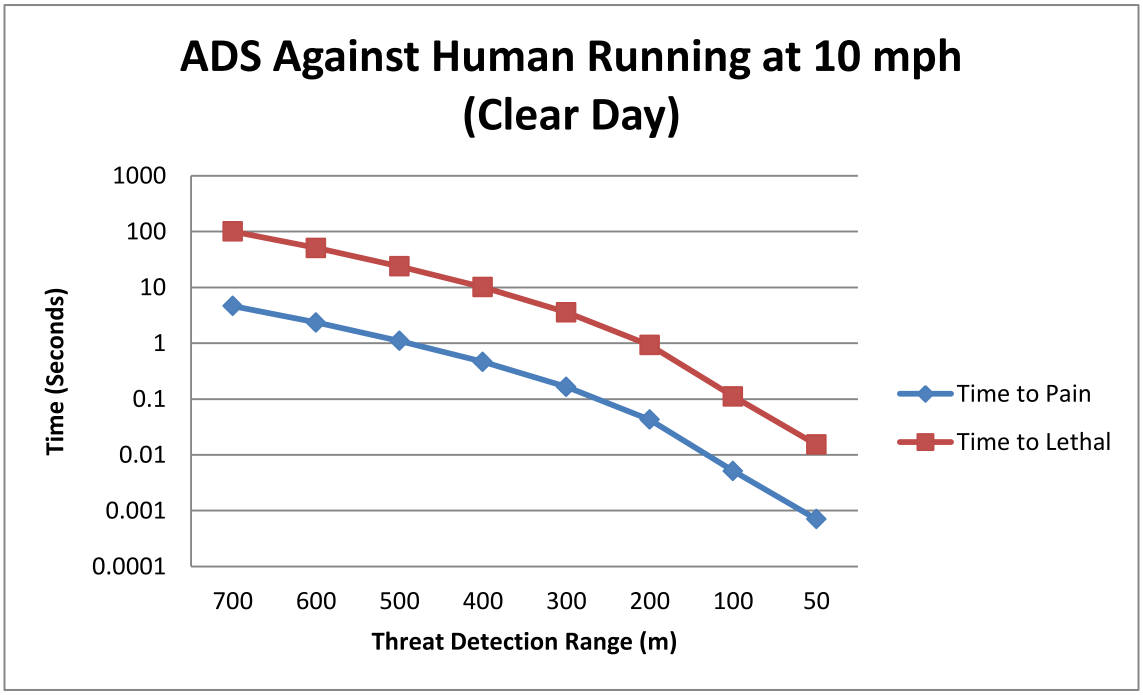

Figure 25. Active Denial System (ADS) Pain vs. Lethal Time Thresholds

In Figure 25, a slightly different interpretation of the same data used to evaluate weather effects can be compared to the threshold for lethality. Upon first inspection of this graph it may seem as though, unlike the actual field tests of the ADS, we are predicting a high probability of lethal effects. However, to interpret this data properly, the lethality definition must be fully understood. As previously discussed, the time thresholds predicted by the mathematical model will calculate the time in seconds to at least a 1% chance of death (actual percentages vary based on intensity and time between 1% and 50% based on the empirical data used to derive the mathematical model. The probability of death corresponds to the level of burn that can be expected, with the lethal threshold set at about a 2nd degree burn (which occurs at a radiation dose of unitless 1200) (Hymes, Boydell and Prescott, Thermal Radiation: Physiological and Pathological Effects 1996, 2). In actual tests, at least 2 subjects were hospitalized due to excessive exposure caused by a safety setting being bypassed in the ADS allowing a longer than intended burst of radiation to be emitted from the ADS (Tressler 2010). Since then, the ADS has been outfitted with a LASER range finder and radiation time controls (Weinberger, Pain Ray Test Subjects Exposed to 'Unconscionable Risks' 2008). Therefore, considering that the mathematical model assumes a continuous exposure at full power without a safety limitation (as in the actual system), then the results for lethal effects limits are valid. Further, should other systems, such as shipboard RADARs like the SPY-1D(V), with its dual beam capability, be modified to be used as an ADS type system then these lethality predictions are crucial to the evaluation of tactics for employing such a weapon if range safety controls are limited due hardware or software upgrade limitations stemming from the fact that a RADAR was not initially designed to be a DEW used to engage humans.

4. Microwave Model Sensitivity

In order to determine the effect of assumptions on the model results and to determine what differences in performance could be realized with changes to weapon technical parameters, a sensitivity analysis of the microwave model was conducted. The baseline case for this analysis was a 100kW microwave, operating at 95GHz, with a 4 m^2 antenna ($4/\pi$ constant), engaging a person running towards it at 4 m/s starting from a range of 700 m. Each parameter was varied from a lower limit to an upper limit given in Table 12.

Table 12. Microwave Sensitivity Factor Values

Parameter	Lower Limit	Upper Limit
Antenna Area (m^2)	1	10
Antenna Efficiency (%)	0.1	0.95
Antenna Proportionality Constant (unitless)	0.5	2.0
Power (W)	10,000	1,000,000

For each parameter, the values were varied from low to high while all other parameters were held constant. Minitab was then used to analyze the data (the full data set is available in Appendix I). Figure 26 shows how varying each parameter affects the microwave's ability to inflict pain on the threat. From a rough order analysis, after about 70 kW, diminishing returns decreases the improvement in time for pain per kW increase. Also, as long as a system's antenna is at least 50% efficient, the system will have tactically relevant performance. Both of these break points in performance are important to note when considering future investments into HPM technology or possible improvements to the ADS.

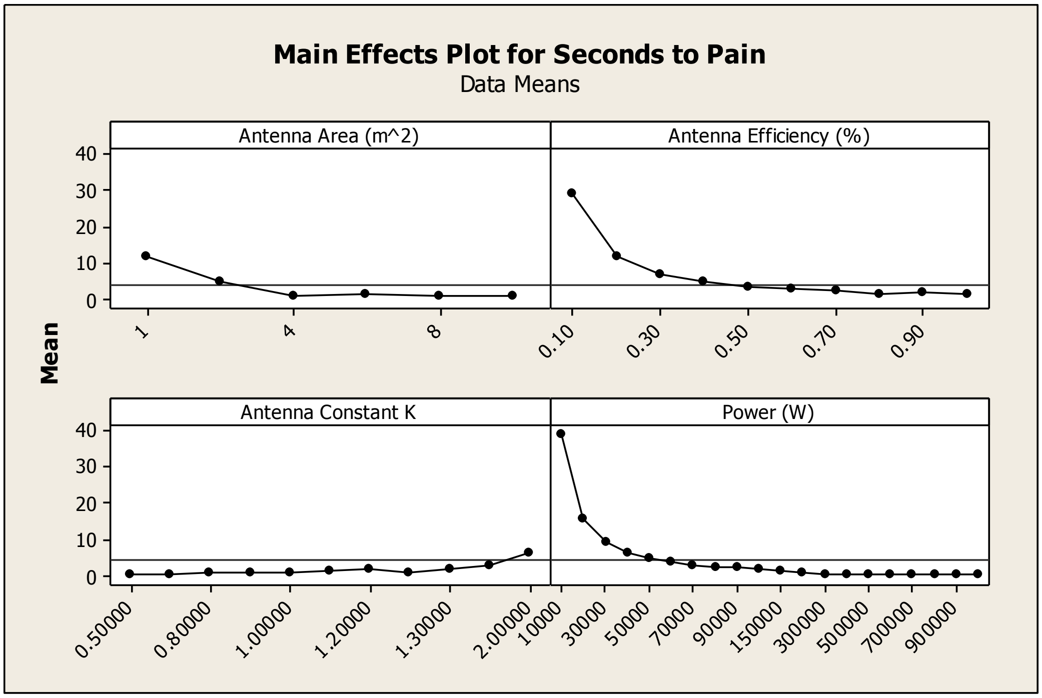

Figure 26. Main Effects Plot for Seconds to Pain (Microwave Model Sensitivity)

Figure 27 shows the same parameter variance effects, but with respect to the time required to have lethal effects. Since the ADS was not developed to have lethal effects, the performance is not very impressive, but if the goal was lethal effects, at the system should output at least 150 kW. Also, antenna efficiency must be higher in order to have lethal effects with reasonable power levels. As in the non-lethal analysis, after 4 m^2 increasing the area of the antenna has diminishing returns.

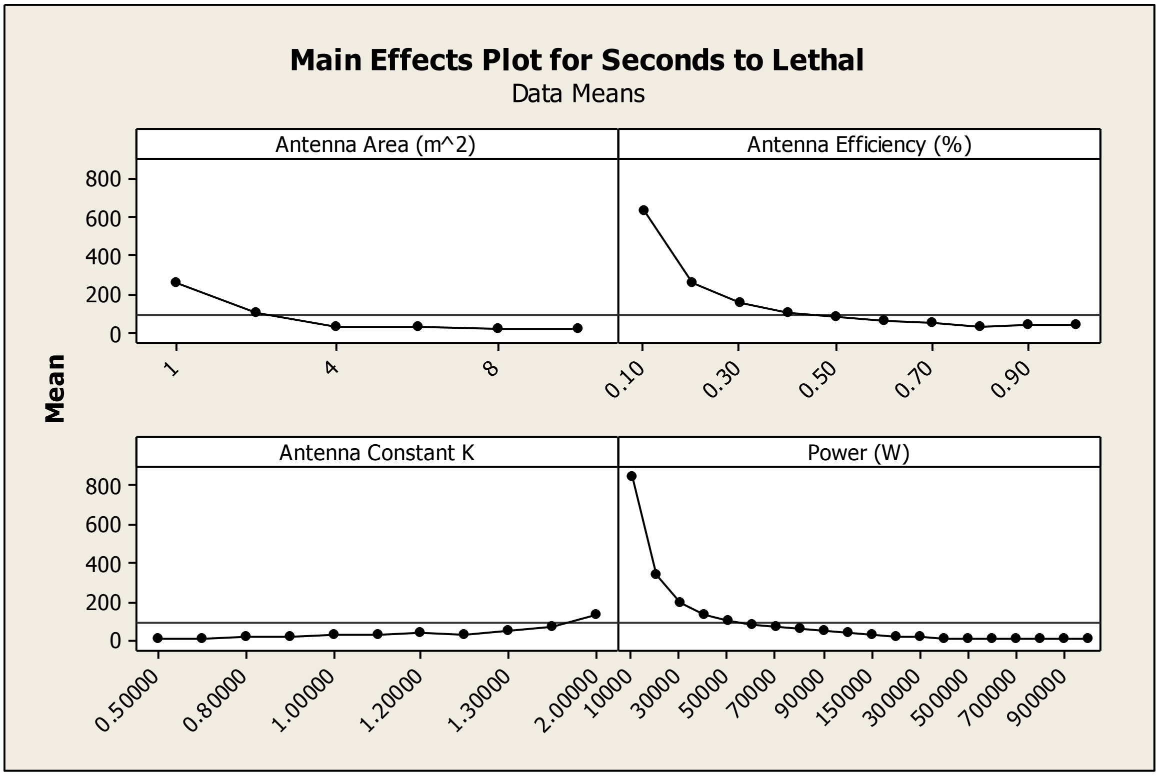

Figure 27. Main Effects Plot for Seconds to Lethality (Microwave Model Sensitivity)

In performing this sensitivity analysis, we also wanted to determine what design features would have the best return in terms of tactical performance. Figure 28 depicts the power level requirements to result in successful Type I and Type II engagements at desired times against a target moving 4 m/s at a distance of 700 yards and atmospheric attenuation is 0.5 dB/km.

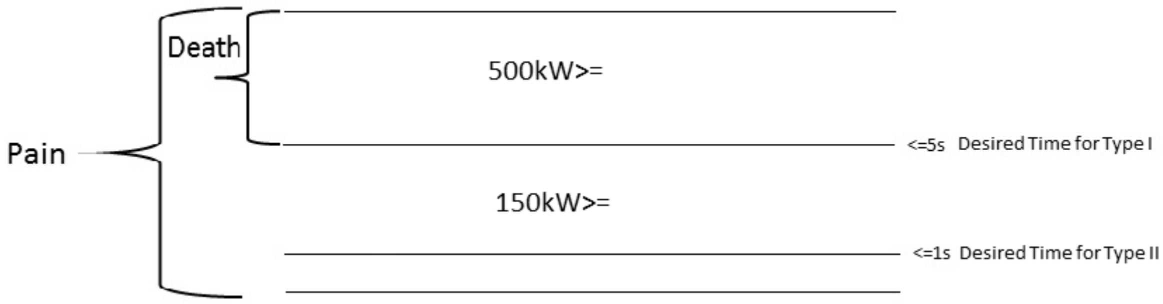

Figure 28. High Power Microwave (HPM) Type Effects

In order to obtain a Type II engagement where the target experiences near-instantaneous pain that leads to disengagement, we have assumed that target heating time has to be no more than 1 second. At 150kW, the effect is produced after an average time of 1.05 seconds which is on the cusp of the allotted timeframe. Therefore, power levels greater than 150kW will meet the 1 second timeframe. For Type I engagements, we have assumed that the heating time that produces a lethal effect has to be no more than 5 seconds. At 500kW and above, a lethal effect occurs prior to 5 seconds.

The ADS can operate at power levels up to 100kW. Figure 29 shows the times for the type effects of a target moving at 4 m/s at 700 yards when the power level is 100kW and atmospheric attenuation is 0.5 dB/km. At 100kW, the Type I and Type II effects are produced in 39s and 1.8s respectively. Although the Type I time is well over the 5 second time to lethality benchmark, it’s not alarming considering the underlying purpose of ADS is to perform non-lethal engagements. However, 1.8s is over the desired time to pain benchmark (less than 1 second). The extra 0.8s comes when the power is 30% less (100kW vice 150 kW) than the power requirement to reach the desired time to pain benchmark.

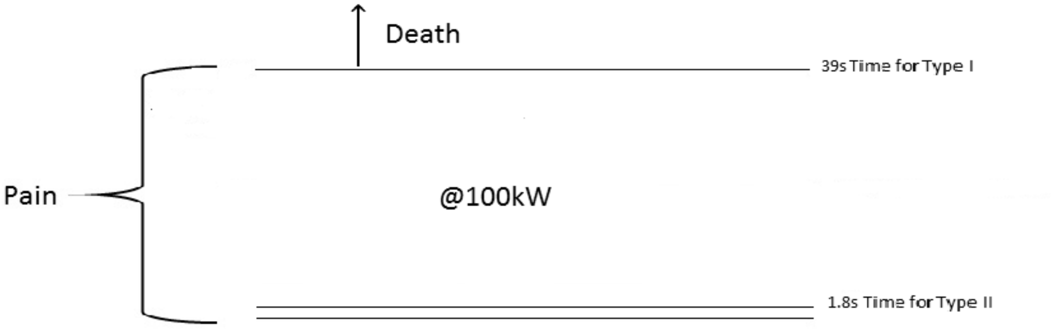

Figure 29. 100kW Type Effects

5. LASER Model Validation

A side-by-side analysis of the LASER weapons was also conducted. Additionally, since the value for the Gaussian Beam Matching Factor was assumed to be 6.5 for all LASER weapon systems, a sensitivity analysis was conducted to see what effect the Gaussian Beam Matching Factor has on results predicted by the mathematical model. The analysis of the LASERs was conducted assuming a clear day in a marine environment, with an equal attenuation for all systems of 0.8 dB/km, and reflectance of 89% from the target. Even though the TLS wavelength is different from the other LASER systems, the atmospheric attenuation analysis of the LASER region concluded that the difference was not significant enough to warrant a separate calculation of attenuation for the mathematical model validation. In all three validation analysis runs, the threats were assumed to be detected at 10km and were tracked inbound to 0km. Because of the logarithmic increase in intensity that is experience by the target as it closes the few hundred meters to the LASER weapon, this analysis evaluated the associated performance ranges, Maximum Effective Range, Range of First Type I Engagement, and Range of First Type II Engagement. The analysis did not account for the number of engagements possible and therefore assumed only one attacker.

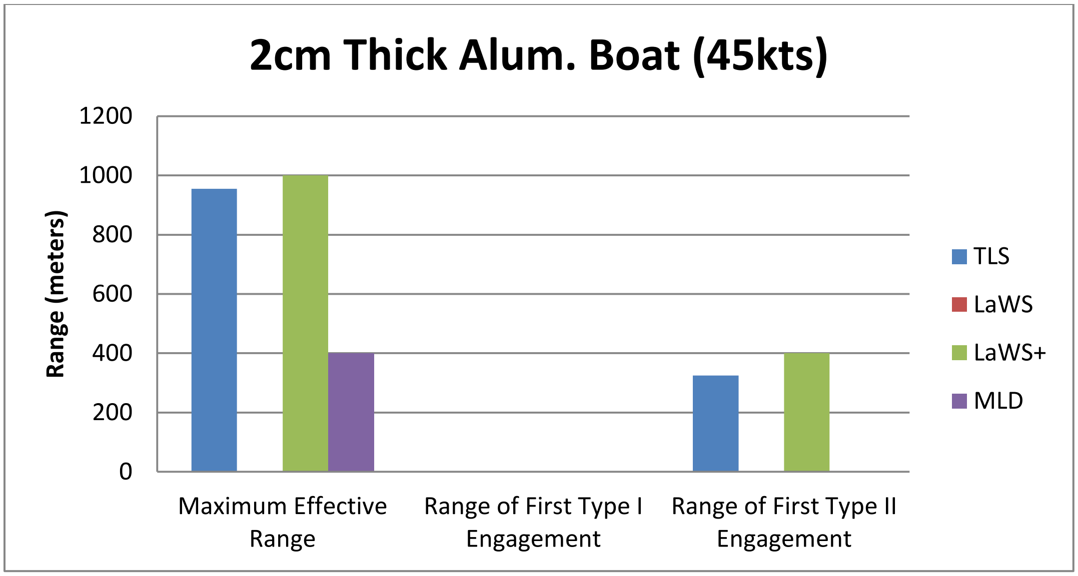

Figure 30. LASER Weapons vs. Aluminum Boat, Clear Day

The results of analyzing the aluminum boat test (Figure 30), indicated that the TLS outperformed the 33kW variant of the LaWS, and the 105kW MLD. This result was surprising due to the low power of the TLS at only 10kW. The reason for this notable performance lies with the wavelength of the TLS, which allows more power to be transmitted to the target than the other weapons. This fact is substantiated by a U.S. Government report, which indicated that the TLS, despite being low power, is on par with all of the other weapons being evaluated (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013). A conservative view of a LASER system defending itself (and the ship on which the LASER is installed) pits the LASER fluence against a pure aluminum boat hull (2cm). While the thickness maybe overestimated, the fluence required to "kill" a boat requires more than simply penetrating the hull. The technical realism in this view point posits a "hard" target against the LASER weapon as a more realistic engagement. Unlike the ADS that targets a fast moving inbound threat, LASER system test data is not available in an unclassified format; however, one article indicates that the MLD is effective in terms of miles not yards against a static threat (Brisbane Times 2011). Therefore, this single test cannot by itself be used to validate the model.

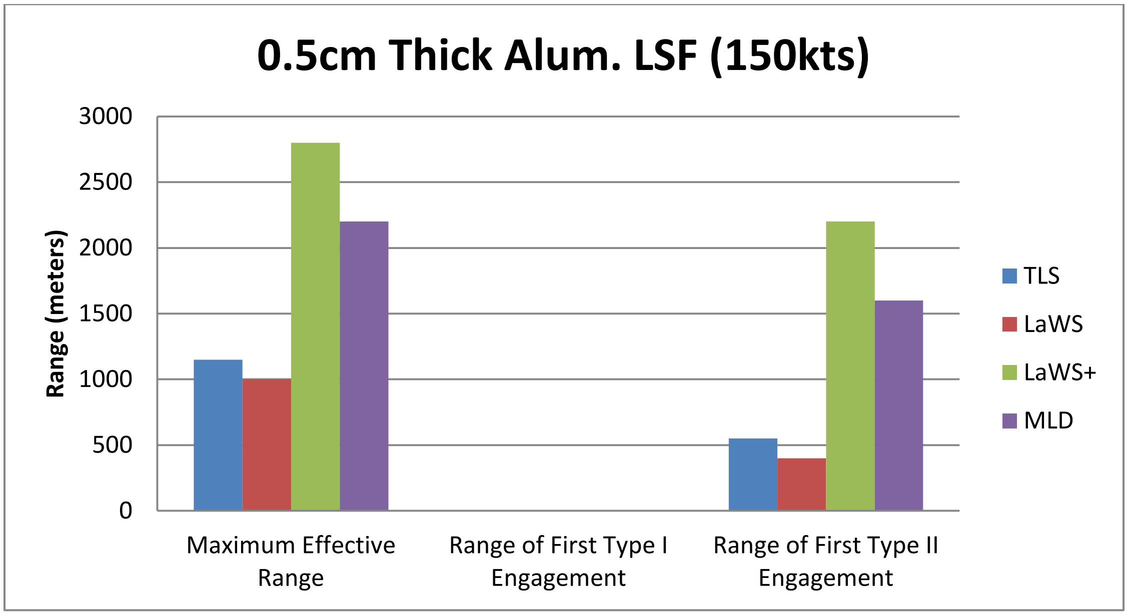

Figure 31. LASERs vs. Aluminum Low Slow Flyer (LSF), Clear Day

The next test against a representative low slow flyer (LSF) shows the effect of material thickness on weapon effectiveness, especially since this threat was moving at nearly 3 times the speed of the boat in the previous example (Figure 30). In this case the MLD performs effectively out to a nautical mile. Again, the TLS is on par with the LaWS. The MLD range modeled in this scenario is closer to the article's assertions of the weapon's effectiveness and points toward the model's validity, assuming that the article accurately reflects the results of the test.

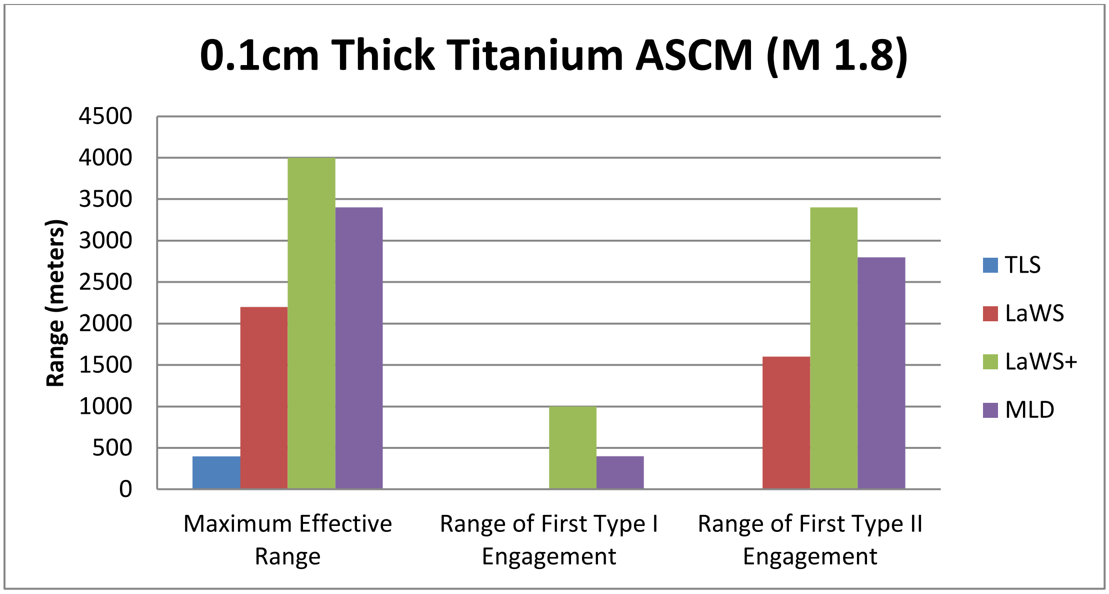

Figure 32. LASER Weapons vs. Titanium Anti-Ship Cruise Missile (ASCM), Clear Day

The anti-ship cruise missile (ASCM) preliminary analysis (Figure 32), like the ADS lethality analysis must be taken in context. At first glance, the graph appears to show that LASERs which have not been able to destroy missiles can in fact kill an inbound missile. However, the LaWS+ 150kW variant achieves a Type I Engagement at about 1,000 meters. This range and fluence is very close to the defending platform noting that the missile in this example is moving at Mach 1.8. Increasing the current 33kW LaWS to the 150kW LaWS+ may result in a system that can be used against missiles, a realistic target engagement. With regards to the Type II Engagement predictions, is the caveat suggests that a theoretical value determined by this analysis, assumes some amount of a titanium sheet will fail under dynamic stress (which certainly pertains to the ASCM scenario). However, this scenario does not include the structural components behind the skin or that the missile may be made of multiple materials. Actual field testing would seem appropriate to quantify that interaction. Although not substantiated in this report, the possible combining of a “lower” powered LASER may weaken an inbound missile so that systems like RAM and CIWS can conserve ammunition and missiles when used in conjunction. Finally, looking at the predicted maximum effective range for MLD in this scenario (nearly 3500 meters), the amount of intensity is indeed effective at the "miles" criterion as touted by the Brisbane Times article. Therefore, in lieu of classified test data and considering all 3 preliminary results in context, it is reasonable to assume that the LASER model is valid. Additionally, a review of the data by Dr. Gary Langford concluded that the model was producing realistic values based on his previous LASER weapon test experience.

6. LASER Model Sensitivity

LASER model sensitivity analysis examined the following factors: wavelength, lens/aperture diameter, output power, Gaussian beam matching factor (m), and target material reflectivity. Therefore, it was necessary to see what effect varying each parameter between high and low values (Figure 33) had. The upper and lower limits of the values used in the sensitivity analysis for each factor can be found below in Table 13 As a baseline, the 33kW variant of the LaWS was used against a titanium ASCM (Harney, Combat Systems Volume 3 2004) traveling toward the DEW at 100 m/s from a starting range of 10km. The unreasonably slow speed was chosen to provide ample time for energy accumulation on the target even at low performance settings in order to collect data for the analysis. This threat profile may realistically resemble a hardened military UAV.

Table 13. LASER Sensitivity Analysis Parameter Ranges

Parameter	Low Value	High Value
Wavelength	1.064 um	1.6 um
Lens Diameter	0.1 m	1.0 m
Gaussian Beam Matching Factor	5.0	8.0
Power	10 kW	500 kW
Target Reflectance	80%	99%

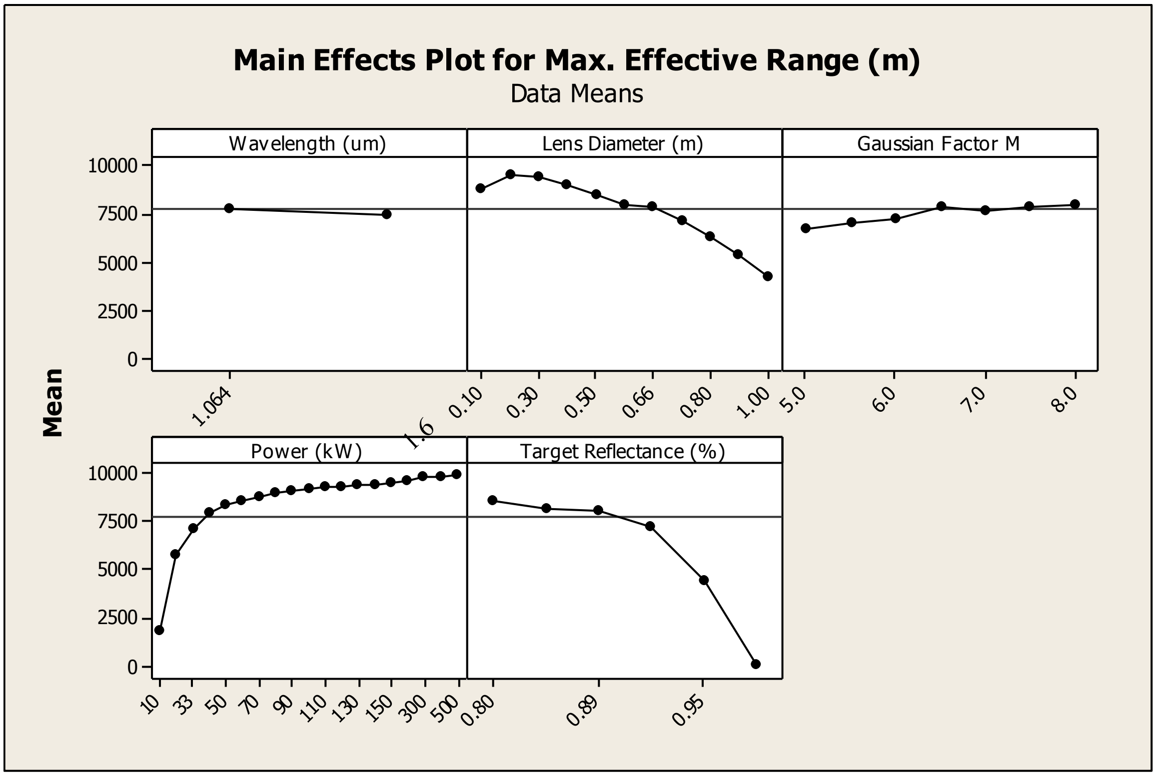

Figure 33. LASER Model Sensitivity Analysis

The results are summarized in Figure 33, which shows the main effect of each parameter on the calculated maximum effective range, measured in meters. Wavelength was shown to have a negligible effect on the maximum effective range as illustrated in the first graph from the left in the top row. One of the most significant factors of the mathematical model was the assumed aperture diameter size, which indicated the optimal size is about 0.2 meters. Power has the largest effect on performance from 10 to about 40 kW, after which there are diminishing returns. The Gaussian Beam Matching Factor affects the performance by about +/- 10% of the maximum effective range from the assumed value of 6.5. Target material reflectance from about 80% to 90% has an indistinguishable effect on performance; however, target reflectance values between 95% and 99% result in a sharp falloff in performance. Figure 34 shows the full range of variability based on the high and low settings for parameter in the sensitivity analysis. The full data set for this analysis is available in Appendix J.

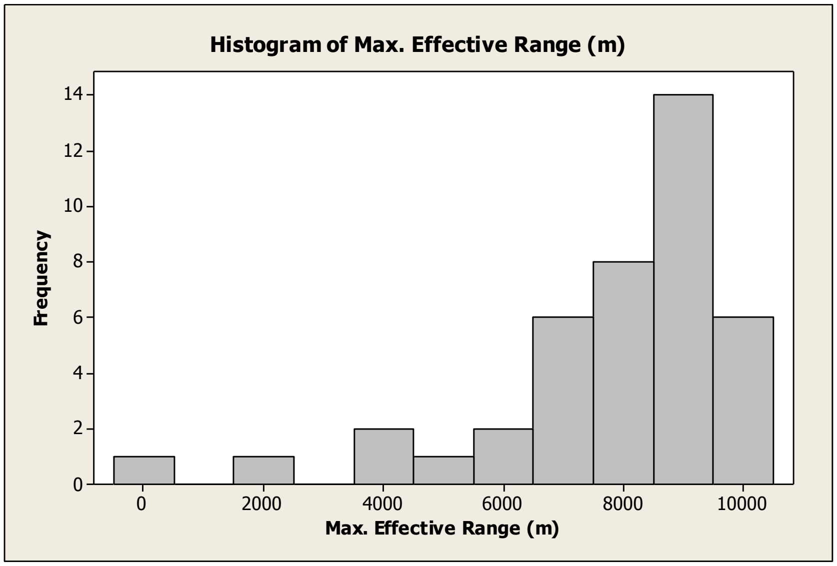

Figure 34. LASER Model Maximum Effective Range Variability

Additionally, an analysis of the variance of each parameter looked at in the sensitivity analysis was done. The results in Table 14 show that the most significant factor is output power, followed by aperture diameter, and then target reflectance. In order to more fully explore the interaction of each parameter on the weapon's effectiveness, a full factorial 2^k experimental design was developed to vary each factor between a low and a high value, which represents the range of parameters between the TLS on the low end and the LaWS+ on the high end. The full data set is available in Appendix K.

Table 14. LASER Component Variance Analysis

```
Variance Components

                              % of
Source               Var Comp.   Total   StDev
Wavelength (um)          -33.416*   0.00   0.000
Lens Diameter (m)         31.050   25.82   5.572
Gaussian Factor M        -35.815*   0.00   0.000
Power (kW)               86.903   72.28   9.322
Target Reflectance (%)     2.282    1.90   1.511
Total                  120.235         10.965

* Value is negative, and is estimated by zero.
```

From the interaction plot (Figure 35), the most significant factor in determining the range of the first Type I Engagement are the material properties of the threat (represented by the reflectance). Of the controllable parameters, the combination of wavelength, Gaussian Beam Matching Factor, and aperture diameter are the most significant in terms of interactions, while the overall output power is the most significant across all factor combinations. However, the interaction of power and reflectance plays a large role as well. Even with maximum power on the target, if the target is highly reflective, the weapon will be ineffective. This is a major downfall of all LASER weapons.

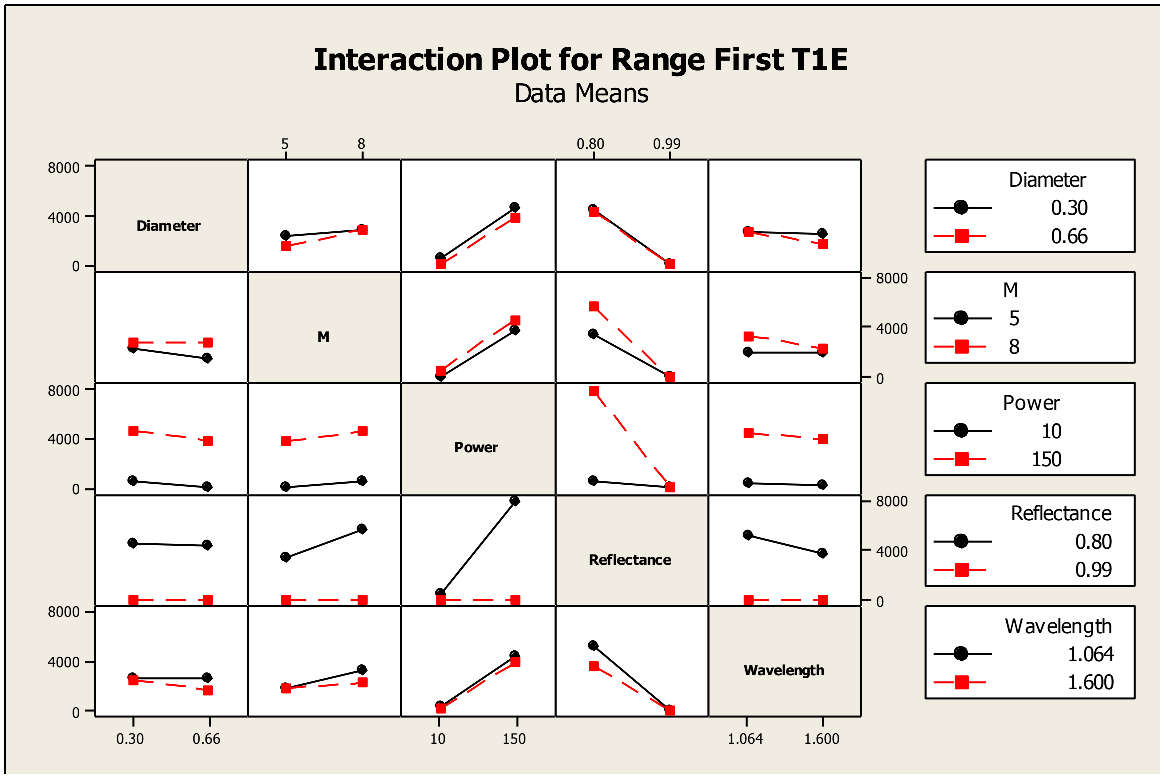

Figure 35. LASER Sensitivity 2^k Interaction Plot for Range of First Type I Engagement

When the effect of each factor is averaged (Figure 36), the two factors which impact the range of the range of the first Type I Engagement the most are aperture diameter and power. A small diameter aperture with a least 100 kW power will yield the most return on investment.

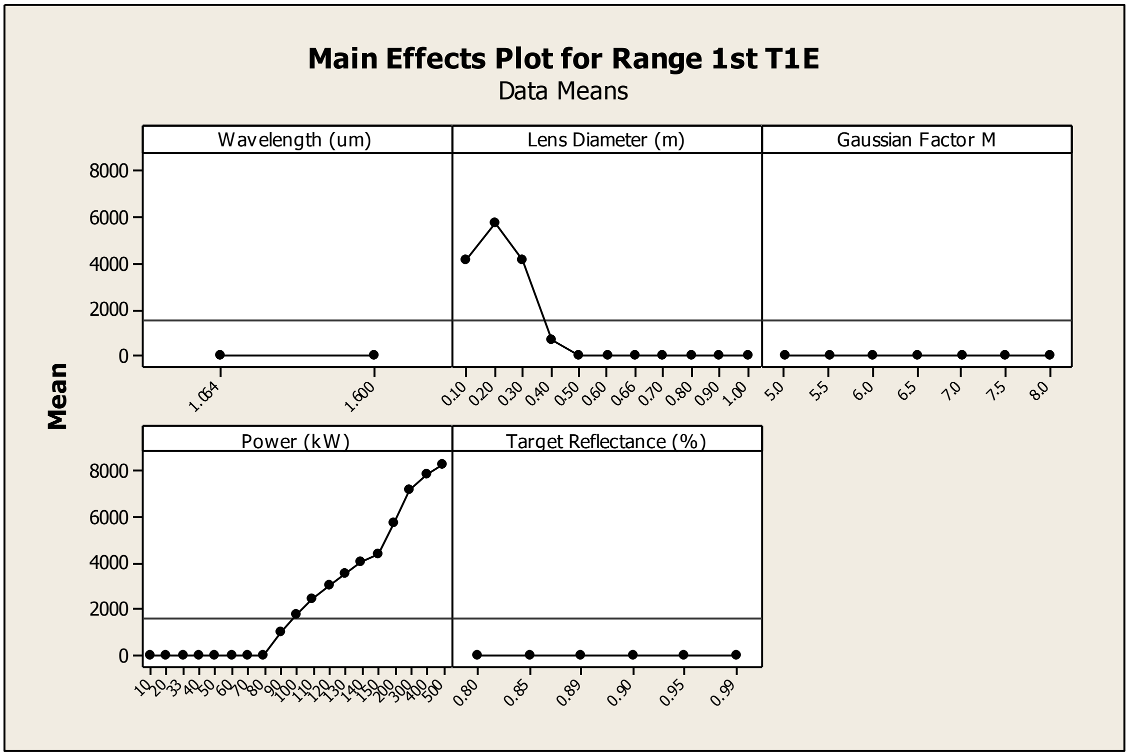

Figure 36. LASER Sensitivity Main Effects on Range of First Type I Engagement

For TYPE II Engagement, the results are different. There is a much larger effect on both range and power at which the LASER can be effective. From Figure 37, we can see that even at the lowest power levels, LASERs can effectively produce Type II Engagement effects.

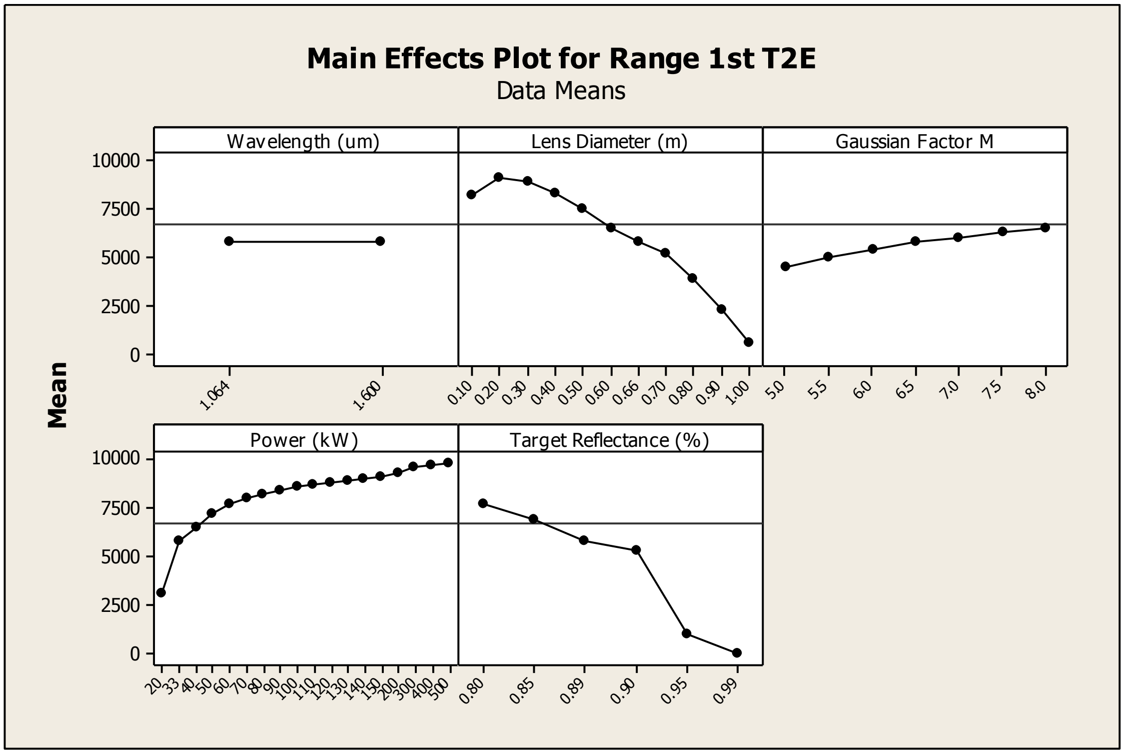

Figure 37. LASER Sensitivity Effects on Range of First Type II Engagement

As power increases, there is an increase in effectiveness. However, we see that for Type II Engagements, that effectiveness seems to be a diminishing return for power levels over about 70 or 80 kW. Therefore, if you consider the damage effects for power, the MLD seems to be in a sweet spot of just enough power for a Type I and more than enough power for a Type II engagement. Tactically, these two graphs show that for a Type I engagement, LASERs will, at best, be on par with the current CIWS guns and RAM missiles. LASERs do have the ability to produce augmenting damage (possibly conserving rounds or resulting in target destruction without burn-through) at ranges well beyond the limits of our current terminal defense weapons (from about 6,000 to 10,000 meters depending on the configuration).

E. GLOBAL INFORMATION NETWORK ARCHITECTURE (GINA) ANALYSIS

1. Model Experimental Design

The full GINA model, based on the project team's assessment of the applicability of DEWs to current Naval missions, a representative sample of realistic threats, and current conventional weapons used in the selected missions, the model was capable of analyzing 1008 separate engagements. While it may be worthwhile to run all of these engagements to paint a complete picture of exactly how DEWs can be used in the future, limiting the scope of mission areas would give a better fit for the current fleet structure. Therefore, it was necessary to consider design of experiment principles, the UNTL hierarchy, and preliminary analysis to reduce the number of experimental factors. The following UNTL requirements had the most priority in terms of relative importance and a perceived mission capability gap or weakness:

- NTA 3.2.1.1 Attack Surface Targets
- NTA 3.2.2 Attack Enemy Aircraft and Missiles
- NTA 3.2.9 Conduct Non-Lethal Engagement
- NTA 6.3.3 Combat Terrorism

By narrowing our modeling effort down to these NTAs, we were able to select fewer overall missions, and consolidate several sub-missions based on similarity and relevance based on guidance from Mr. Bill Glenny, Deputy Director of the CNO's Strategic Study Group. That left the missions shown in Table 15 as ones that were worth conducting a full analysis on.

Table 15. Experimental Design Mission Breakdown

Mission	Mission Threats
SUW 1.10	3
AW 1.2	3
ATFP 12	1
NCO 19.6	2
ATFP 15	1
ATFP 9	2

By only considering these missions and their associated threats, we were able to cut down the number of engagement combinations from 1008 to 212. An engagement was then created for each mission, using each mission threat, each mission weapon, and each model environment. For each mission threat, the detection altitude and ground range was assumed based on project team experience since little to no unclassified data was available for flight profiles or RADAR detection ranges. The vital area radius was specified for each mission (Table 16) and was the "engage by" range that determined whether or not a mission was successfully engaged or not. During the data entry process, the project team found that there was extra time available for additional engagements to be entered. Therefore, the remaining engagements were randomized and as many engagements were entered as possible. In total, 337 unique engagements were created and analyzed by the model. Each engagement is specified in Appendix L.

Table 16. Global Information Network Architecture (GINA) Model Mission Vital Area Assumptions

Mission ID	Mission Description	Vital Area Radius (m)
ATFP 12	Pier Demonstration/Passive Protest Exercise	50
ATFP 15	Nighttime Small Boat Attack at Anchor	100
ATFP 4	Entry Control Point (ECP)Threat	200
ATFP 8	Pier side Small Boat Attack Exercise	100
ATFP 9	Terrorist A/C Attack Exercise	500
AW 1.1	Provide area defense for a strike group	5000
AW 1.12	Provide air defense for non-combatant evacuations operations	500
AW 1.13	Provide air defense for naval/joint/ combined TF operations	5000
AW 1.2	Conduct air self-defense using AW Weapons	500
AW 1.4	Provide area defense for a convoy or underway replenishment group	1000
AW 1.5	Provide area defense for amphibious forces in transit and in the amphibious objective area	3000
AW 1.6	Provide area defense for a surface action group	3000
AW 9.1	Engage medium/high altitude, high-speed airborne threats with AW weapons	1000
AW 9.3	Engage low altitude threats with AW weapons	500
AW 9.4	Engage low/medium altitude airborne threats with AW weapons	1000
NCO 19.6	Conduct seizure of noncombatant vessels	200
NCO 19.9	Conduct drug traffic suppression and interdiction operations	200
SUW 1.10	Conduct close–in surface self-defense using crew operated SUW Weapons	100
SUW 2.3	Engage surface targets with assigned anti-surface sector	1000

2. Model Results and Analysis

The results of all the engagements were then queried from GINA and exported into a master spreadsheet. The spreadsheet was then imported into Minitab to perform statistical analysis on the results. The first thing that we wanted to know what how well each weapon covered the different warfare areas and how well they covered all warfare areas. Figure 38 shows a radar plot of the percentage of missions within each warfare area in which there was either a successful Type I or Type II engagement.

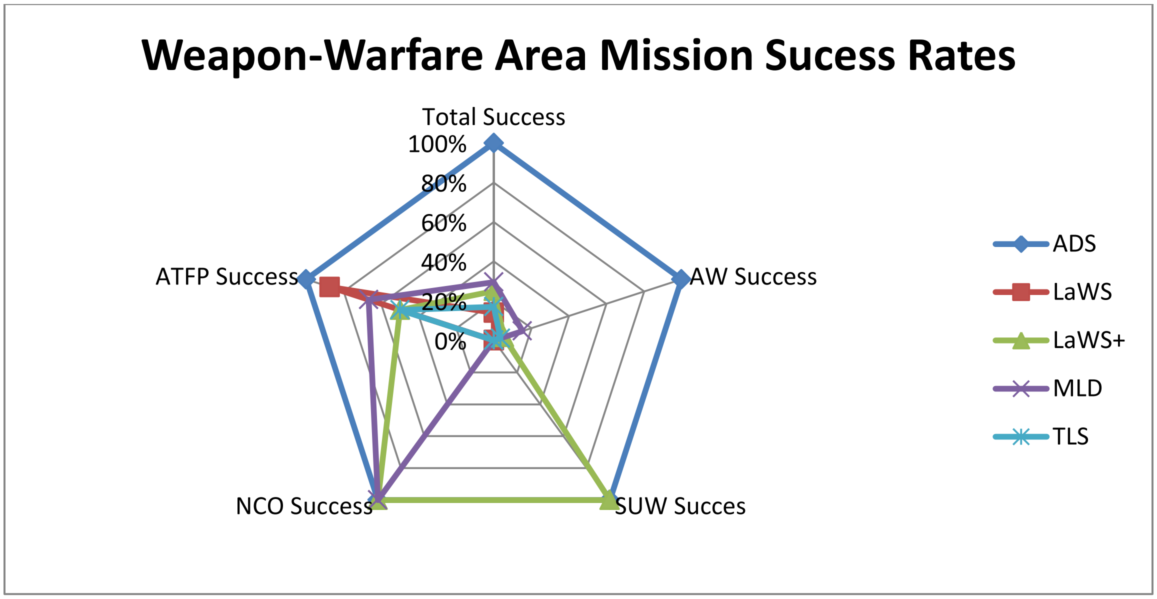

Figure 38. Weapon-Warfare Area Mission Success Rates

ADS was 100% successful in all weather conditions in all warfare areas. This success of ADS is due to the fact that most ADS engagements take place at short ranges, where attenuation is unlikely to have a significant effect. As can be seen, not all weapons were modeled against missions in all warfare areas. This is due to the abbreviated set of missions that we chose to analyze due to time constraints and should be further pursued in follow-on research. Overall, for LASER weapons, the MLD was successful in the most engagements, followed by LaWS+. However, it should be noted that if close-in AT/FP applications are the intended sub-set of threats, then the current LaWS may be sufficient.

3. Type I Engagement Analysis

Next the range of the first Type I Engagement was analyzed. The range of the first Type I Engagement was averaged for successful missions. Therefore, this average will provide the decision maker with an average level of performance predicated on the assumption that the weapon is being employed in a mission/threat context that is appropriate for that particular weapon. These ranges, shown in Figure 39, are shown side-by-side with the conventional weapons that were also evaluated. In addition, the maximum range for a Type I Engagement of all missions is shown.

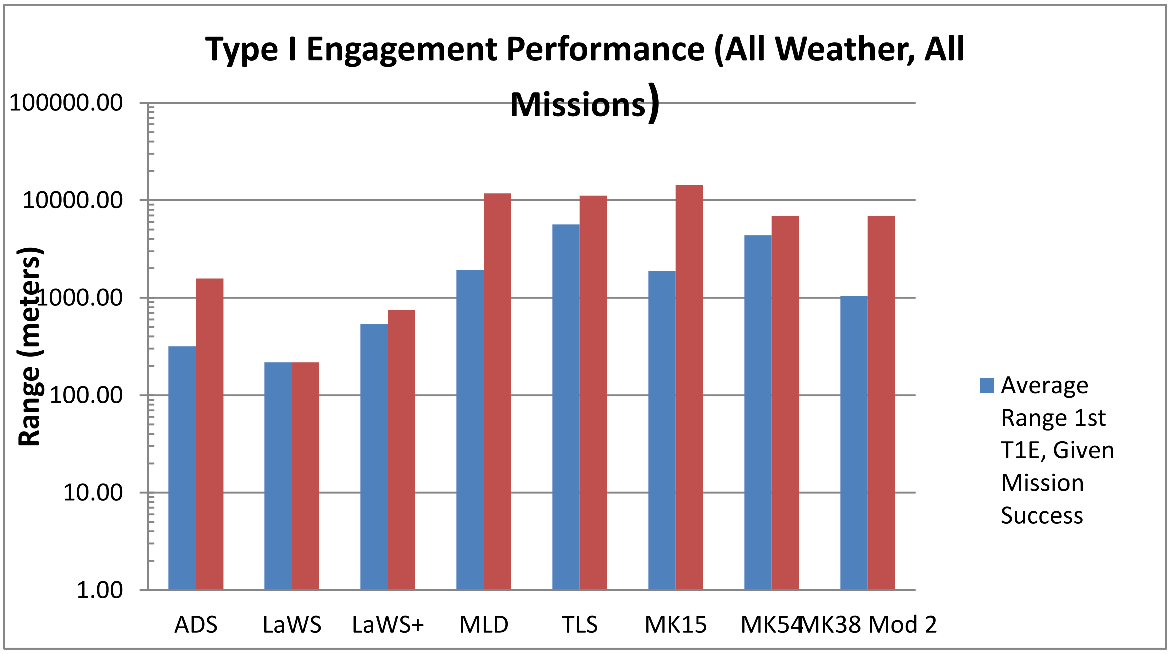

Figure 39. Average and Maximum Ranges of First Type I Engagement (Given Mission Success)

With respect to the DEWs, the ranked order based on greatest to least average range is TLS, MLD, LaWS+, ADS, and LaWS. The TLS has a high average based on one outlier from an engagement associated with AW 9.4 against a Cessna threat. Although this use of TLS may seem far-fetched, we showed through our model validation and sensitivity analysis that the TLS benefits from a different wavelength, a smaller aperture diameter, and better beam quality to produce the same effects with less power as the other LASERs produce with higher power (findings that are substantiated by a 2012 Congressional Research Service report on Navy HEL programs (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2012)). This TLS performance shows the potential of a lower power LASER in a niche application for AT/FP threats that tend to be more lightly armored since they are typically not military-grade weapons, but rather suicide variants of commercial vehicles. Therefore, even though TLS only accomplishes 20% of the AT/FP mission, that 20% represents a majority of the specific threats that need to be addressed. This success of TLS is captured well in Figure 40, which shows the average maximum effective range (of all missions, not only successful ones) by threat.

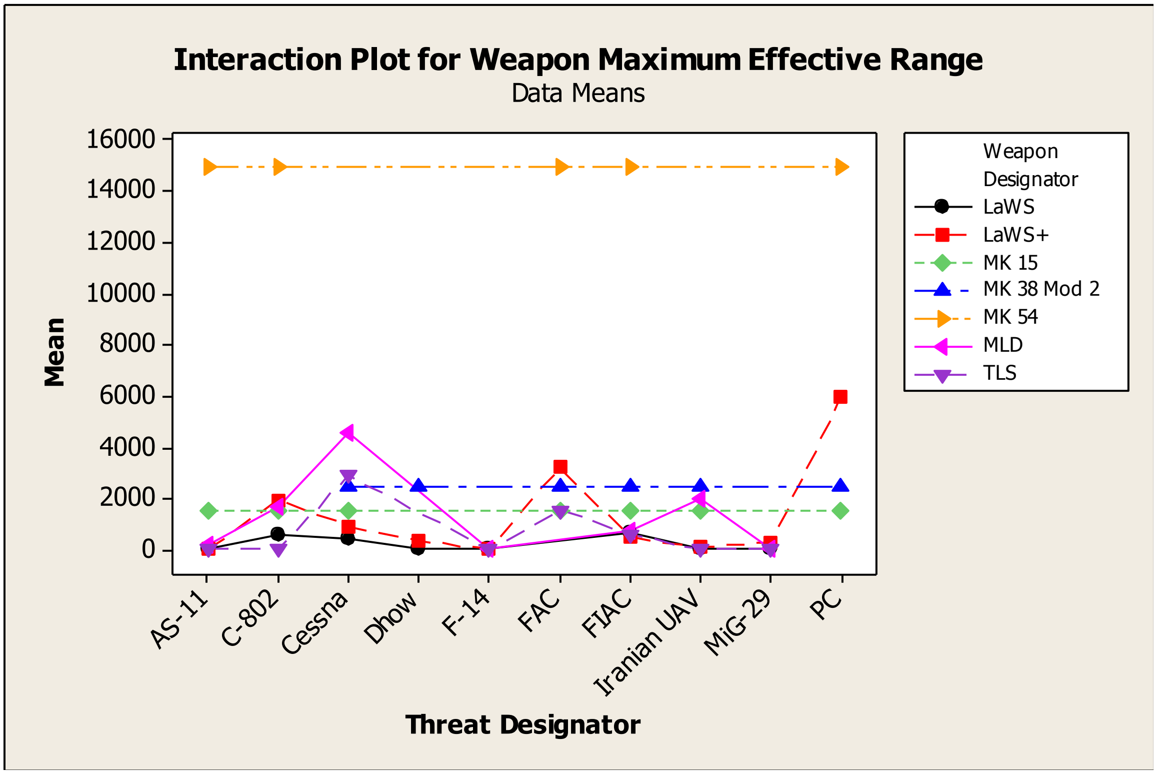

Figure 40. Interaction Plot of Weapon Maximum Effective Range by Threat

In the case of the TLS, it performs well against Cessnas, FAC, and FIAC. In the use case of a Cessna 150, TLS and the MLD both outperform the MK15 CIWS and the MK38 Bushmaster. In the use case of FAC threat, TLS and the LaWS+ are either on par or outperforming the CIWS. These results suggest a LASER has potential for close-in defense augmenting (or potentially replacing) crew-served weapons and allowing the CIWS to conserve ammunition for ASCM threats. However, the maximum effective range, as defined in this model as being 1% of the total fluence required for a Type I Engagement does not translate into a kill range, rather this is the range damage effects start to occur.

Considering the number of Type I Engagements that are possible by threat, we can get a better idea of how each weapon can be employed. Figure 41 shows the mean range of Type I Engagements (for all missions, not just successful), and we can see that overall when it comes to a Type I Engagement, the clear winners are the current conventional weapons for an all-weather, multi-threat solution. The best performing DEW is the ADS, which is not designed to produce these types of damage effects, but could if the current non-lethal safety controls were removed. The disparity between ADS and the HEL systems is a representation of the relative ease of heating a human with a microwave device, vice trying to burn through or structurally weaken a hardened vehicle. The reason by the number of Type I Engagements for HELs is so low is that the first Type I Engagement happens at such a close range, that follow-on engagements are not possible (assuming a swarm of threats in which they all start from the same range and move inbound being engaged one at a time and then moving on to the next closest threat).

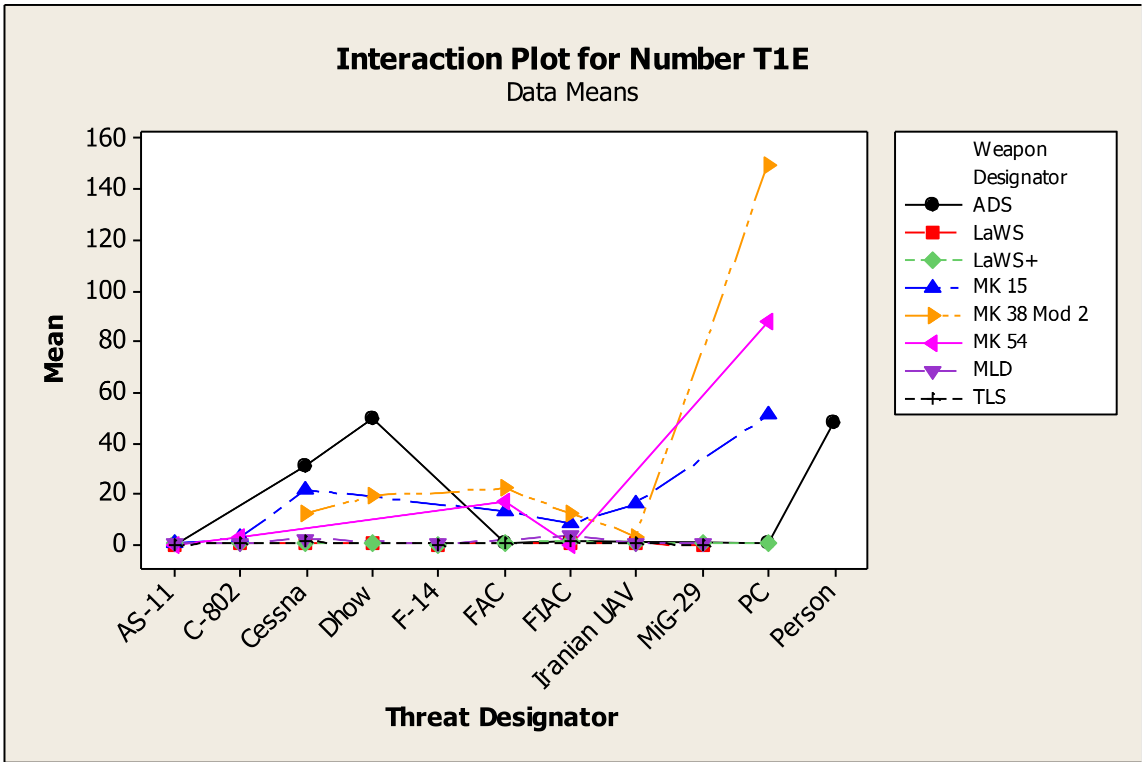

Figure 41. Interaction Plot for Mean Number of Type I Engagements by Threat Type

Figure 42 shows the ranges of Type I Engagements for all missions. Figure 42 shows that LASER weapons are not very effective in their current or near-term (as in the LaWS+) state in producing Type I Engagements. Nearly all of these engagements occur at ranges less than 1,000 meters, with a very few outliers against lightly armored threats. However, it is reasonable to assume that the tracking and aiming systems associated with these weapons are far more accurate than what could be expected from a crew-served weapon such as an M2 .50 caliber machine gun or a MK38 mod 1 crew-served Bushmaster. Considering that, there is a niche for DEWs to provide Type I Engagement effects that would be comparable to current conventional weapons, but that niche would not include replacing the CIWS or the MK 54 5” gun on a ship.

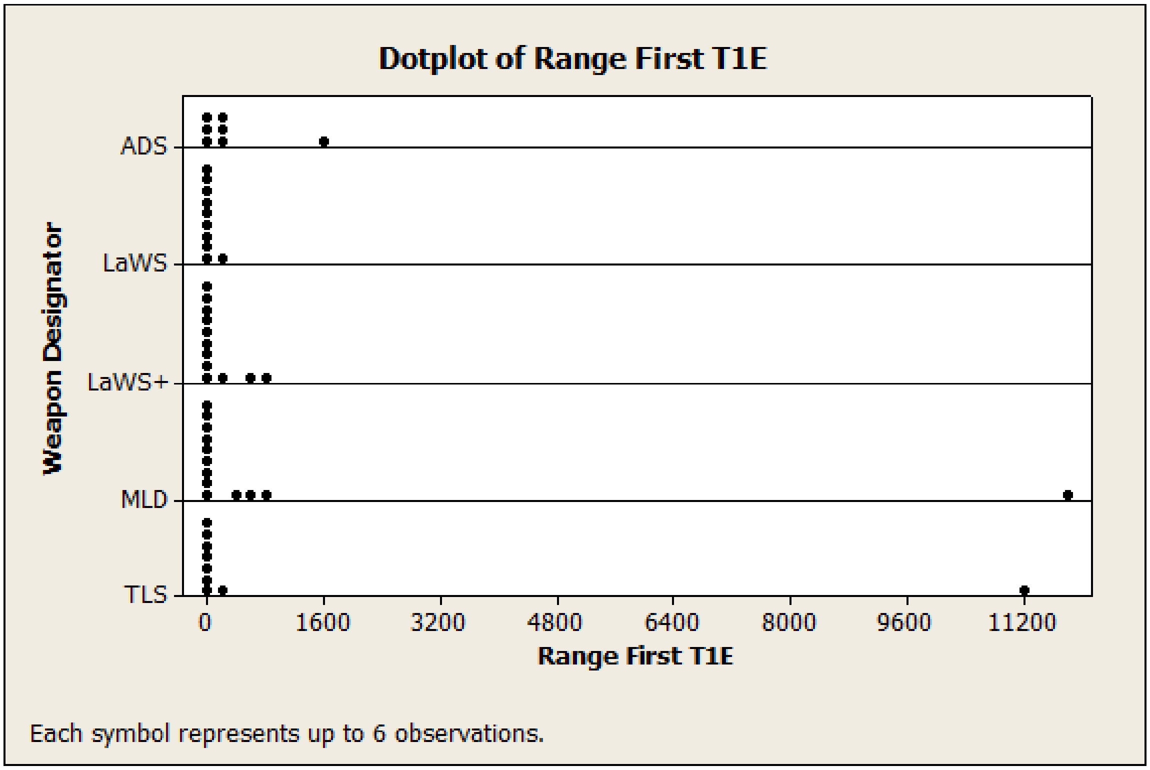

Figure 42. Dot Plot of Range of First Type I Engagement by Weapon

4. Type II Engagement Analysis

Type I Engagements are not the only type of damage that DEWs can provide. DEWs can also provide Type II Engagements which in the case of a LASER is the ultimate structural failure of a threat vehicle by heating the material with one-sixth of the fluence needed for a complete burn-through of the material (Type I Engagement). In the case of a HPM, a Type II Engagement means heating a human to the point of intolerable pain without causing permanent damage to the human body. The ability to produce a Type II Engagement gives added value to the Navy because it is a type of damage effect that is not inherent to conventional weapons. A Type II Engagement is similar to a conventional "mission kill" in which the weapon produces enough damage to degrade or inhibit a threat's ability to attack friendly forces, without actually completely destroying the threat. For example, using an SM-2 missile against an enemy combatant ship would be unlikely to sink the ship because the SM-2's small warhead is designed to fragment and destroy missiles, but it could potentially destroy a fire control radar or kill crew members thereby reducing or eliminating the combatant's war making ability. The difference is that in the conventional case these mission kills are due to the fact that conventional weapon is not sufficient to actually destroy the threat or a because a gunner gets a lucky shot and with DEWs a Type II Engagement can be just as effective as a Type I Engagement when threats are under dynamic stress (for LASERs) or when a non-lethal application is desire (for HPMs) and is an *intended* end result of the weapon, not the unintentional result of using a conventional weapon against a threat for which it was not designed to engage or is not capable of fully destroying. Therefore, with lower powered DEWs, Type II Engagements is a unique niche for naval applications.

Figure 43 shows the average range of the first Type II Engagement for each DEW for missions that were successful as well as the maximum range of the first Type II Engagement. With respect to Type II Engagements, the ranked order based on greatest average range to least range is MLD, LaWS+, TLS, ADS, and LaWS. The similarity in performance both at the average and maximum ranges for TLS, MLD, and LaWS+ should be noted as this illustrates an opportunity to make cost and space trades without significantly impacting performance. We also see that the ADS is successfully engaging threats at about 700m on average, which mirrors the advertised maximum effective range of about 700 yards from the Air Force (Center for Army Lessons Learned 2008). However, even though ADS is operating in a maritime environment, it is possible to effectively engage threats with the ADS out to about 1200 meters, which has significant implications for a wide range of AT/FP, NCO, and SUW threats that could potentially overwhelm conventional weapons by attacking in swarms or cause commanders to pause due to collateral damage concerns.

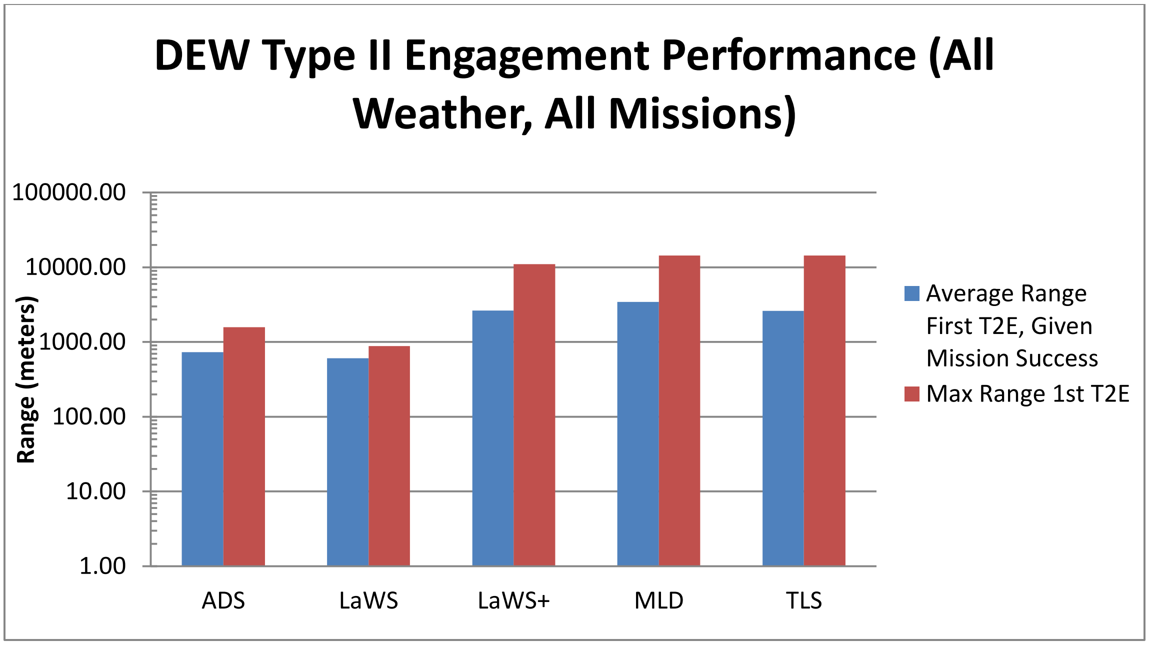

Figure 43. Average and Maximum Ranges of Directed Energy Weapon (DEW) First Type II Engagement (Given Mission Success)

When broken down by mission, all of the DEWs evaluated bring some added value to the Navy in terms of their ability to produce Type II Engagements on a wide variety of threats, in various weather conditions, and at various detection ranges. From the mean range of Type II Engagements by mission shown in Figure 44, the most consistent performer is the MLD, which is no surprise based the fact that it had the greatest average range of first Type II Engagement. On the low power end of the spectrum, TLS is effective against, AT/FP and AW threats. Therefore, if UAVs, LSFs, and small boats are the primary concern, then TLS would be the best choice as it can engage comparable threats at comparable ranges to the MLD and the LaWS+. We also see that for Type II Engagements, the LaWS is also capable of successfully engaging a variety of threats. However, the best performer in our analysis of the data is the ADS. It is the only weapon that is able to successfully produce Type II Engagements prior to threats reaching the vital area 100% of the time.

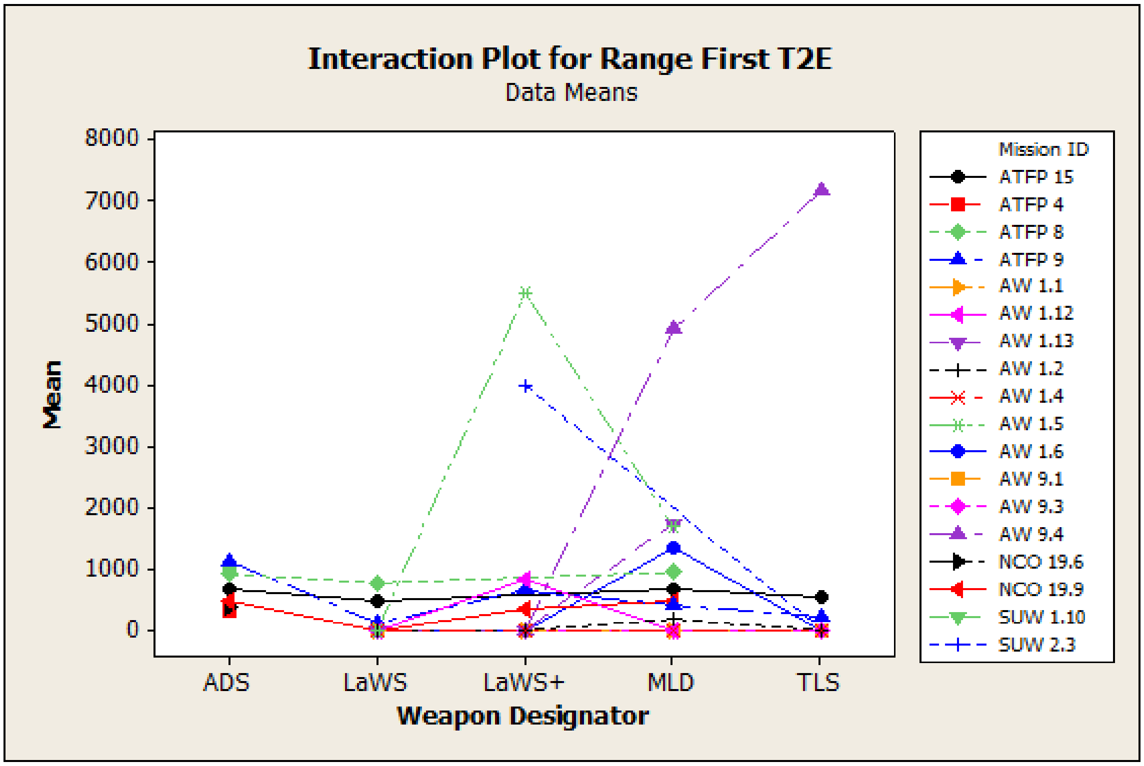

Figure 44. Interaction Plot for Range of First Type II Engagement by Mission

We also evaluated the number of Type II Engagements by threat type, show in Figure 45. This graph also shows how much more efficiently the ADS is at heating human skin as compared to LASERs heating metals and other threat materials. Additionally, threats mapped to the ADS also move relatively slower, allowing more time for follow-on engagements. This chart shows the value that ADS brings to the fight for the Navy, engaging a broad spectrum of threats effectively using non-lethal effects. With respect to the LASER performances, it is clear that even if you did achieve a Type II Engagement against a threat, the ability to re-engage is limited to single digits at best. Therefore, the accuracy of a LASER would have to be weighed against the accuracy of a conventional weapon which could put more rounds out of the barrel, but may not be as accurate (crew-served weapons being a prime example of high rate of fire, low accuracy weapons).

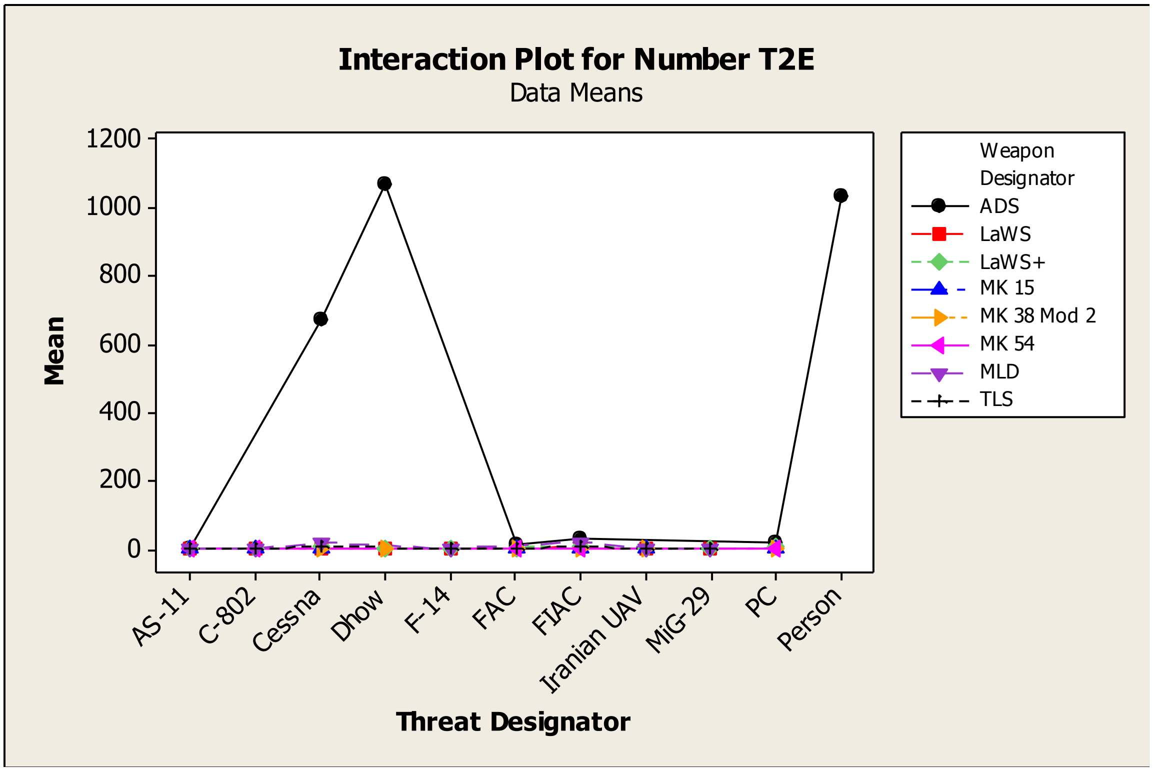

Figure 45. Interaction Plot for Number of Type II Engagements by Threat Type

Finally, we looked at a dot plot of the raw data for the range of the first Type II Engagement for all missions and environments, shown in Figure 46. The chart shows again that the ADS is the only weapon that was able to achieve a Type II Engagement in 100% of the mission/threat/environment combinations that we modeled it against. The chart also shows that the MLD, LaWS+, and TLS do provide some Type II Engagement ranges, but unlike the ADS, they do not work well against all threats and are confined to lightly armored, AT/FP-type threats.

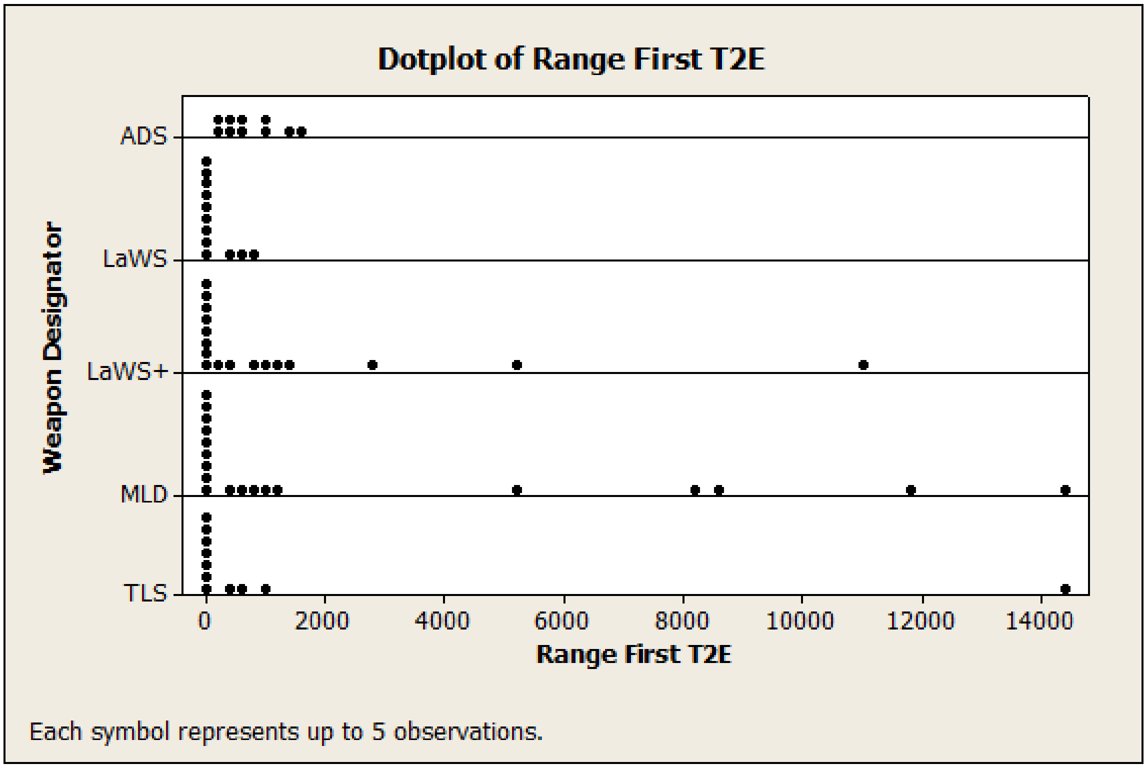

Figure 46. Dot Plot of Range of First Type II Engagement (All Missions, All Environments)

5. Conclusions

With the exception of the LaWS, all of the DEWs evaluated were able to provide some level of value across the board. The most consistently best performer was the ADS, which has the added unique ability to provide a non-lethal Type II Engagement, very rapidly, at tactically relevant ranges out to about 1,000 meters against threats that are either difficult to engage with conventional crew served weapons or might be difficult to determine hostile intent, decreasing the commander's desire to use a lethal engagement option. With respect to LASERS, the MLD was the best overall performer due to the combination of its relatively high power and small aperture. The LaWS, with its larger aperture required the 150kW output power of the LaWS+ variant to be effective and even still was not as effective as the MLD.

Future research should be done to complete the full analysis of all the possible engagements based on the threats and environments that were selected by the project team. Additionally, adding the actual data to the GINA model, if it were migrated to SIPR, would provide a more accurate analysis. Finally, the conventional weapon comparison was made simplistic in order to distil the engagement equation outputs to values that had cross-domain relative comparability, but an actual validated combat model should be used to evaluate the conventional weapon performance, using the actual weapon parameters in order to account for sources of weapon failure such was weather effects which were impossible to capture in a deterministic model at the unclassified level.

F. SIMULATION

One of the requirements in our tasking statement was to develop a preliminary concept of operations (CONOPS) for the selected DEWs. The modeling effort provided a deterministic approach that plays a role in CONOPS development, but simulation was necessary to fill the gap of how these weapons would perform in a stochastic environment with multiple threat types and a maneuvering weapon platform. Therefore, two simulation efforts were developed to emphasize different simulation strengths: an agent-based simulation in Map Aware Non-Uniform Automata (MANA) and a Monte Carlo simulation in Excel. Since the majority of the systems being evaluated were LASERs, the simulation effort focused entirely on LASER weapon analysis.

1. Map Aware Non-Uniform Automata (MANA)

MANA is a cellular automaton model that was developed by New Zealand’s Defence Technology Agency (DTA) (McIntosh, MANA (Map Aware Non-Uniform Automata) Version 4 User Manual 2007). MANA allows the assignment of characteristics and behavior rules to multiple individual autonomous agents (or automata), which then can be analyzed as a system.

The main advantage of using MANA is the ability to learn about complex behaviors that can emerge from the interactions of individuals. MANA allows the researcher to control many options, such as the terrain, the personality of the agents, the weapon and sensor characteristics (such as probability of kill and probability of detection, which can both depend on distance), the ability to communicate with other units, etc. However, the current MANA version (version 5) does not include a LASER model (McIntosh, MANA-V (Map Aware Non-Uniform Automata - Vector) Supplementary Manual 2009).

a. Modeling LASERs with Map Aware Non-Uniform Automata (MANA)

The two weapon models included with MANA are for kinetic energy weapons and explosives. The project team chose to adapt the kinetic energy weapons model for LASER analysis. In the kinetic energy weapons model, a hit is a binary function – that is, the shot can either kill the target or not (with a certain probability P_k, which may depend on distance to the target, among other parameters). By contrast, the physics of LASERs is such that a specific cumulative amount of energy, whether transferred over a short or long period of time, is required to kill a target.

As in the kinetic energy model, one of the parameters affecting the amount of energy that can be delivered from the LASER is distance. Figure 47 depicts the amount of time required for a Type I Engagement as a function of the distance to the target for a sample LASER.

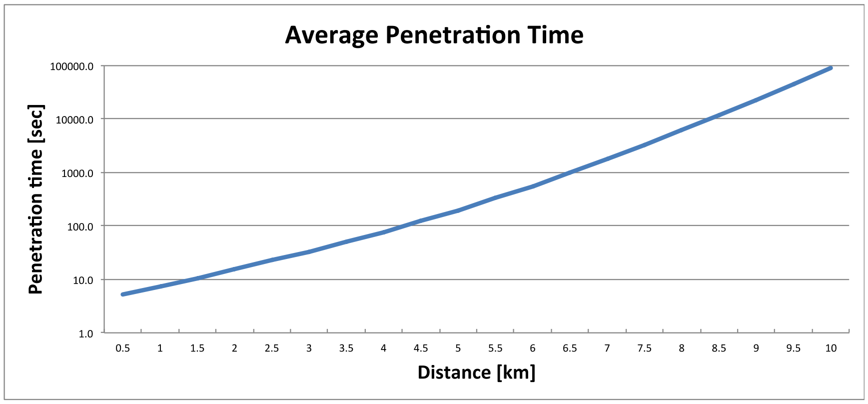

Figure 47. Average penetration time

The LASER model assumes knowledge of the time required for kill per distance, $t_k(r)$. In order to model a LASER using the tools given in MANA, the following values were assigned:

- Every target was assigned N "life points" in the "number of hits required for kill" field. (This assignment can also be interpreted as the thickness of the armor that should be penetrated).
- The LASER weapon was set to a kinetic weapon that is able to shoot s shots per second.
- The probability of a Type I Engagement using a LASER was set to depend on the distance r.

$$P_K(r) = \frac{N}{s \cdot t_k(r)}$$

Equation 20. Probability of Type I Engagement

The time required for a Type I Engagement for a given distance is assumed to have a geometric distribution of $Geo(P_k(t))$. The time required for a Type I Engagement was based on the preliminary GINA model development analysis which suggested a geometric relationship between Type I and II Engagements and time. The average number of shots for a Type I Engagement is shown in Equation 21, which leads to an average time of $t_k(r)$ seconds as required.

$$\frac{1}{P_K(r)} = \frac{s \cdot t_k(r)}{N}$$

Equation 21. Average Time for Type I Engagement

As the distance of the target changes, the average Type I Engagement time changes, causing the probability of achieving a Type I Engagement to change. For the entire model to produce realistic performance results, s and N must be chosen such that the Type I Engagement probability is less than one (the larger the value for N and s, the more realistic the simulation).

$$P_K(r) = \frac{N}{s \cdot t_k(r)} < 1$$

Equation 22. LASER Probability of Type I Engagement Limitation

In the MANA simulation developed, N and s were on the order of magnitude of 100. It should be noted that this magnitude (or threshold calculation) is a completely unique way of using MANA that, as far as the project team and MANA subject matter experts at the NPS SEED Center are aware. This project is the first attempt at using a completely unique methodology to using MANA to simulate DEWs. The methodology for adapting MANA to DEW simulations represents a possible solution to the current problems with binary Navy weapons models as highlighted in the 2012 report *Laser Weapon System (LAWS) Adjunct to the Close-In Weapon System (CIWS)* published by NSWC Dahlgren.

b. Assumptions

The main assumption is that the criterion for deciding whether a target is killed is the cumulated energy received. This assumption means that according to the LASER model, even after long interruptions the target will “remember” that it already received a given amount of energy and will require less additional energy in order to be killed. One drawback to this method is that, unlike the GINA model, the different wavelength and beam quality of TLS is not taken into account, which puts the TLS at a disadvantage for this type of analysis. Further research in this area is needed to identify a correction factor to account for beam quality and wavelength.

c. Found Software Bug in Map Aware Non-Uniform Automata (MANA)

While working with MANA, a critical bug was encountered for LASER modeling: The “number of shots per second” field in the weapons tab may not be read correctly by MANA. This fault did not adversely affect the results of our analysis, but was reported to the NPS SEED Center to be fixed in the latest revision of MANA-V. In order to ensure that this bug did not influence our results, a workaround was crafted by the project team. Instead of adjusting shots per second, the time step was adjusted, which had the same effect, allowing the simulated DEW to “fire” at the correct number of shots per second. The version of MANA used by the project team, which will require this workaround is MANA-V, version 5.01.04.

d. Map Aware Non-Uniform Automata (MANA) Simulation Vignettes and Scenarios

In order to compare the performance of each type of LASER weapon, four scenarios designed to simulate how well each of LASER weapons perform under realistic conditions and how many threats each LASER weapon can engage were developed. These four scenarios are FAC/FIAC swarm attack, counter UAV, counter ASCM, and an integrated scenario comprised of all three previous scenarios. For each scenario, a vignette was written by the U.S. Navy project team members to guide simulation development and goals.

e. Fast Attack Craft (FAC)/Fast Inshore Attack Craft (FIAC)

One of the greatest threats facing the United States Navy is the asymmetric threat posed by small, fast surface craft in the Anti-Surface Warfare (SUW) mission area. A swarm attack in the littorals or during choke point transits against a single U.S. Warship could have devastating effects.

The current Fast Attack Craft (FAC)/Fast Inshore Attack Craft (FIAC) threats are fast, highly maneuverable craft armed with short range missiles, rockets, and heavy machine guns. While FAC/FIAC threats may not have sufficient firepower to actually sink a surface combatant, a “swarm” of maneuvering FIACs could nevertheless obstruct ship operations, harass consorts, deny maneuver space, distract form the primary mission objective and inflict damage to ship sensors and communications (even jet-skis could be used to launch a rocket propelled grenade) (Scott 2011). The FAC/FIAC threat has the advantage of operating at high speeds, and with lower drafts and can operate in shallow water where larger Warships are most vulnerable. The small size of a FAC/FIAC threat also makes them difficult to detect both visually and on RADAR reducing the Warship’s reaction time. These small boats often operate in groups of 2 to 5 in order to maximize their firepower while providing mutual protection and take advantage of the battlespace.

The typical CONOPS for a U.S. Navy Warship is to increase to max speed and set a course away from the swarm threat (usually toward deeper water). In doing this maneuver, ships are able to increase the distance from the threat while creating a large wake that could potentially swamp or deter the incoming boats. This defense CONOPS continues until all threats have been neutralized, or enough distance has been placed between the threats that they can no longer engage the Warship.

f. Fast Attack Craft (FAC)/Fast Inshore Attack Craft (FIAC) Simulation Parameters

Table 17 outlines the squad physical properties used in the MANA simulation tool. The Blue force represents a single DDG with one LASER weapon installed on the ship capable of 360 degree coverage. In all scenarios, weapon placement was not considered, and therefore weapon coverage zones were not studied in this simulation. The Red force is comprised of seven small boats attacking the DDG. These boats move simultaneously toward the DDG, starting from 10km where they are detected by the DDG. After detecting the threat, the DDG navigates away from the boats at 16 m/s. Figure 48 shows a screen shot of the MANA simulation being executed.

Table 17. Fast Attack Craft (FAC)/Fast Inshore Attack Craft (FIAC) Simulation Parameters

	Name	Number	Speed (m/s)	Detection Range (km)	Weather Condition
Blue Force	DDG	1	16	N/A	Good (attenuation =0.8 dB/km)
Red Force	Small Boat	7	25	10	

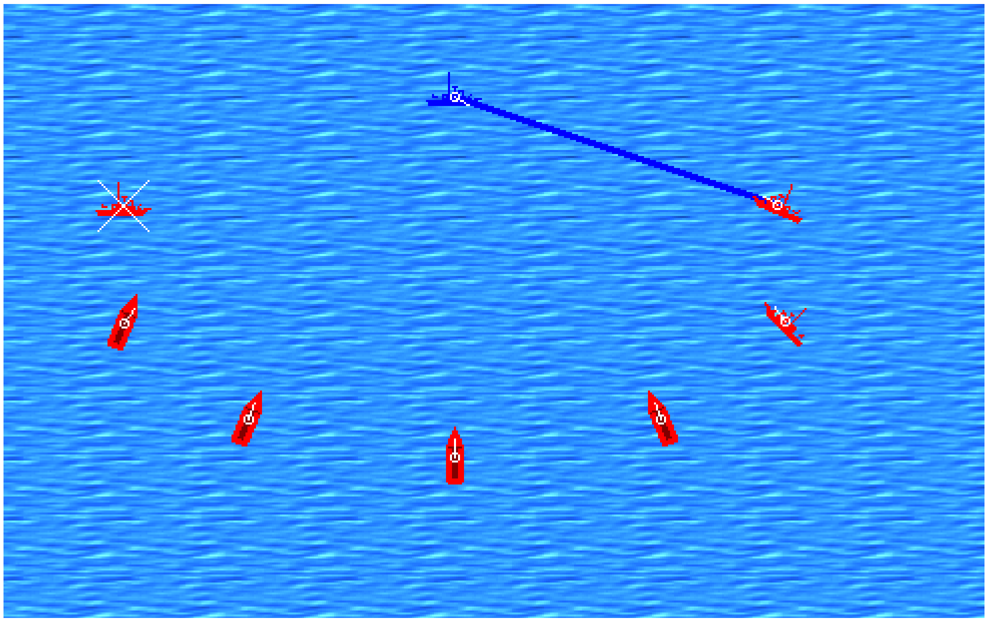

Figure 48. Fast Attack Craft (FAC)/Fast Inshore Attack Craft (FIAC) Map Aware Non-Uniform Automata (MANA) Screen Shot of DDG Engaging Fast Attack Craft (FAC)/Fast Inshore Attack Craft (FIAC) Threats with a LASER

The results of the LASER interactions with the attackers from this scenario are listed in Table 18. The enhanced version of the LaWS was able to engage all seven small boat threats. The current LaWS and the MLD were about on par with each other, destroying between two and three small boats each. The TLS did not engage any of the small boats effectively. This simulation confirms there is a role for LASER weapons in a FAC/FIAC engagement. These results also highlight this simulation methods inherent reliance on output power as the key driving force in determining burn through rates, which biases the results against systems like the TLS.

Table 18. Fast Attack Craft (FAC)/Fast Inshore Attack Craft (FIAC) Simulation Type I Engagement Results

	LaWS	LaWS+	TLS	MLD
Average	2.567	7.000	0.000	3.033
Standard Error	0.092	0.000	0.000	0.033
Confidence Level (95.0%)	0.188	0.000	0.000	0.068

g. Low Slow Flyer (LSF) / Unmanned Aerial Vehicle (UAV)

Low Slow Flyers (LSFs) are aircraft that fly at low altitudes with speeds less than 300kts. They typically have low infrared signatures and little distinctive electronic emissions. These aircraft can fly in patterns and altitudes similar to civilian air routes allowing them to incorporate easily with normal air traffic. In addition, they are sometimes difficult to detect by RADAR until in close proximity due to their low speeds and altitudes. If they are detected, it can be problematic to classify them as friend or foe due to their flight profiles. For these reasons, LSFs are viable threats to ships. In preparing against LSFs, ships typically use scenarios where the LSFs are in close proximity. Since LSFs are not expected to be detected and classified until they are within a close proximity to the defender, they require the use of close-quarter weapon systems employed by the ships’ Small Craft Action Teams (SCAT) such as the M2 .50 caliber and MK38 25mm machine guns.

Unmanned Aerial Vehicles (UAVs) are aerial vehicles that do not have a human pilot onboard the craft. They are advantageous in situations where the dangers of risking a human life are too high. UAVs can be flown from remote ground stations or by auto-pilot programming. They can be used for reconnaissance, electronic attack, strike missions, and suppression of enemy air defense (SEAD). Due to these various capabilities, UAVs pose a significant threat, especially in maritime environments.

h. Low Slow Flyer (LSF) / Unmanned Aerial Vehicle (UAV) Simulation Parameters

The Low Slow Flyer/Unmanned Arial Vehicle simulation parameters are outlined in Table 19. Like the FAC/FIAC scenario, the Blue force represents a DDG with a single LASER weapon. The Red force is comprised of seven attacking LSF/UAVs which fly toward the DDG simultaneously; starting from a detection range of 10km and moving inbound at 40 m/s. After detecting the LSF/UAVs, the DDG navigates away from the LSF/UAVs at 16 m/s (see Figure 49)

Table 19. Low Slow Flyer (LSF) / Unmanned Aerial Vehicle (UAV) Simulation Parameters

	Name	Number	Speed (m/s)	Detection Range (km)	Weather Condition
Blue Force	DDG	1	16	N/A	Good (attenuation =0.8 dB/km)
Red Force	LSF/UAV	7	40	10	

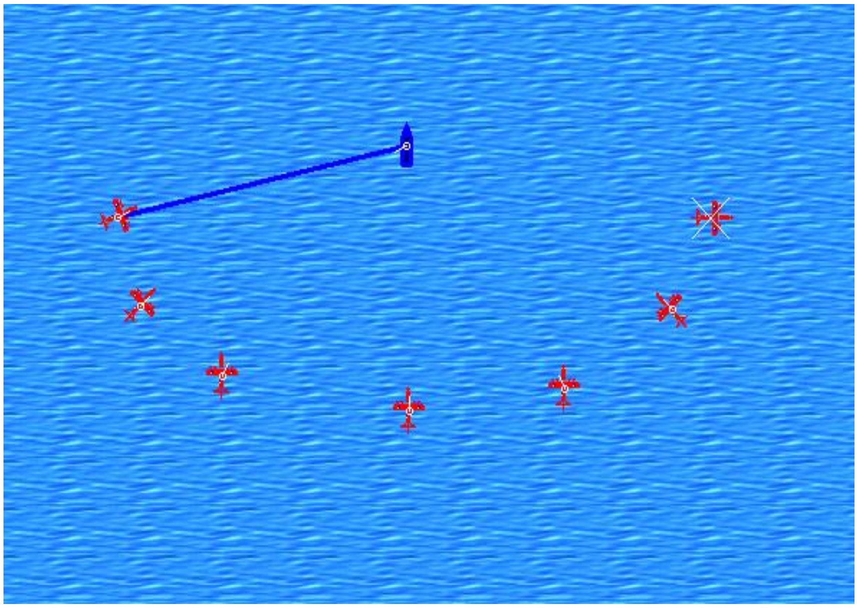

Figure 49. Low Slow Flyer (LSF) / Unmanned Aerial Vehicle (UAV) Map Aware Non-Uniform Automata (MANA) Simulation Screen Shot

In this scenario, all of the LASER systems are somewhat effective in engaging LSF/UAV threats (Table 20). Again, LaWS and the MLD are on par with each other and the TLS lags behind, with the LaWS+ as the clear front runner.

Table 20. Low Slow Flyer (LSF) / Unmanned Aerial Vehicle (UAV) Scenario Results

	LaWS	LaWS+	TLS	MLD
Average	3.567	7.000	0.433	4.900
Standard Error	0.092	0.000	0.092	0.056
Confidence Level (95.0%)	0.188	0.000	0.188	0.114

I. Anti-Ship Cruise Missile (ASCM)

Another significant threat to the Navy is ASCMs that are designed to fire against large boats and warships. ASCMs can be launched by warships, submarines, and various kinds of aircraft, making the probability of having to defend against an ASCM attack during wartime very high. Avoiding detection, destroying the missile launch platform before it fires its missile and shooting down or decoying the incoming missile are three main strategies to counter the ASCM. The scenario parameters are listed in Table 21.

Table 21. Anti-Ship Cruise Missile (ASCM) Scenario Parameters

	Name	Number	Speed (m/s)	Detection Range (km)	Weather Condition
Blue Force	DDG	1	16	N/A	Good (attenuation =0.8 dB/km)
Red Force	Subsonic ASCM	5	300	10	
Red Force	Supersonic ASCM	5	1000	10	

Two ASCM scenarios were considered: a subsonic ASCM attack and a supersonic ASCM attack. The Red force is comprised of five ASCMs fired simultaneously at the DDG. After detecting the ASCMs, the DDG navigates away the ASCM at 16 m/s.

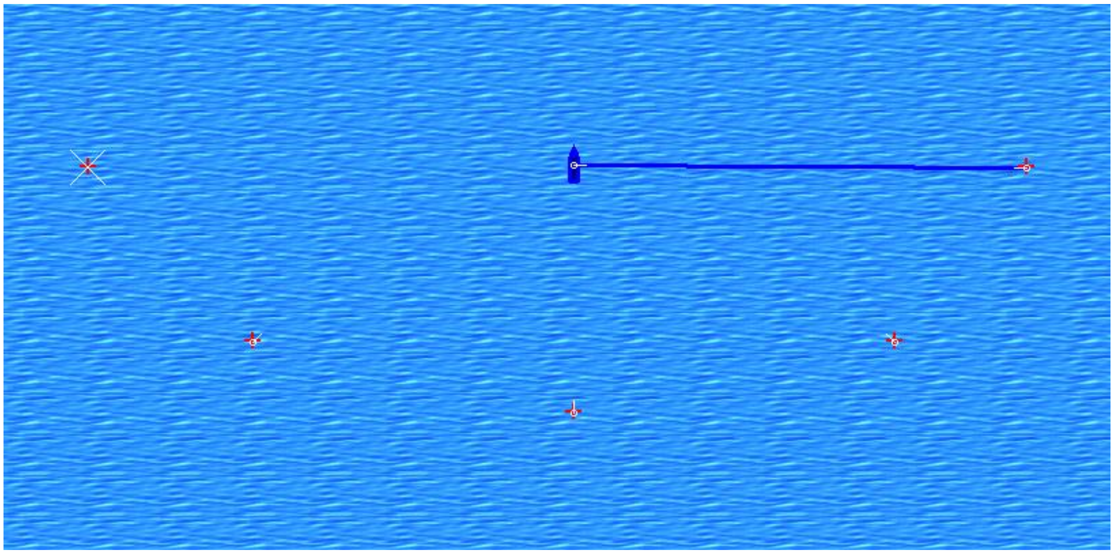

Figure 50. Anti-Ship Cruise Missile (ASCM) Simulation Screenshot

The subsonic ASCM scenario results are in Table 22 and the supersonic ASCM results are in Table 23. The results of this simulation are somewhat optimistic, showing that the LaWS+ would be able to effectively engage a subsonic ASCM 100% of the time; however, it does show that even with the low powered LaWS there is a potential to have some positive effect on the outcome of an ASCM engagement. This result suggests that the current plan to install a hybrid LASER weapon in conjunction with CIWS could be an added value to the Navy by potentially conserving ammunition.

Table 22. Subsonic Anti-Ship Cruise Missile (ASCM) Scenario Results

	LaWS	LaWS+	TLS	MLD
Average	1.233	5.000	0.000	2.000
Standard Error	0.079	0.000	0.000	0.000
Confidence Level (95.0%)	0.161	0.000	0.000	0.000

Not surprisingly, none of the weapons fared well against the supersonic ASCM threat, even in this somewhat optimistic simulation. The LaWS+ was able to engage nearly two ASCMs successfully on average, suggesting that if missile defense is a primary concern, then this weapon, paired with the CIWS would most likely show tactically significant gains over the standard CIWS configuration.

Table 23. Supersonic Anti-Ship Cruise Missile (ASCM) Scenario Results

	LaWS	LaWS+	TLS	MLD
Average	0.000	1.900	0.000	0.000
Standard Error	0.000	0.056	0.000	0.000
Confidence Level (95.0%)	0.000	0.114	0.000	0.000

j. Coordinated Attack

The final scenario simulated in MANA is a combination of all of the above threat types in a coordinated attack shown in Figure 51. The scenario parameters are listed in Table 24.

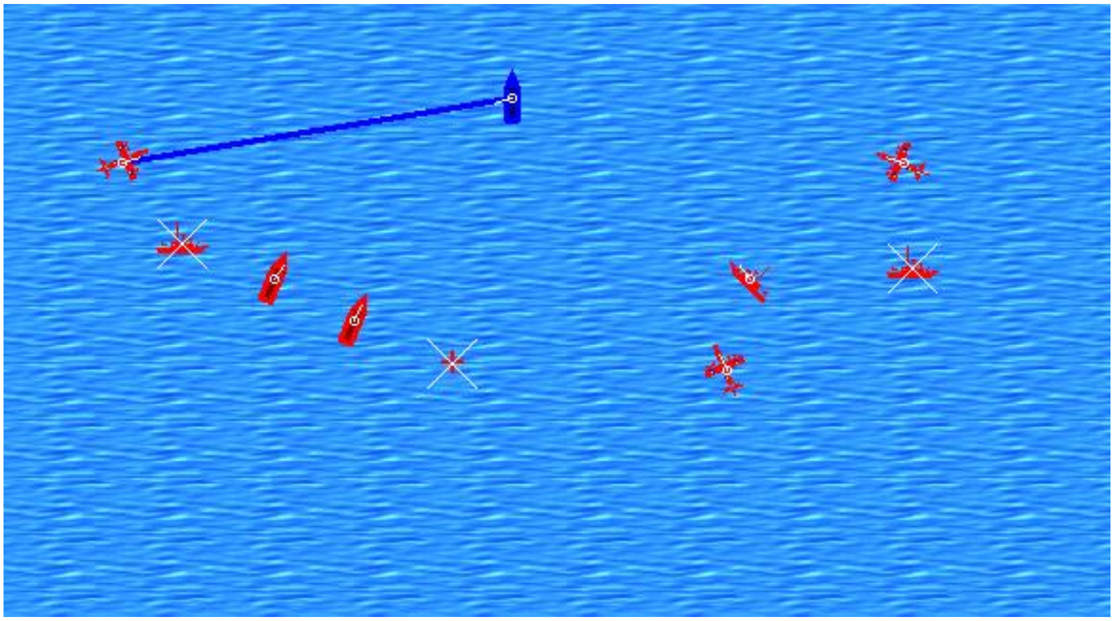

Figure 51. Coordinated Attack Simulation Screen Shot

Table 24. Coordinated Attack Parameters

	Name	Number	Speed (m/s)	Detection Range (km)	Weather Condition
Blue Force	DDG	1	16	10	Good (attenuation =0.8 dB/km)
Red Force	Small Boat	5	25	10	
Red Force	UAV	3	40	10	
Red Force	Subsonic ASCM	1	300	10	

The results of the coordinated attack scenario, listed in Table 25, show some surprising conclusions. Whereas in a single threat type environment, it is easy to distinguish between the systems performance based on power alone, in the coordinated attack scenario, the LaWS, LaWS+, and MLD all performed about the same, with the LaWS+ able to kill a few more small boats than the other two. Again, TLS was not effective in this scenario. While the accuracy of these numbers of successful engagements can be debated, there is a clear indication that even a single LASER weapon system of relatively low power has a clear role in the layered defense of a ship under attack from multiple threat types simultaneously.

Table 25. Coordinated Attack Scenario Results

LaWS			
	Subsonic ASCW	UAV	Small Boat
Average	1.000	3.000	1.100
Standard Error	0.000	0.000	0.403
Confidence Level (95.0%)	0.000	0.000	0.150
LaWS+			
	Subsonic ASCW	UAV	Small Boat
Average	1.000	3.000	5.000
Standard Error	0.000	0.000	0.000
Confidence Level (95.0%)	0.000	0.000	0.000
MLD			
	Subsonic ASCW	UAV	Small Boat
Average	1.000	3.000	2.433
Standard Error	0.000	0.000	0.679
Confidence Level (95.0%)	0.000	0.000	0.254
TLS			
	Subsonic ASCW	UAV	Small Boat
Average	0.000	0.000	0.000
Standard Error	0.000	0.000	0.000
Confidence Level (95.0%)	0.000	0.000	0.000

For every scenario, there were thirty simulations conducted for each type of DEW. The 30 simulations were then averaged to represent the performance of the DEWs. These results are shown in Appendix M.

2. LASER Monte Carlo Simulation

The purpose of performing a Monte Carlo simulation was to evaluate four different LASER systems quantitatively according to their operational performance. ADS was not considered because it was the only microwave weapon and the team wanted to further discriminate between the different LASER weapons evaluated by the project. The LASER systems evaluated were:

- LaWS
- LaWS+
- MLD
- TLS

We considered scenarios in which a single vessel, nominally a DDG-51 class destroyer, is attacked by swarms of missiles and small boats. The vessel would try to defend itself by shooting the attackers down using its current weapons (guns and anti-missile missiles) and the LASER systems. Our prime goal was to gain insights into the effect of different weapon systems on ship survivability**.** In addition, we considered situations in which the LASERs replace some of the ship's existing weapons to see what combinations of weapons yielded the best outcomes.

a. Simulation Methodology

The simulation developed was a stochastic Excel based simulation. It modeled the defense capability of a vessel against a swarm of threats. The model allowed the vessel to "shoot down" the threats using the available weapons, which could include anti-missile missiles, guns, LASERs, or a combination of these weapon types. Each type of weapon is modeled to have a certain probability of intercepting the incoming attacker, resulting in the stochastic nature of the engagement outcome. Attackers which are not shot down by any of the weapons would be considered leakers. Therefore, any electronic warfare methods or any evasive maneuvering that might normally be employed to combat these threats was ignored in order to isolate the effects of only the weapons.

The vessel would be considered to have survived a swarm attack when there were zero leakers in an engagement/simulation run. Running each scenario numerous times, the survival chance of a vessel for the certain scenario was computed as the percentage of simulation runs in which there are no leakers. The complete model takes into consideration the attributes as listed in Table 26.

Table 26. List of Modeling Attributes

Defense Capability Characteristics				**Target/Attacker Characteristics**	**Environmental Characteristic**
Missile	**Gun**	**LASER**	**Sensor**		
Probability of Intercept	Probability of Intercept	Probability of Intercept	Detection Range (km)	Target Material Specific Heat Capacity	Atmospheric Attenuation
Maximum Effective Range	Maximum Effective Range	Power		Operating Temperature	
Minimum Engagement Range	Minimum Engagement Range	Aperture Diameter		Target Material Melting Point	
Average Speed	Rate of Fire	Wavelength		Target Material Thickness	
Launch Interval	Engagement Duration	Beam Quality		Thermal Coupling Coefficient	
Number of Missile Launchers	Number of Guns	Number of LASER Weapons		Target Material Density	
Number of Missiles on Vessel				Thermal Diffusivity of Target Material	
				Average Speed	
				Number of Attackers	
				Heat of Fusion	
				Thermal Conductivity	

These attributes account for the impact of the defense capabilities, threats and environment on the survival of the vessel.

(1) Simulation LASER Modeling Methodology. The simulation team developed a similar, but independent model for LASER performance from the GINA modeling team to provide more depth to the overall performance analysis by not constraining the mathematical model to one set of assumptions. The following

performance terms and metrics were used to adjudicate weapon performance in the simulation by way of mathematical performance models.

Time to Effect. The time required for a target to be destroyed from the point the trigger is pushed, to the point when the threat has been eliminated.

Maximum Effective Engagement Range. The maximum range at which the LASER can destroy a stationary target in 100 seconds.

Number of Engagements within Kill Window. The number of targets that can be destroyed by a weapon system within its kill window.

LASER Equations. The MOPs are dependent on various factors that are bounded by the laws of physics and related by various mathematical equations. These equations are used to model the LASER system and determine the MOPs. Several of the equations have been modified from the earlier model. The equations of interests are highlighted below.

Time to Effect For a stationary target. The time taken for LASER to penetrate a stationary target is calculated by dividing the fluence required to penetrate/kill the target by the intensity of the LASER at the target, as shown in Equation 23 below.

$$\boxed{\boldsymbol{Time\ to\ effect\ for\ stationary\ target, t_{eff} = \frac{E_{min}}{I_t}}}$$

Equation 23. Time to Effect for Stationary Target

E_{min} is the fluence required to penetrate the target, as given in Combat Systems Volume 3, equation 17.8 (Harney, Combat Systems Volume 3 2004) and is as shown in Equation 24. I_t is the LASER intensity at the target calculated by multiplying the output intensity and the transmittance (as defined by Beer’s Law).

$$\boldsymbol{Fluence\ required\ to\ destroy\ target\ \left[\frac{Joule}{cm^2}\right], E_{min} = \frac{\rho(th)[L_m + C(T_m - T_0)]}{6 \times \alpha_{tc}}}$$

Equation 24. Fluence Required for Type II Engagement

$$\boldsymbol{Laser\ Intensity\ at\ Target}\ \left[\frac{\boldsymbol{Watt}}{\boldsymbol{cm^2}}\right], \boldsymbol{I_t = I_0 \times \left(\frac{1}{10^{\frac{A_{atm}\times R_{engage}}{10}}}\right)}$$

Equation 25. LASER Intensity at Stationary Target

$$\begin{gathered}
\text{Where}:\ \alpha_{tc} = \text{material thermal coupling coefficient for specified wavelength} \\
\mathrm{I}_0 = \text{laser output intensity } \left(\frac{\text{watts}}{\text{cm}^2}\right) \\
\mathrm{A}_{\text{atm}} = \text{atmospheric attenuation coefficient } \left(\frac{\text{dB}}{\text{km}}\right) \\
\mathrm{R}_{\text{eng}} = \text{Engagement slant range (km)}, \\
\rho = \text{density of target material } \left(\frac{\text{grams}}{\text{cm}^3}\right), \\
\text{th} = \text{thickness of target} \\
\mathrm{L}_{\text{m}} = \text{latent heat of fusion of target material } \left(\frac{\text{joules}}{\text{gram}}\right), \\
\mathrm{C} = \text{specific heat capacity of target material } \left(\frac{\text{joules}}{\text{gram} \times \text{Kelvin}}\right), \\
\mathrm{T}_{\text{m}} = \text{melting point of target material (Kelvin)} \\
\mathrm{T}_0 = \text{operating temperature of target (Kelvin)}
\end{gathered}$$

(2) Time to Effect for Approaching Targets. Total fluence that can be transmitted over an engagement window (J/cm^2) is calculated by integrating the LASER intensity on target over the duration of engagement as shown in Equation 26.

$$\boldsymbol{E_{total} = \int_0^t I_t\, dt = I_0 \times \int_0^t e^{-\alpha_{atm}\times R_{engage}}\, dt}$$

Equation 26. Calculation for Total Fluence that can be transmitted over an Engagement Window

$$\begin{gathered}
R_{engage} = R_{detect} - V_{target} \times t \\
R_{detect} = Range\ at\ which\ target\ is\ detected\ and\ engagment\ begins\ [km] \\
V_{target} = Average\ radial\ speed\ of\ target\ \left[\frac{km}{sec}\right] \\
t = duration\ of\ engagement\ \ [sec] \\
\alpha_{atm} = atmospheric\ attenuation\ coefficient\ \left(\frac{1}{km}\right)
\end{gathered}$$

Atmospheric attenuation is often expressed in dB/km, A_{atm}, and can be converted to α_{atm} using the following relation obtained from Combat Systems Volume 1((Harney, Combat Systems Volume 1 2004) as shown below.

$$\boldsymbol{\alpha_{atm} = \frac{A_{atm}}{4.343}}$$

Equation 27. Conversion of atmospheric attenuation from dB scale to normal scale

Time to effect is calculated by equating $E_{min}$to E_{total} as follows:

$$E_{min} = E_{total} = I_0 \times \int_0^{t_{eff}} e^{-\alpha_{atm}\times(R_{detect}-V_{target}\times t)}\, dt$$
$$= I_0 \times e^{-\alpha_{atm}\times R_{detect}} \int_0^{t_H} e^{\alpha_{atm}\times(V_{target}\times t)}\, dt$$
$$= \frac{I_0 \times e^{-\alpha_{atm}\times R_{detect}}}{\alpha_{atm}\times V_{target}} \times \left[e^{\alpha_{atm}\times(V_{tar}\times t_{eff})} - 1\right]$$
$$\boxed{\mathbf{t_{eff}} = \frac{\mathbf{ln}\left[\dfrac{\mathbf{E_{min}} \times \boldsymbol{\alpha}_{\mathbf{atm}} \times \mathbf{V_{target}}}{\mathbf{I_0} \times \mathbf{e}^{-\boldsymbol{\alpha}_{\mathbf{atm}}\times \mathbf{R_{detect}}}} + \mathbf{1}\right]}{\boldsymbol{\alpha}_{\mathbf{atm}} \times \mathbf{V_{target}}}}$$

Equation 28. Time to effect for approaching target

(3) Maximum Effective Engagement Range. Defining maximum effective range, R_{max}, as the range at which a LASER can destroy a stationary target in 100s, we calculate the R_{max} as follows:

$$\frac{E_{min}}{I_{\max range}} = 100s$$
$$E_{min} \times \frac{10^{\frac{A_{atm}\times R_{max}}{10}}}{I_0} = 100\text{s}$$
$$\boxed{\boldsymbol{R_{max} = \frac{10}{A_{atm}} \times \mathbf{lg}\left[\frac{100 I_0}{E_{min}}\right]}}$$

Equation 29. Maximum Effective Engagement Range of LASER

(4) Number of Engagements within Kill Window. The number of engagements that can be made within a kill window is calculated with the following equation:

$$\boxed{\#_{\boldsymbol{engagements}} = \frac{\boldsymbol{E_{total}}}{\boldsymbol{E_{min}}}}$$

Equation 30. Number of Engagements within Kill Window for LASER

(5) Assumptions. The following are the assumptions made for the model that was created:

- A target will be destroyed/eliminated when a sixth of the fluence required to melt through the target's external material, has been applied to the target. This assumption is made on the basis that the pressure generated as the material melts is sufficient to cause physical failure of the material even before the LASER melts through the whole thickness of the material. This is an estimate for all LASER wavelengths based on empirical data from an interview with Dr. Gary Langford.
- Target material that has been melted will be removed from the surface of the target by forces of gravity and air flowing across the surface of the target.
- Rate of heat loss from the target to its surrounding is negligible compared to rate at which energy is transferred from the LASER beam to the target.
- Range at which target is detected is always more than the maximum effective range of LASER.
- All LASER weapons can operate continuously for the whole duration of an engagement. This assumption is made due to the lack of information and would result in overly optimistic results for LASER. This assumption should be taken into consideration when comparing LASER with other weapon systems. This assumption would not have an impact on the relative performance of different LASER systems, but would skew the difference in performance, in the favor of higher power LASERs.
- Uniform beam profile for all LASERs.
- The beam quality values specified in the official reports were measured using M^2 criteria.

- Beam waist is determined using Equation 31

$$\textbf{Beam Waist}, \boldsymbol{w_0} = \boldsymbol{M^2}\frac{\boldsymbol{2 \times \lambda \times z}}{\boldsymbol{\pi \times D}}$$

Equation 31. Diffraction limited multimode Beam Waist (from Ophir-Spiricon 2010)

$\lambda = wavelength\ of\ laser,$
$z = focal\ length\ (set\ to\ 2km\ for\ all\ Laser\ systems)$
$D = Diameter\ of\ weapon\ aperture$
$M^2 = Beam\ Quality\ Factor$

- Model assumes a thermal coupling factor, α_{tc} of 0.01 for all material.
- Variations in atmospheric attenuation due to different LASER wavelengths are ignored.

(6) Simulation Engagement Adjudication Process. The simulation developed is a stochastic Excel based simulation. It models the defense capability of a vessel against a swarm of attackers. The model allows the vessel to shoot down the attackers using the available weapons, which may include anti-missile missiles, guns, LASERs or any combination of them. Each type of weapon is modeled to have a certain probability of intercepting the incoming attacker, resulting in the stochastic nature of the engagement outcome. Attackers which are not shot down by any of the weapons would be considered leakers.

The vessel would be considered to have survived a swarm attack when there are zero leakers in an engagement/simulation run. Running each scenario numerous times, the survival chance of a vessel for the certain scenario is taken to be the percentage of simulation runs in which there are no leakers. The simulation model follows the engagement process as shown in Figure 52.

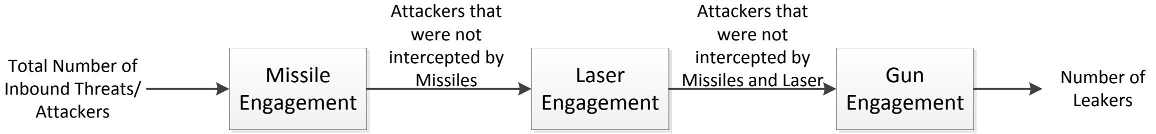

Figure 52. Engagement Process for Simulation Model

The model assumes that all inbound threats would always be engaged first with missiles, followed by LASER and lastly by guns. Threats that survive the earlier engagement will be passed on and be engaged by the next weapon type. This process is subjected to the availability of the weapon. For example, if missiles are not available or cannot be used in a certain scenario, a LASER would be used first followed by a gun. This engagement process is a reasonable model of reality, since missiles have a much further engagement range than the other two weapons and LASERs have the potential to engage beyond the maximum effective range of guns based on the GINA model validation analysis.

b. Engagement Modeling

(1) Missile Engagement Model. For the simulation, the probability of a missile intercepting its target is set to be 0.7. With this probability of intercept, when more than one missile is fired, the expected number of hits/intercepts is simply the number of missiles fired, n, multiplied by the 0.7. However, given the probabilistic nature of engagement, this number (of hits) can vary about the mean. For the missile engagement simulation, this variation is modeled as a binomial distribution. The number of hits (by the missiles) is generated randomly from a binomial distribution in Excel using Equation 32.

$$\boxed{\boldsymbol{MIN(CRITBINOM(\$B\$16, \$B\$4, RAND()), B23)}}$$

Equation 32. Random Generator for Number of Hits achieved by Missile

The cell references in the equation are defined as follows:

- \$B\$16 – Number of missiles fired within the engagement window. This is the maximum number of missiles that can be launched within the available time ((Engagement Window)/ (Time Interval between Launch)), or the number of missiles in the inventory, based on whichever is less. The Engagement Window is calculated with Equation 33.

$$[(Detection\ Range - Minimum\ Engagement\ Range)/(Speed\ of\ threat) \\ - (Minimum\ Engagement\ Range)/(Speed\ of\ Missile)]$$

Equation 33. Engagement Window

- \$B\$4-Probability of Intercept
- B23-Number of inbound threats

The CRITBINOM function generates a random number (of hits) from a binomial distribution based on the number of engagements possible within the kill window, and the probability of success. The MIN function is included to ensure that the number of hits does not exceed the number of threats.

(2) LASER Engagement Model. The stochastic nature of LASER engagement outcome is modeled by randomly varying the fluence required to destroy each target in each engagement. This model is adopted as it reflects the reality in which it is a matter of time before a LASER weapon will destroy its target and the time taken to destroy a target can vary significantly depending on several factors (different aim point, jitter, moving target, etc.). With the varying fluence required to destroy a target, the number of hits/kills (by LASER) would vary, given the finite amount of energy that can be transmitted from the LASER within the kill window. This model is implemented in Excel using Equation 34 and Equation 35.

$$\boxed{\boldsymbol{INT}(\$\boldsymbol{N}\$\mathbf{39}/(\boldsymbol{FSK}+\boldsymbol{MAX}(\boldsymbol{FSK}\ast\boldsymbol{SQRT}(-\mathbf{2}\ast\boldsymbol{LN}(\boldsymbol{RAND}()))\ast\boldsymbol{SIN}(\mathbf{2}\ast\boldsymbol{PI}() \ast\boldsymbol{RAND}()),\mathbf{0}))\ast\$\boldsymbol{C}\$\mathbf{12})}$$

Equation 34. Random Generator for Number of Engagements that can be made by LASER within the kill window

$$\boxed{\boldsymbol{MIN}(\boldsymbol{CRITBINOM}(\boldsymbol{D}\mathbf{23},\$\boldsymbol{C}\$\mathbf{4},\boldsymbol{RAND}()),\boldsymbol{B}\mathbf{23}-\boldsymbol{C}\mathbf{23})}$$

Equation 35. Random Generator for Number of Type II Engagements achieved by LASER

Equation 34 is used to generate (randomly) the number of engagements that can be made by the available LASER weapon systems and Equation 35 is used to generate the number of Type II Engagements achieved from the LASER engagements. The cell references and terms in the equations are defined as follows:

- N39 – Total fluence that can be transmitted from the Laser within the engagement window
- C12-Number of Laser weapon system on vessel
- D23-Number of engagements that can be made by the laser weapon within the engagement window
- C4-Probability of intercept, which is defined as the probability that a target that has been engaged (penetrated) by the Laser will not hit the vessel
- (B23-C23)-represents the number of threats remaining after the missile engagement

The MAX function is used in the equation to ensure that the fluence required to destroy the target is at least equal to FSK (fluence required for a Type II Engagement). The INT function is used to ensure that only complete engagements are considered.

The probability of intercept is included to account for the chance in which a target that has been penetrated/”killed” by LASER, can still strike the vessel and cause damage. As with the missile engagement model, the CRITBINOM function would generate a random number (of hits) from a binomial distribution based on the number of engagements possible within the kill window, and the probability of success. The MIN function is included to ensure that the number of hits does not exceed the number of threats.

(3) Gun Engagement Model. As with the missile engagement model, the stochastic nature of the gun engagement outcome is modeled using the CRITBINOM function as shown in Equation 36. The probability of intercept for gun is calculated using Equation 37 and Equation 38.

$$\boxed{\boldsymbol{MIN(CRITBINOM(\$D\$16,\$D\$4,RAND()),B23-C23-E23)}}$$

Equation 36. Random Generator for Number of kills achieved by guns

$$\boxed{\boldsymbol{2*(LN(D6*1000)-LN(D7*1000))/((D6-D7)*1000)}}$$

Equation 37. Mean probability of kill against missile targets, for each round fired by the gun within a 2000m range

$$\boxed{\boldsymbol{MIN(0.999,N50*N51*D9)}}$$

Equation 38. Mean probability of kill for a specified duration of engagement using the gun within a 2000m range

Cell references in the equations are defined as follows:

- \$D\$16 – Total number of 5 sec engagements that can be made within the engagement window
- \$D\$4 - Probability of Intercept for a 5 sec continuous gun engagement
- (B23-C23-E23) - Number of threats remaining after Missile and Laser engagements
- D6 & D7-The maximum effective and minimum engagement range of gun respectively
- N50-The probability of kill for one round fired from the gun
- N51- The number of rounds fired within a second of engagement
- D9- The duration of each engagement, which is assumed to be 5 seconds for the model

As before, the CRITBINOM function would generate a random number (of hits) from a binomial distribution based on the number of engagements possible within the kill window, and the probability of intercept. The MIN function is included to ensure that the number of hits does not exceed the number of threats.

Equation 37 returns the expected probability of kill/intercept for a missile target, by each round that is fired from the gun within a 2000m range. The probability of kill by each round at a distance r, measured in meters, is taken to 2/r as derived from the LDP-17 Design Exercises (Tibbitts 1998). Equation 37 is essentially a finite integral of that function from 100m to 2000m and dividing by the range in consideration. For a boat target, the probability of kill by each round fired from the gun within a 2000m range is taken to be a constant of 0.005, as stated in the LDP-17 Design Exercises (Tibbitts 1998).

Equation 38 returns the probability of kill/intercept by the gun, given a specified rate of fire and the duration of engagement, which is taken to be 3000rds/min and 5s respectively for the model. This probability is capped at 0.999 (using the MIN function) as firing an excessive amount of rounds on a target can never achieve a probability of kill of more than 1.

(4) Determining Survival Rate. With the engagement models for the various weapon systems, the number of leakers is calculated easily by subtracting the number of threats that are intercepted by the various weapon systems from the number of inbound threats. Survival rate is determined by repeating each scenario (and the associated set of engagements) 50 times (or runs) and calculating the percentage of runs that have zero leakers.

(5) Missile Characteristics. The missile defense capability that is modeled is based on generic subsonic anti-missile missile systems and has the attributes as listed in Table 27. The probability that a missile that is launched towards the threat will hit the threat is assumed to be 0.7 (Tibbitts 1998). The time between launch is the time required to prepare a missile system for the next launch and set to be 3 seconds for the model. The number of missiles on board a vessel is set to be 60 and it represents that maximum number of missiles that can be launched. To determine the contribution of missile system to the defense of the vessel, the number of launchers on board the vessel was varied during the simulation.

The minimum engagement range of the missile weapon system is set to be 2km. This may be considered to be the arming distance of the missile or a safety distance that is established to prevent collateral damage on friendly forces.

Table 27. Modeled Missile Characteristics

Missile Characteristics						
Probability of Intercept	Maximum Effective Range	Minimum Engagement Range	Average Speed	Time between Launch	Number of Missile Launchers	Number of Missiles on Vessel
0.7	100 km	2 km	1000 km/hr	3 sec	Variable (0,1, or 2)	60

(6) Gun Characteristics. The guns are modeled to resemble the 20mm Phalanx CIWS, which represents a typical terminal defense capability of naval vessels. The characteristics of the guns are as listed in Table 28. The probability of intercept represents the probability of killing the target with 5 seconds of engagement at the specified rate of fire. This probability varies with the type of threat (Missile and Boat) as shown in Table 28. To explore the contribution of the terminal defense capability to the overall defense of the vessel, the number of guns on the vessel is varied in the simulation.

The gun characteristics are extracted from the LPD-17 Design Exercises (Tibbitts 1998) and shown in Table 28, with 2 added assumptions. First, the guns can only engage in bursts of 5 seconds (or 250 rounds). The assumption that a gun can only fire 250 round bursts would imply that guns in the model are not able to switch between threats within the 5 seconds of engagement even if a target is destroyed in less than 5 seconds. Second, while the ship would usually hold a large number of rounds, the time taken to reload a gun is assumed to be too long, therefore limiting the ammunition available to a gun to 3000 (assumed to be the maximum that can be preloaded) for each scenario.

Table 28. Modeled Gun Characteristics

Guns Characteristics						
Probability of Intercept (Missile Targets)	Probability of Intercept (Boat Targets)	Maximum Effective Range	Minimum Engagement Range	Rate of Fire	Duration of each Engagement	Number of Guns
0.788	0.999	2 km (Tibbitts 1998)	0.1 km (Tibbitts 1998)	3000 rds/min (Tibbitts 1998)	5 sec	Variable (0,1, or 2)

(7) LASER Characteristics. The probability of intercept is considered to be the probability that a destroyed target will not reach the vessel. It accounts for the chance that the target may still reach and destroy the vessel despite being penetrated by the LASER. This probability is larger for missile threats, compared to boat threats as it is assumed that it is more difficult for missile threats to maintain their course of movement after being penetrated by LASERs. It should be noted that this definition probability of intercept is unique to LASER engagements. The values selected for these probabilities were strongly managed assumptions based on the Directed Energy Weapons chapter of Dr. Robert Harney's *Combat Systems* text and the idea that simply penetrating the hull of a boat will likely cause much less damage (requiring multiple "shots") than penetrating the casing of a missile under dynamic stress. These probabilities are shown in Table 29.

Table 29. Modeled LASER Characteristics

LASER Characteristics	**Type of LASER (Variable)**				
	No LASER	**LaWS**	**LaWS+**	**MLD**	**TLS**
Probability of Intercept (Boat)	0.8	0.8	0.8	0.8	0.8
Probability of Intercept (Missile)	0.99	0.99	0.99	0.99	0.99
Power	-	33 kW (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013)	150 kW (Chernesky 2012)	105 kW (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013)	10 kW (Keller 2009)
Aperture Diameter	-	0.66 m (Tressler 2010)	0.66 m (Tressler 2010)	0.49 m (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013)	0.3 m (Department of Defense 2010)
Wavelength	-	1.06 μm (O'Rourke,	1.06 μm (O'Rourke,	1.06 μm (O'Rourke,	1.6 μm (Keller

		Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013)	Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013)	Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013)	2009)
BQ (M^2)	-	17 (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013)	17 (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013)	3.83 (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013)	1.5 (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013)
Number of LASER System	0	1	1	1	1

(8) Sensor Characteristics . The detection ranges for missile and boat targets differ. For the simulation, the detection range for missile targets is set to be 50km and that for small boats varies between 0.5 km and 4 km. The variation in detection range for small boat targets is to allow assessment of the performance of the vessel defense under varying visibility.

(9) Target Characteristics. Two types of targets are considered for the simulation: Small Boats and Surface Skimming Missiles. The characteristics of the targets are as listed in Table 30. The type of target is defined by the scenario and the

number of targets is varied in each scenario to allow differentiation in performance for various weapon combinations.

Table 30. Modeled Target Characteristics

	Type of Target	**Boat**	**Missile**
Target/Attacker Characteristics	Number of Targets	Variable (100–300)	Variable (10–50)
	Operating Temperature	300 K	300 K
	Average Speed	50 km/hr	2000 km/hr
	Target Material	Aluminum	Stainless Steel (604)
	Target Material Thickness	2 cm	0.5cm
	Thermal Coupling Coefficient	0.01	0.01
	Density	2.7 g/cm^3 (MakeItFrom.com n.d.)	7.8 g/cm^3 (MakeItFrom.com n.d.)
	Melting Point	933.5 K (MakeItFrom.com n.d.)	1700 K (MakeItFrom.com n.d.)
	Specific Heat Capacity	0.897 J/gK (MakeItFrom.com n.d.)	0.5 J/gK (MakeItFrom.com n.d.)
	Heat of Fusion	396.9 J/g (MakeItFrom.com n.d.)	250 J/g (MakeItFrom.com n.d.)

(10) Environment Characteristics. The impact of atmospheric attenuation on LASER performance has been analyzed in earlier LASER Performance Analysis and is not explored in the simulation. For the simulation, atmospheric attenuation is set to be 0.8dB/km. This atmospheric attenuation would resemble operations in good weather conditions.

c. Scenarios

(1) Scenario 1: Missile Swarm Attack. The following parameters were changed:

- Number of incoming missiles (10, 20, 30, 40 , 50)
- Type of LASER (No LASER, LaWS, LaWS+, MLD, TLS)
- Number of Missile Launchers (0, 1, 2)
- Number of Guns (0 or 2)

The following factors were constant:

- Target Characteristics:
    - Material: Stainless Steel
    - Speed: 2000km/hr
    - Material Thickness: 0.5cm
- Weapon Characteristics
    - Missile Max range > detection range
    - Detection Range : 50km
    - Speed: 2000km/hr
    - Launch Interval: 3s
    - P(intercept): 0.7
    - Missile Inventory: 60 per ship
    - Attenuation (0.8 dB/km)

(2) Scenario 1.1: Missile Swarm Attack – without Anti-Missile Missiles. The following parameters were changed:

- Type of LASER (No LASER, LaWS, LaWS+, MLD, TLS)
- Number of Targets (2, 4, 6, 8, 10)
- Number of Guns (0 or 2)

The following factors were constant:

- Target Characteristics:
    - Detection Range:20km
    - Material: Stainless Steel
    - Speed: 2000km/hr
    - Material Thickness: 0.5cm
- Weapon Characteristics
    - Number of launchers: 0
    - Attenuation: 0.8dB/km
    - Missile Max range > detection range

    - Speed: 2000km/hr
    - Launch Interval: 3s
    - P(intercept): 0.7
    - Missile Inventory: 60 per ship

(3) Scenario 1.2: Missile swarm attack – with 2 anti-missile systems. The following parameters were changed:

- Type of LASER (No LASER, LaWS, LaWS+, MLD, TLS)
- Number of Targets (10, 20, 30, 40, 50)
- Number of Guns (0, 2)

The following factors were constant:

- Target Characteristics:
    - Detection Range:40km
    - Material: Stainless Steel
    - Speed: 2000km/hr
    - Material Thickness: 0.5cm
- Weapon Characteristics
    - Number of launchers: 2
    - Attenuation: 0.8dB/km
    - Missile Max range > detection range
    - Speed: 2000km/hr
    - Launch Interval: 3s
    - P(intercept): 0.7
    - Missile Inventory: 60 per ship

(4) Scenario 2: Boat Swarm Attack. The following parameters were changed:

- Detection Range (0.5, 1, 2, 4km)
- Type of LASER (No LASER, LaWS, LaWS+, MLD, TLS)
- Number of Guns (0, 1, or 2)
- Number of threats (10, 20, 30, 40, 50)

The following factors were constant:

- Target Characteristics:
    - Material: Aluminum
    - Speed: 50km/hr
    - Material Thickness: 2 cm
- Weapon Characteristics

- Number of Missile Launcher = 0 (Missiles N/A for scenario)
- LASER Engagement Range = 0 - 10km
- Gun Engagement Range = 0 - 2km
- Attenuation = 0.8dB/km

d. Analysis

The experiment design implemented for our analysis is full factorial design with 50 runs for each data point. This design is very robust and does not require assumptions on the different parameters and the interactions between them. For every scenario, the following analysis was conducted using Minitab:

- Main effects analysis
- Interaction analysis
- One-way t-test

e. Results

(1) Scenario 1: Missile Swarm Attack. In this scenario, which includes a missile swarm attack, we have varied the number of missile launchers, number of guns, number of incoming targets and the LASER type. Figure 53 depicts the main effects analysis. In main effects analysis, each graph shows the effect of a single parameter while averaging the rest of the parameters.

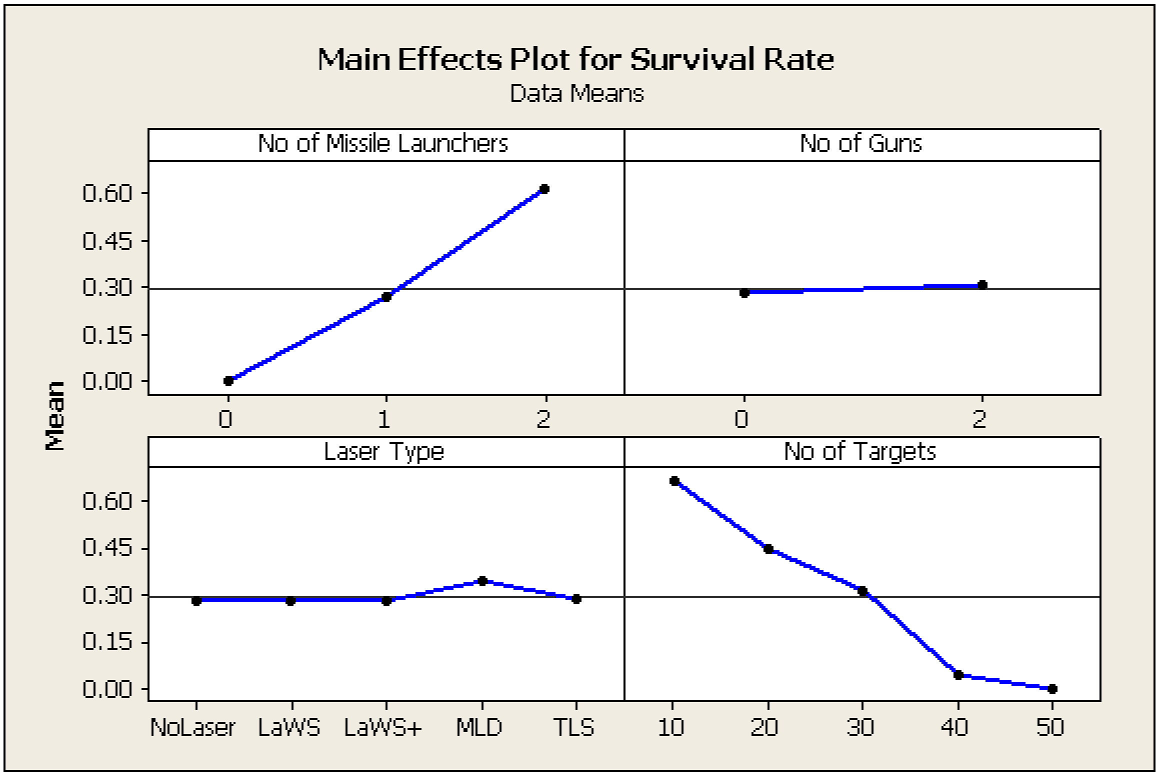

Figure 53. Missile Swarm Attack Scenario Main Effects Analysis

The main two parameters influencing the result are the number of missile launchers and number of incoming targets. Figure 54 depicts the interaction plot. Similarly to main effects analysis, in interaction analysis each graph shows the interaction effect of two parameters while averaging on the rest of the parameters.

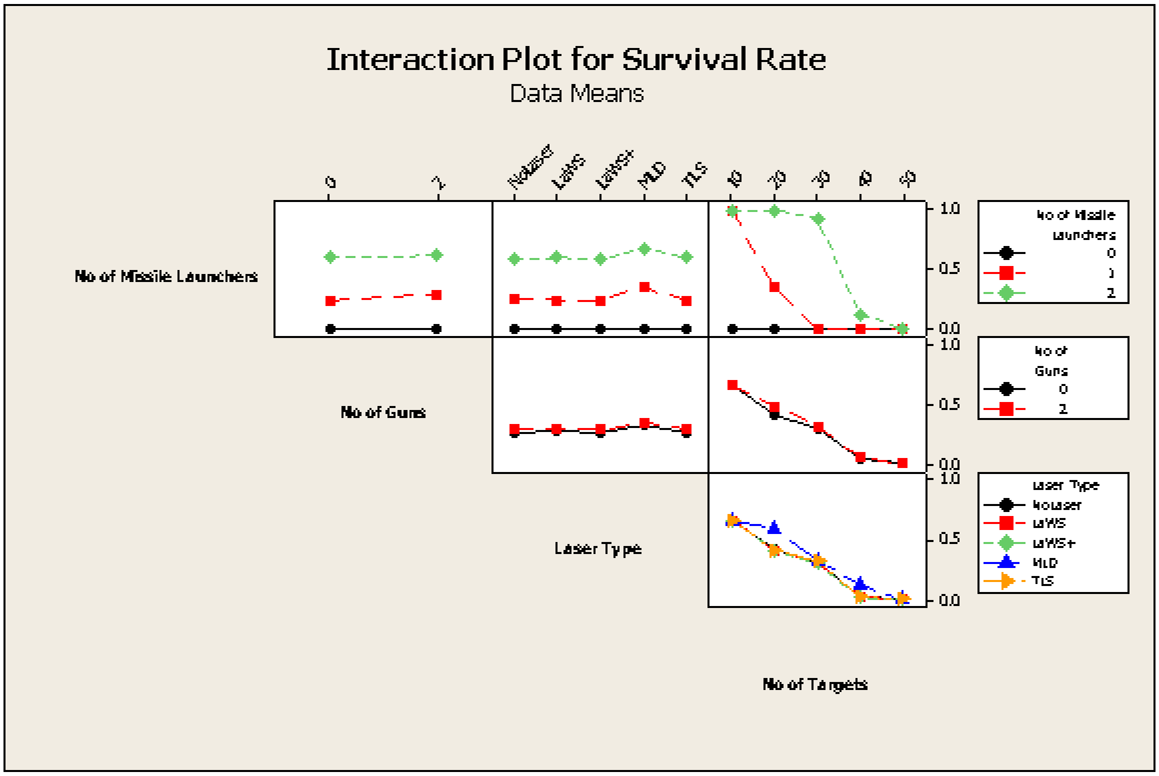

Figure 54. Missile Swarm Attack Scenario Interaction Plot

From the graphs in the top row, without missile launchers the probability of survival is close to 0. From the top-right graph, a single missile launcher can handle approximately 10 targets (up to 20 with low survival probability), while two launchers can handle about 30 incoming missiles. From the LASER type-number of targets interaction plots, the MLD is slightly better than the other LASERs in situations in which the missiles ensure some, but not full, survival rate. The rest of the LASERs do not have significantly different results in comparison with using only conventional weapons.

Figure 55 depicts an interaction plot again with a t-test for a 95% confidence interval around the mean. Although MLD appears somewhat better than the other LASERs, the overlap of the confidence intervals indicates the difference is not statistically significant (at least to the 95% confidence level). Given this limited testing, the MLD appears to be the best candidate for follow-on test and evaluation.

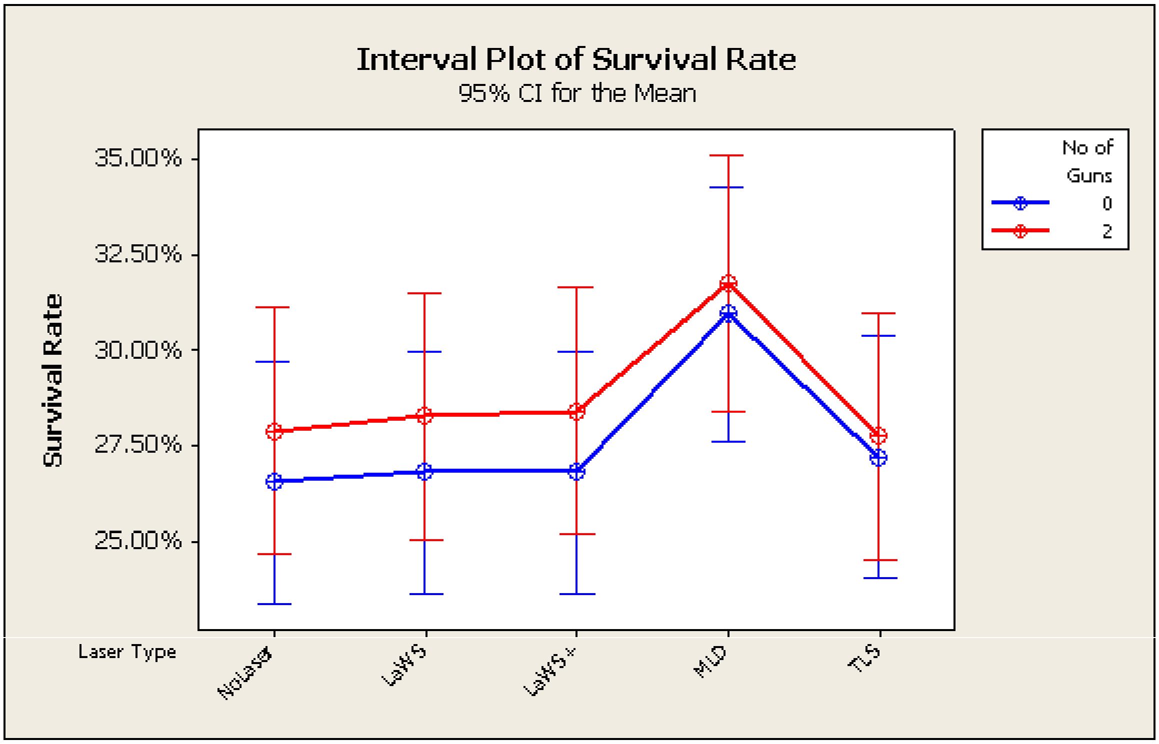

Figure 55. LASER type/Number of Guns Interaction

Figure 56 shows that MLD is significantly better than other LASERs when there are 20 targets. The reason is that in those cases, one or two missile launchers (in that order) will have some effect, but not a full one, and the MLD helps to improve the outcome. When the missile launchers are either 100% or 0% effective, a LASER does not change the outcome.

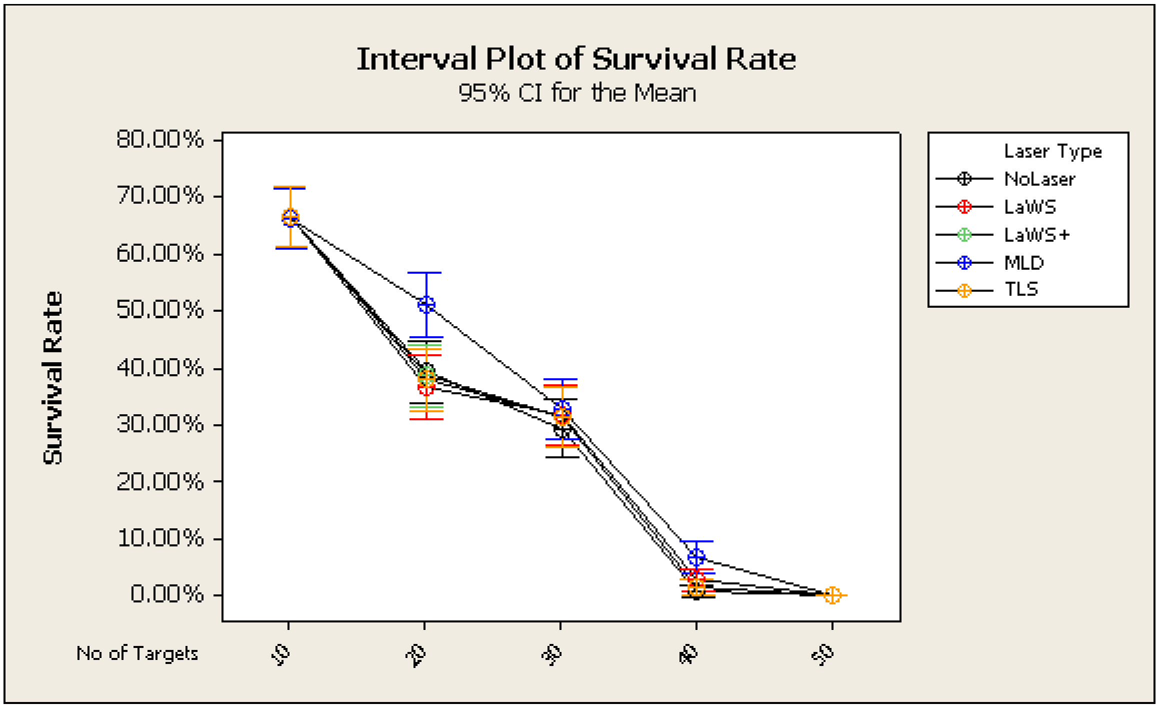

Figure 56. LASER type/Number of Targets Interaction

(2) Scenario 1.1: Missile Swarm Attack – without Anti-Missile Missiles. In order to learn more about the performance of the different LASERs in a missile swarm scenario, we simulated conditions in which there were no anti-missile missiles. This kind of a situation can occur if there is a malfunction in the anti-missile system or if a missile was launched inside of the minimum engagement range/arming range for the anti-missile system. The number of targets that can be handled is much lower in this scenario.

Figure 57 and Figure 58 depict the main affect and interaction plots for this scenario. MLD is the only effective LASER weapon for this scenario. This effectiveness is significant for less than five of incoming targets, as can be seen in Figure 59.

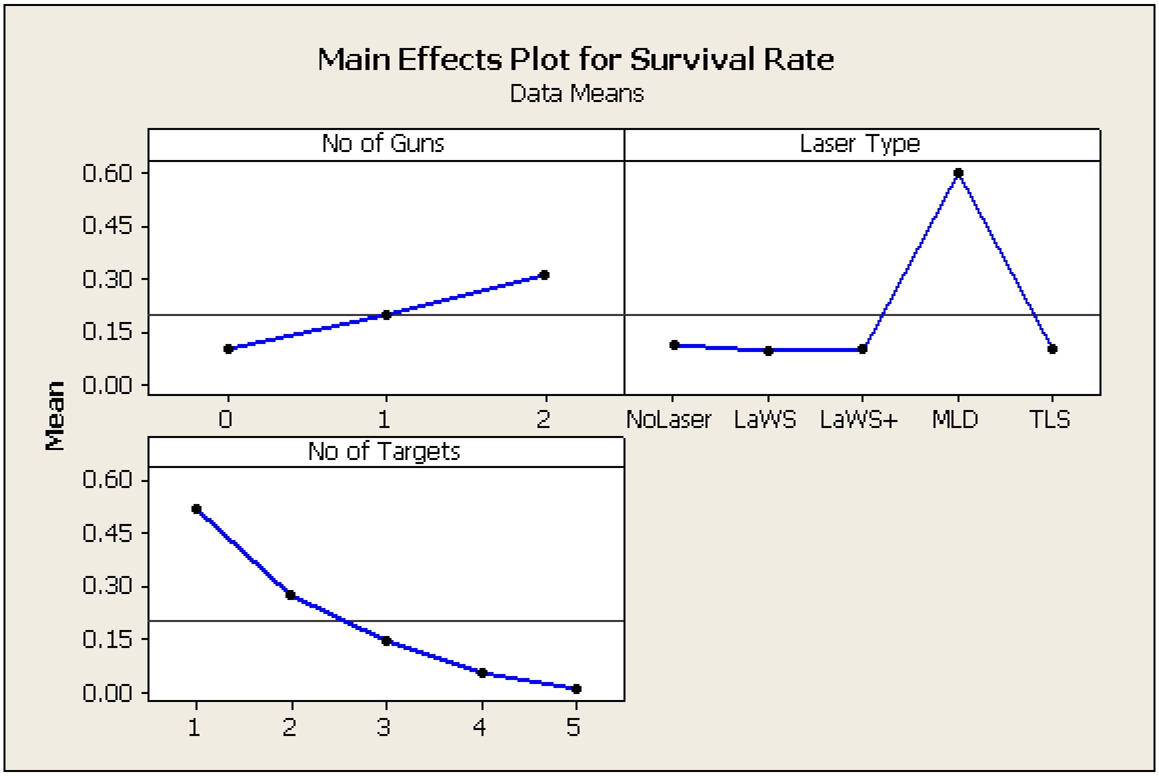

Figure 57. Missile Swarm Attack Scenario without Anti-Missile Missiles Main Effects Analysis

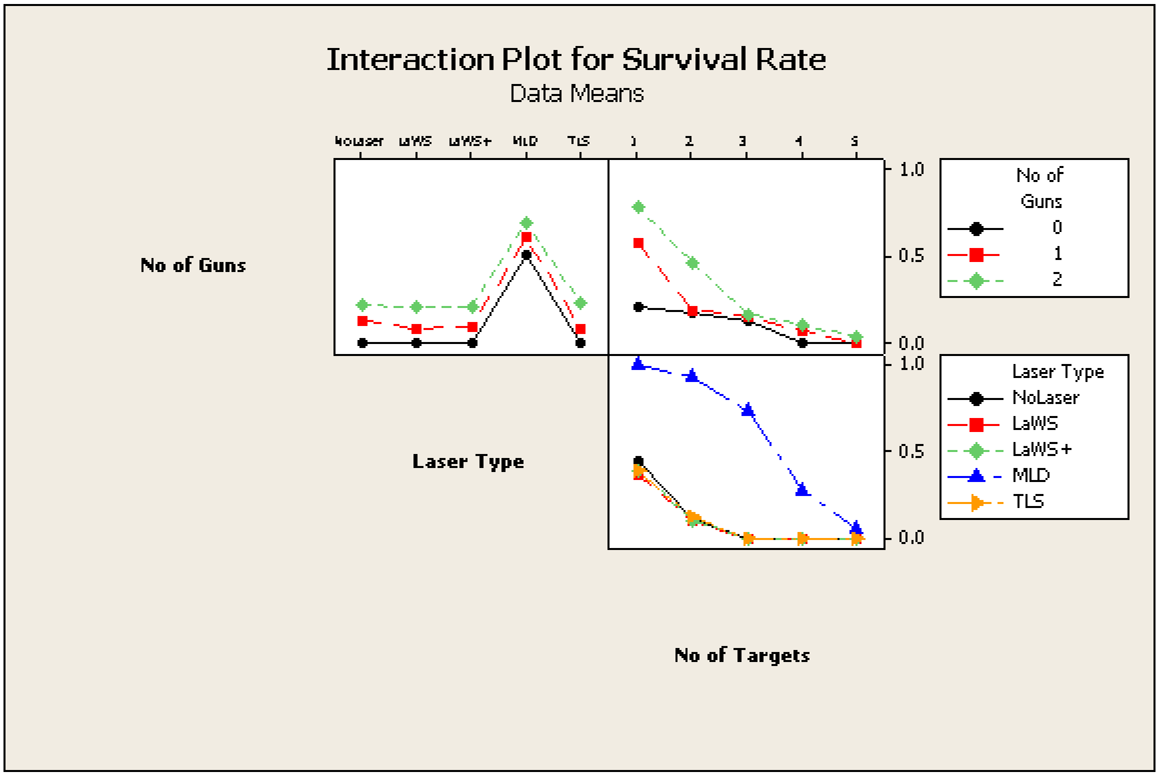

Figure 58. Missile Swarm Attack Scenario without Anti-Missile Missiles Interaction Plot

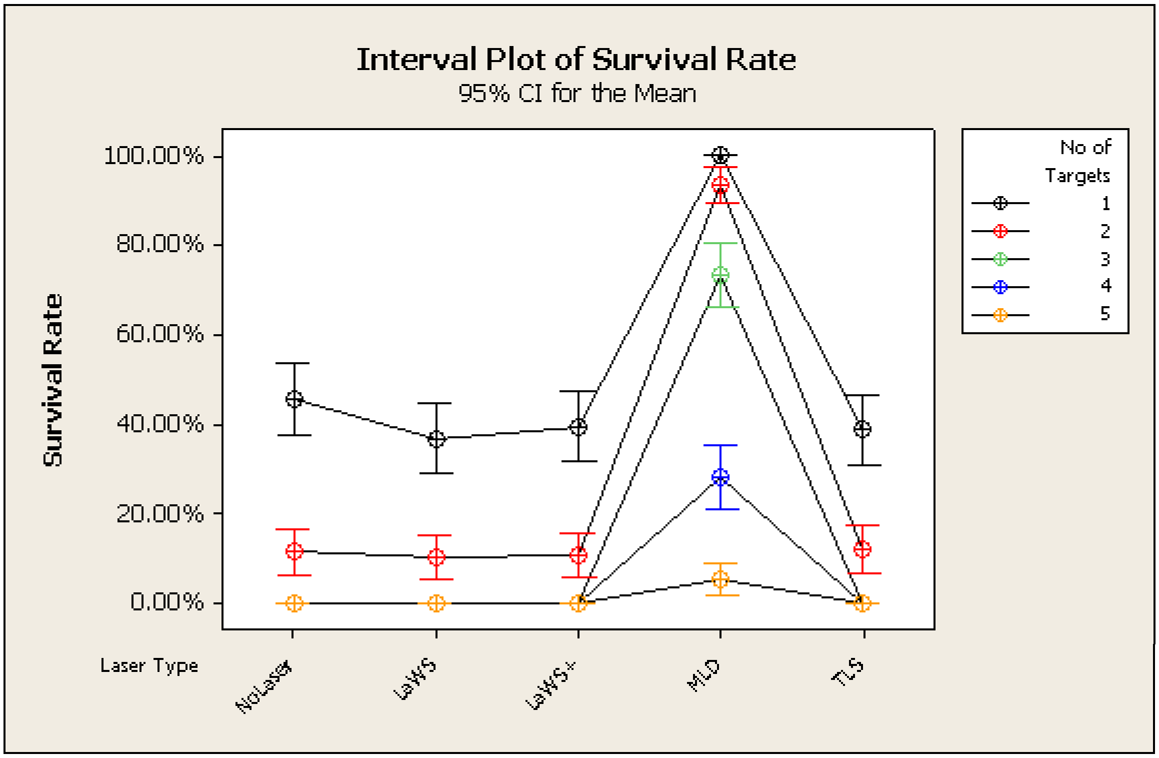

Figure 59. LASER Type/Number of Targets Interaction

To compare the effectiveness of LASERs and guns we will focus on the situation where there are one or two incoming targets (Figure 60 and Figure 61). MLD, even with no guns at all, is significantly better than two guns with no LASERs.

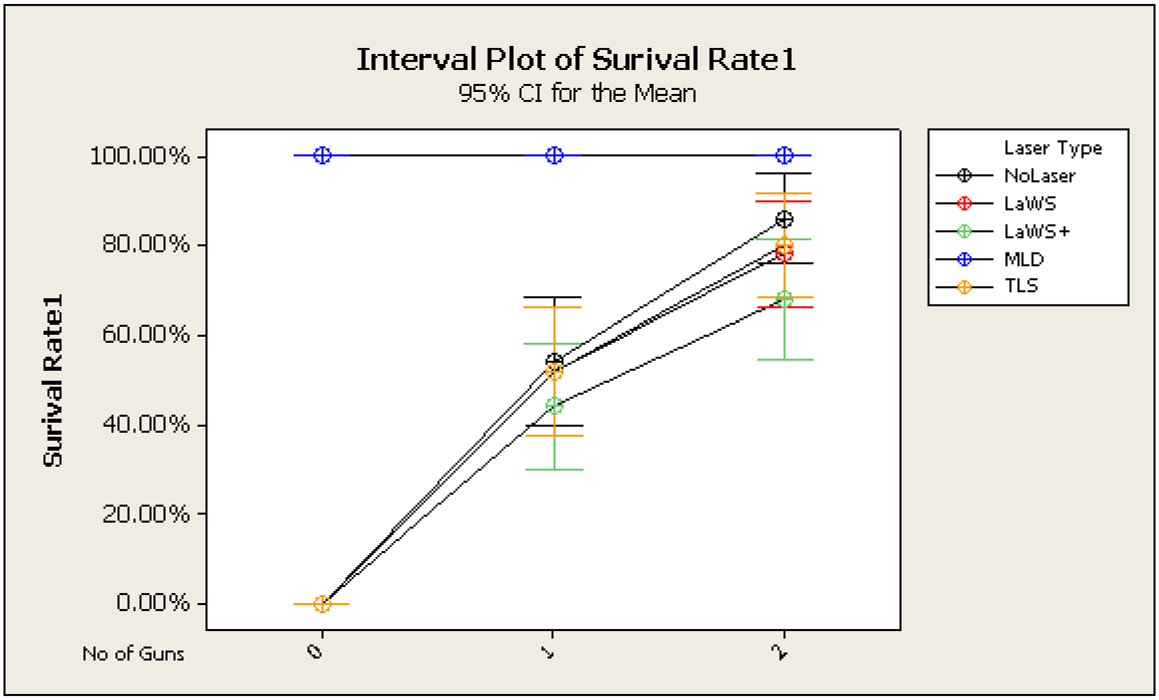

Figure 60. LASER Type/Number of Guns Interaction (One target)

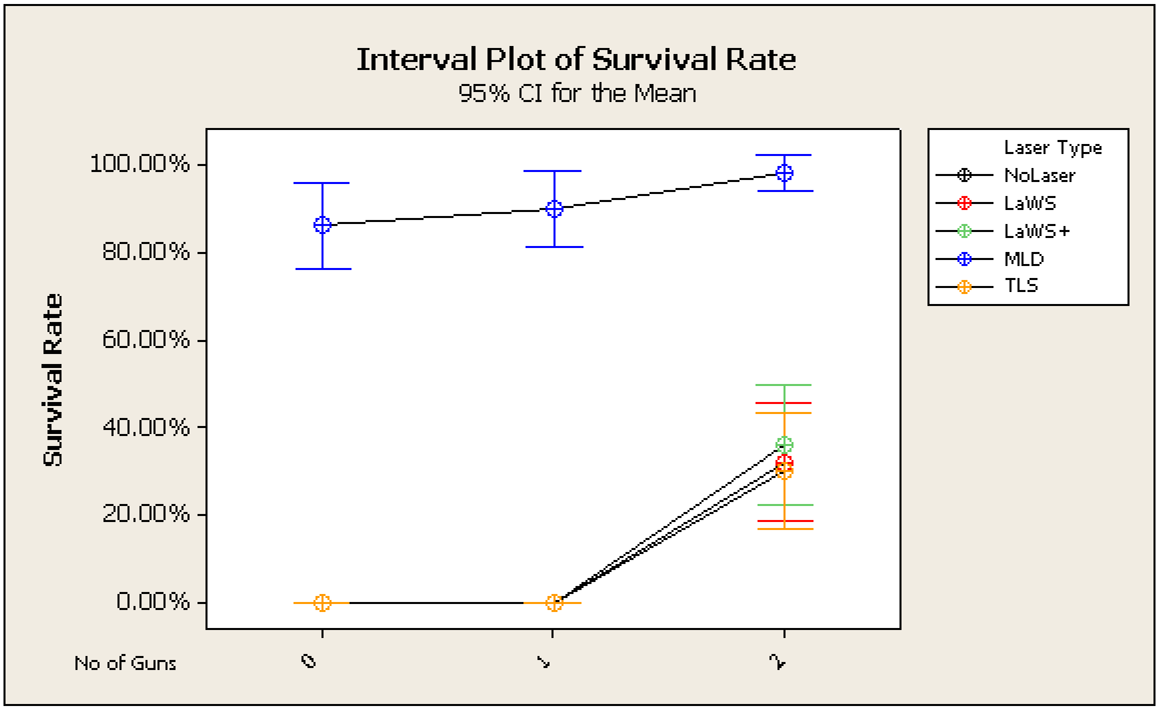

Figure 61. LASER Type/Number of Guns Interaction (Two targets)

(3) Scenario 1.2: Missile Swarm Attack – with Two Anti-Missile Systems. To complete this scenario analysis, we also take a look at the situation where two anti-missile missile systems exist and function. In this case the main effects are shown in Figure 62.

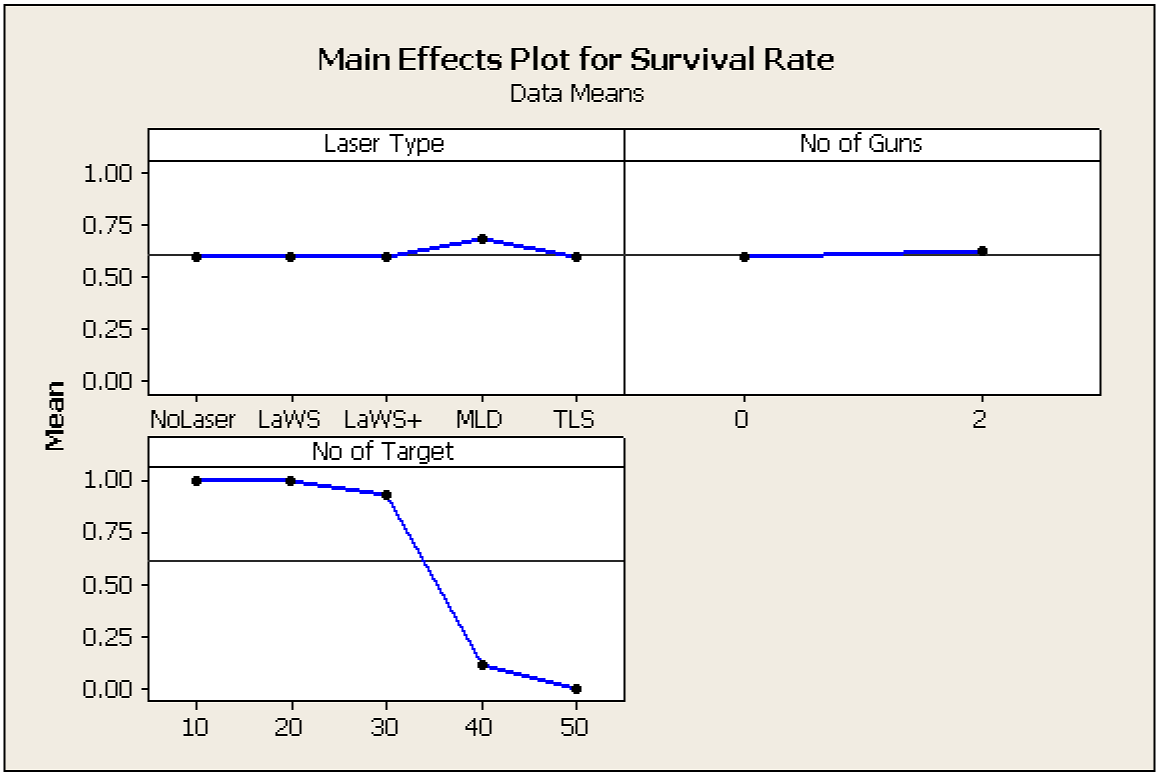

Figure 62. Missile Swarm Attack Scenario with Two Anti-Missile Systems Main Effects Analysis

From the main effects plot, guns have only a slight effect on the survivability of the ship and that the MLD also has a slight positive effect on survivability without anti-missile missiles. Also, in this type of scenario, the maximum number of threats that can be engaged is about 30 before survivability is significantly impacted.

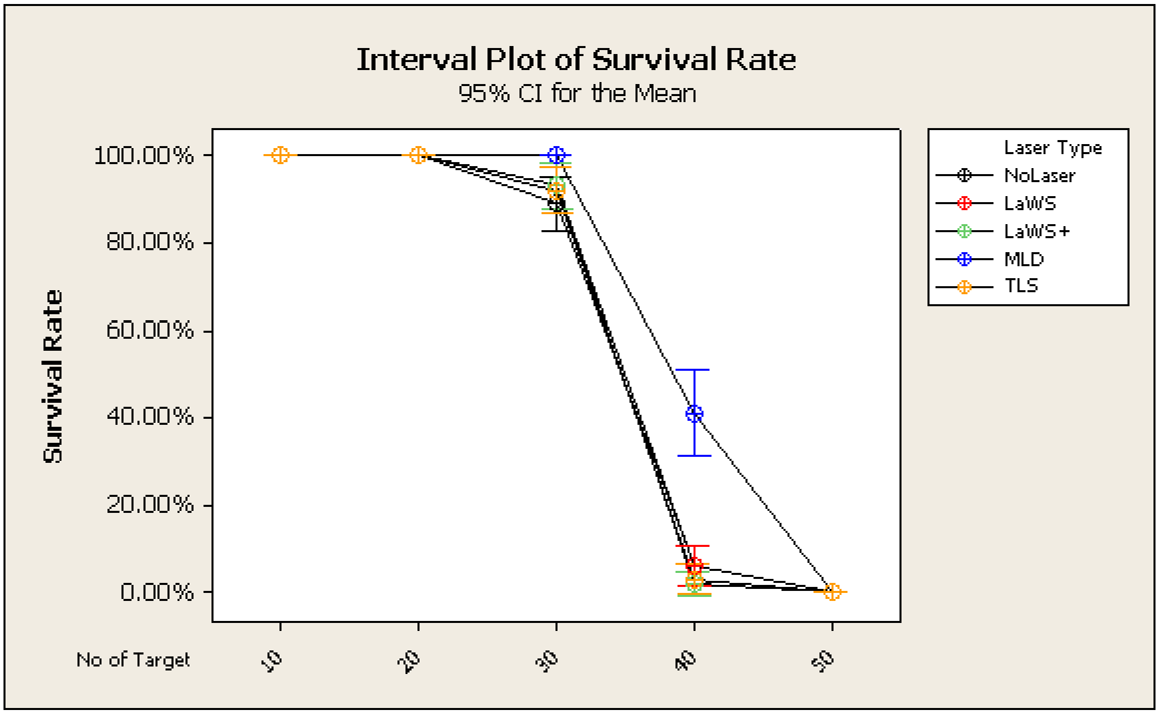

Figure 63. LASER Type/Number of Guns Interaction (Two Anti-Missile Systems)

The only LASER that has a significant contribution to the survival rate is the MLD. The two anti-missile systems can handle up to 20 incoming targets. With 30 targets, the survival rate is smaller when most of the LASERs are incorporated. However, MLD improves the survival rate. With 40 targets, the MLD can improve the survival rate significantly, from about 5% to 40%, but even 40% is not an acceptable survival rate.

(4) Scenario 2: Boat Swarm Attack. In this scenario, we analyze the performance of the different LASERs against swarms of suicide boats. We assumed that missiles are irrelevant in this scenario since they would not be used against this type of target. In our analysis we varied the detection range, the number of attacking boats, the number of guns and the number of attacking targets. Figure 64 and Figure 65 depict the main effects and the interactions analysis.

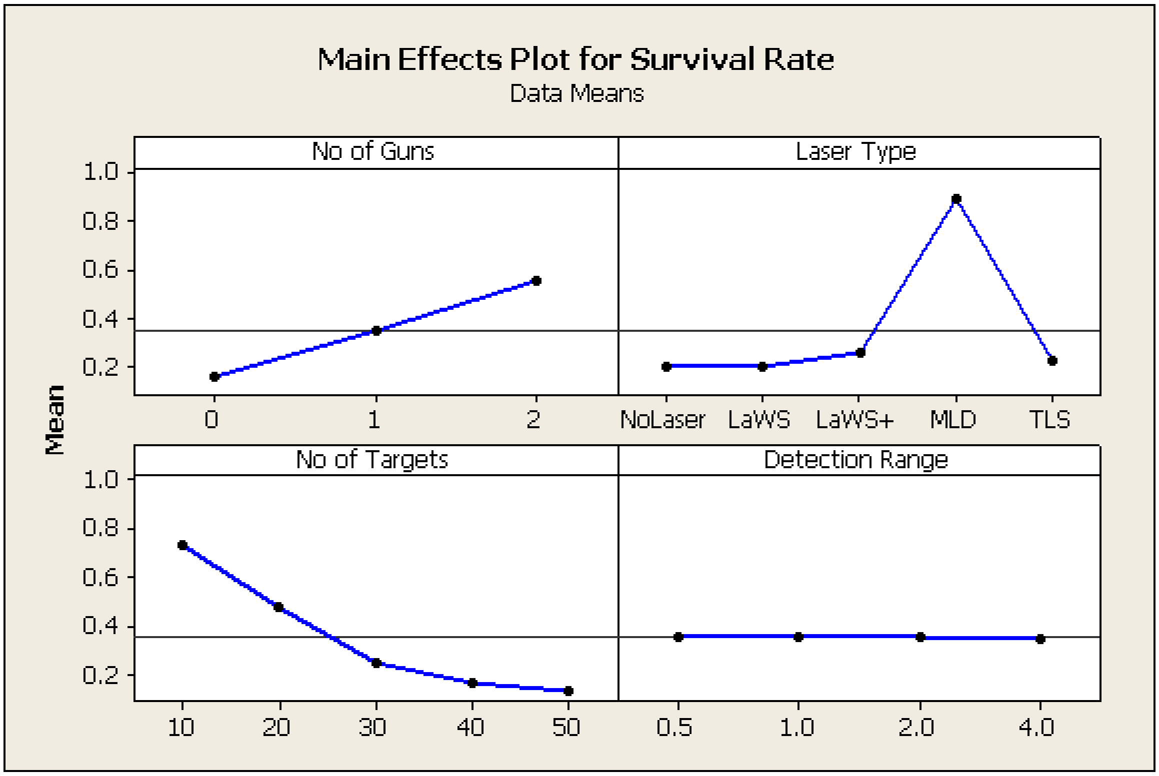

Figure 64. Boat Swarm Attack Scenario Main Effects Analysis

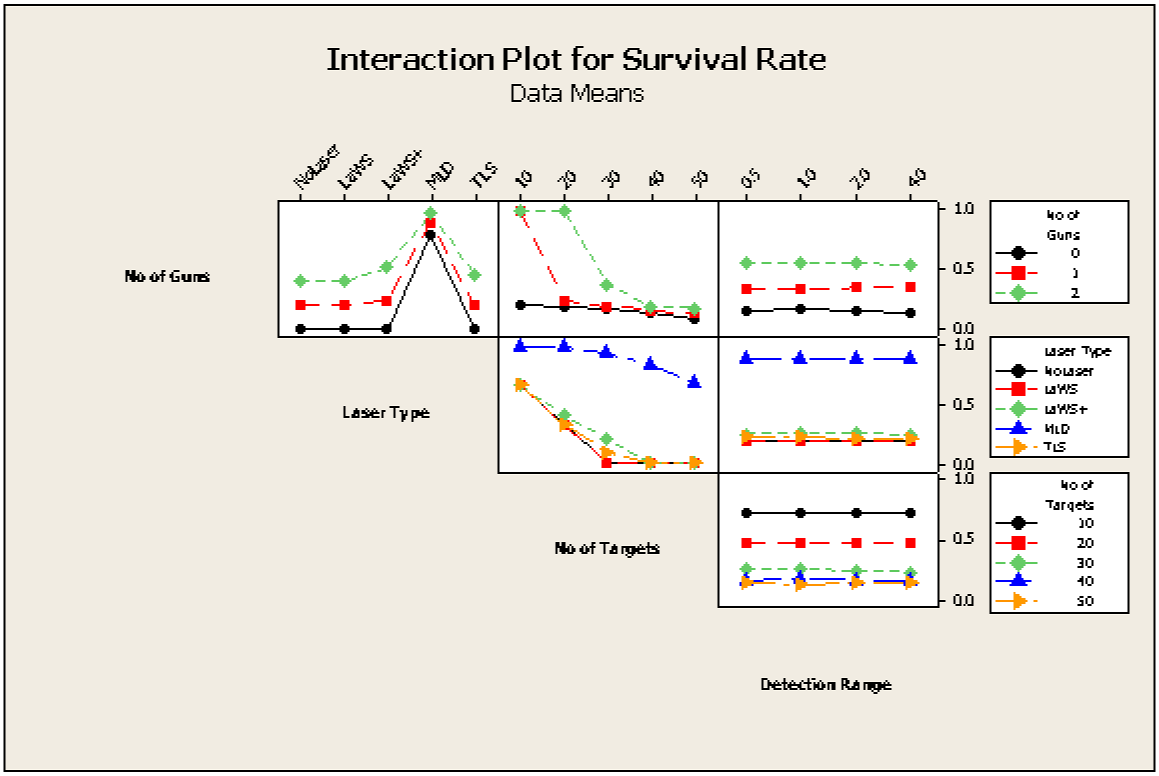

Figure 65. Missile Swarm Attack Scenario Interaction Plot

From the interaction between number of guns and number of targets (middle right plot), one gun can handle about 10 targets, and two guns can handle about 20 targets. From the middle interaction plot, the only LASER that has any effect is the MLD. This effect occurs when combined with one or two guns (shown in detail in Figure 66).

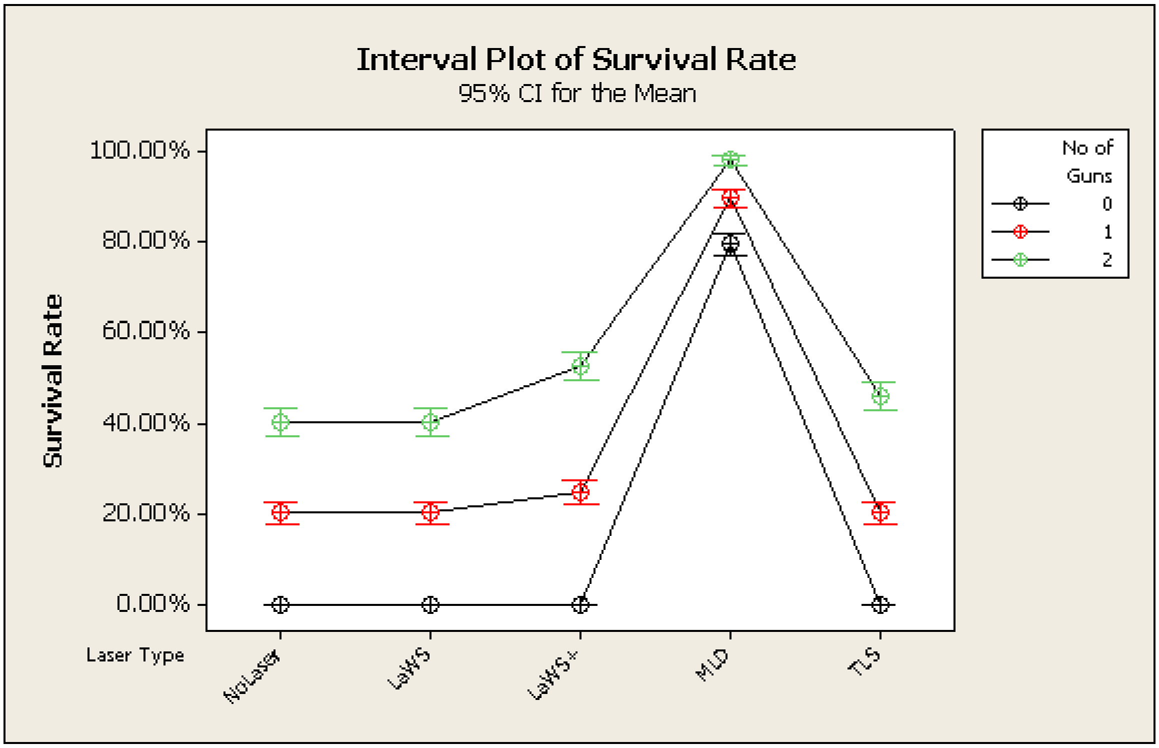

Figure 66. LASER Type/Number of Guns Interaction (Boat Swarm Scenario)

The detection range has no effect on the outcome in the scenario examined. Figure 67 shows the interaction between the number of targets and the LASER type. MLD has a substantial (and significant) effect even when there are up to 50 targets while the other LASERs lose any appreciable effect with more than 30 targets.

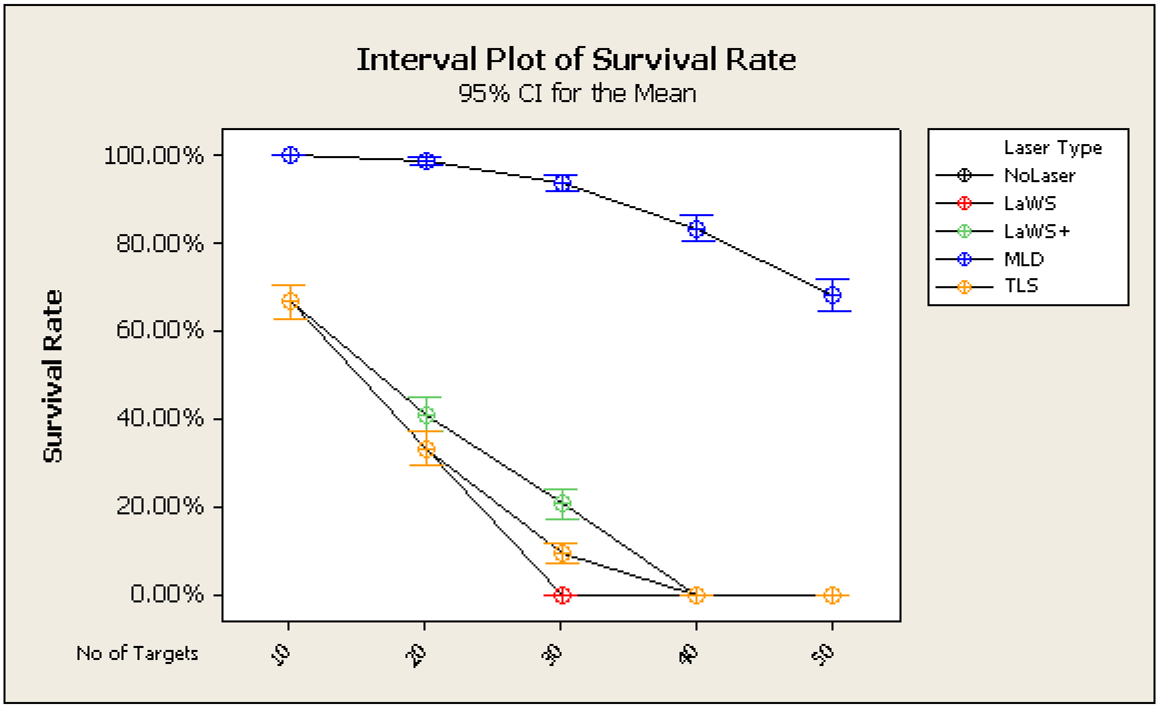

Figure 67. LASER Type/Number of Targets Interaction (Boat Swarm Scenario)

f. Findings

Based on our simulation analysis, none of the LASERs tested can replace the ship’s missiles systems or guns despite the optimistic assumptions. The MLD was found to be the most effective of the LASERs, and significantly better than the other LASERs tested. The rest of the LASERs tested were indistinguishable from not using LASERs in almost all the scenarios and situations tested. The additional value of using LASERs is rather small. None of the LASERs can replace the current systems. However, the MLD can offer some complementary abilities where the existing weapons are not sufficient due to large number of targets.

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V. INTEGRATION

A. SHIPBOARD INTEGRATION

In order to move DEW prototypes (or any weapon system for that matter) from test demonstrations to actual deployment and integration onto naval surface ships, the impact of doing so must be considered. If a new weapon system meets all performance requirements but cannot be integrated onto the appropriate platform, then the weapon is useless. Considerations to Size, Weight, and Power (SWaP) constraints, cooling requirements, combat systems integration, and weapon coverage are critical for the installation of any weapon system. While there are various Navy ship classes that may potentially support the integration of a DEW, "the DDG [destroyer] provided the best opportunity to match new capabilities with emerging needs with higher-energy LASER weapons capabilities and the class (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013)." As outlined in the project scope, only the DDG-51 will be addressed in this project. The purpose of the shipboard integration section is to determine the feasibility of fully integrating the four possible prototypes, LaWS, MLD, TLS, and ADS on an Arleigh Burke Class Destroyer.

1. LASER Weapons System (LaWS) Shipboard Considerations

On April 8, 2013, the Navy announced that it would install a prototype solid state LASER called the LASER Weapon System (LaWS) on a ship stationed in the Persian Gulf in early 2014 to conduct continued evaluation of shipboard LASERs in an operational setting (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013). The proposed LASER was a 100 KW variant of the 33 kW prototype that was temporarily installed on the USS Dewey (DDG-105) (Marks 2013). It should be noted that LaWS will not be fully integrated into the combat systems suite or be permanently mounted for the maiden deployment but serve as an operational test for LASERs (specifically LaWS) at sea.

The LaWS prototype is at TRL 6 and incoherently combines light beams from six fiber SSLs—commercial, off-the-shelf (COTS) welding LASERs. The light from the six LASERs is incoherently combined because the individual beams are not merged into a true single beam; and although the beams are quite close to one another, they remain separate and out of phase with each other, and are steered and focused by the beam director so that they converge into a single spot when they reach the intended target (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013). This reduces the complexity of the system and hence the associated costs.

a. Size, Weight, and Power (SWaP) Constraints

The selected platform to initially deploy with the LaWS prototype is the USS PONCE. The USS PONCE is a LPD-4 hull that has been converted to an Afloat Forward Staging Base, Interim (AFSB-I). However, LaWS on PONCE is considered a temporary installation of a 100 kW self-contained LASER system that provides power and cooling independent of associated shipboard systems. The Navy believes that the LASER power levels likely to be available in the near term, within reasonable size and cost, are in the neighborhood of 100 kW of radiated power (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013). For this reason we decided to look at the feasibility of a permanent installation of a 100 kW version of the LaWS on a DDG-51 ship. It goes without saying that if the 100 kW systems are determined to be feasible with respect to size, weight and power, then any lower power level variants including the current 33 kW system will also be feasible.

(1) Size and Weight. The main components of the LaWS are the LASER head, the LASER generation, and power source. The following section assumes that a 100kW LASER is the target power level for the system. Figure 68 shows that the current LaWS prototype requires enough space to fill an entire DDG-51 FLT IIA class flight deck. However, by integrating the system into the ship and utilizing the available power and cooling, the overall size can be greatly reduced with only the

LASER remaining on deck. The LaWS uses COTS welding LASERs from IPG Photonics (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013). The largest LASER unit YLS-10000 is a 10 kW self-contained LASER unit each with dimensions of 4.6’x2.8’x2.65’ (Photonics 2012). A total of 10 of these LASER units will be required for a 100 kW system resulting in a total volume of 341.32 cubic feet of shipboard space.

Figure 68. LASER Weapon System (LaWS) prototype onboard USS DEWEY (DDG-105) (from news.com.au 2013)

The current plan is to integrate the LASER optics with a CIWS mount. Utilizing an existing CIWS mount would alleviate the need for additional deck space by joining the DEW with an existing conventional weapons mount. The fire control interface module will most likely be installed in the ship’s Combat Information Center (CIC).

The weight of the LaWS system excluding the power supply and cooling subsystems is approximately 10,000 pounds (Sprangle 2012). This weight can be further reduced by assimilating the LaWS optics with the CIWS mount currently employed on DDG-51 class ships. The estimated weight of the LASER head is 1100 lbs. with the remaining weight belonging to the 10 LASER units and associated equipment. As a result, an estimated 10,000 lbs. will be added to the ship. By utilizing a Microsoft Excel spreadsheet provided by NPS Professor Fotis Papoulias, we were able to calculate the impact of adding this weight with respect to draft and stability. We assumed that the metacentric height at a draft of 20’ was 5’, while the assumed center of gravity was at 25’. Based on an estimate that all the weight would be placed on the ship’s centerline at 59’ above the keel, the additional weight of the LaWS will result in an increase in draft of .103 inches and a decrease in the ship’s metacentric height of .0037, or .37%. Given the relatively small increase in total shipboard weight by the addition of the LaWS, it is unlikely that the ship’s stability will be significantly affected by the placement of the system.

(2) Power. The current LaWS rely upon its own generator for power. A major factor in reducing the overall size of the LaWS is by eliminating this generator by supplying the ship’s electrical power to the system. LaWS is about 25% efficient, meaning that about 400 kW of ship’s power would be needed to operate a future version of LaWS producing 100 kW of LASER light. The remaining 300 kW of electrical energy would be converted into waste thermal energy (heat) that needs to be removed from the system using the ship’s cooling capacity (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013).

The current DDG-51 electrical plant consists of three Gas Turbine Generator Sets (GTGs) rated at 2500 kW each and supplies 450 VAC, three-phase, 60 Hz power throughout the ship. While the DDG-51 class peace time ship electrical load is typically less than the generator rating (currently 2500kW), the practice is to have a minimum of two GTGs on line at all times to ensure continuity of service should there be a system fault, or casualty to one of the GTGs (Mahoney, et al. 2010). This operation of at least two generators at all times essentially represents 2500 kW of unused power that could be utilized by additional systems. The LaWS system would represent a load increase of 8% to the current shipboard electrical power plant produced during dual generator operations. The current DDG-51 Flight IIA configuration can easily support this requirement for a single LaWS system during normal electrical plant lineup, but would most likely come to full power in the event the system was to be employed.

b. Cooling

The DDG-51 class combatant ship has four 200-ton A/C plants on board and is designed to supply 44°F chilled water throughout the chilled water system (Fang, et al. 2011). The DDG-51 FLT IIA's are being outfitted with five of these plants and plans are in place to upgrade the five plants from 200-tons to 300-tons on the FLT III's. Two of these plants are online and operating at any given time during normal operations to provide cooling to critical shipboard systems. Because the LaWS operates at approximately 25% efficiency, 300 kW of waste heat will need to be removed (so as not to interfere with the beam propagation). This translates to approximately 86 tons of cooling required for single system operation. The current cooling load requirement for a DDG-51 in FY13 is approximately 155 tons (Vandroff 2013). Based on the 86 tons of cooling required and an existing cooling system capable of handling 400 tons, the current DDG-51 is able to support at least one 100 kW LaWS.

c. System Placement

Due to the scarcity of topside real estate on modern ships, a major advantage of the LaWS is its ability to be integrated into the current CIWS mount. Through the combined use of this low-cost mount technology, warfighters can gain an increase in capability without having to sacrifice current capabilities. Therefore, when considering adding a single LaWS to the ship, decision makers have two choices; forward or aft. The two CIWS mount locations are shown in Figure 69.

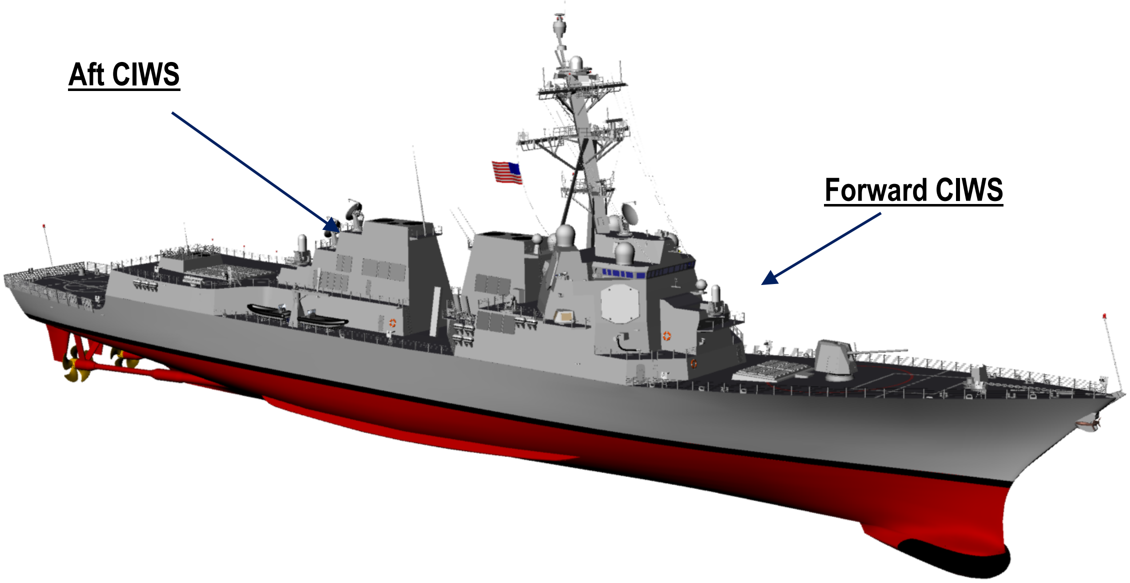


Figure 69. Proposed LASER Head Placement Locations (after Vandroff 2013)

While the LASER head will be co-located on a CIWS mount, the remaining equipment must be installed below deck. The shipboard experience of many of the project team members assisted in determining possible locations for equipment. In the case of the aft CIWS mount, the LASER units will likely be stored directly below the CIWS in the aft CIWS equipment room. Additional space is available in the #2 and #3 director equipment rooms located directly below the two aft fire control directors. Similarly in the case of a forward CIWS installation, the forward CIWS equipment room will house the LASER equipment.

d. Combat Systems Considerations

As previously mentioned, the current integration plan for the LaWS on the DDG-51 is for it to be integrated with the CIWS. This integration will allow the LaWS to be controlled via the same methods that currently control the CIWS. Figure 70 depicts an artist rendition of the combined systems.

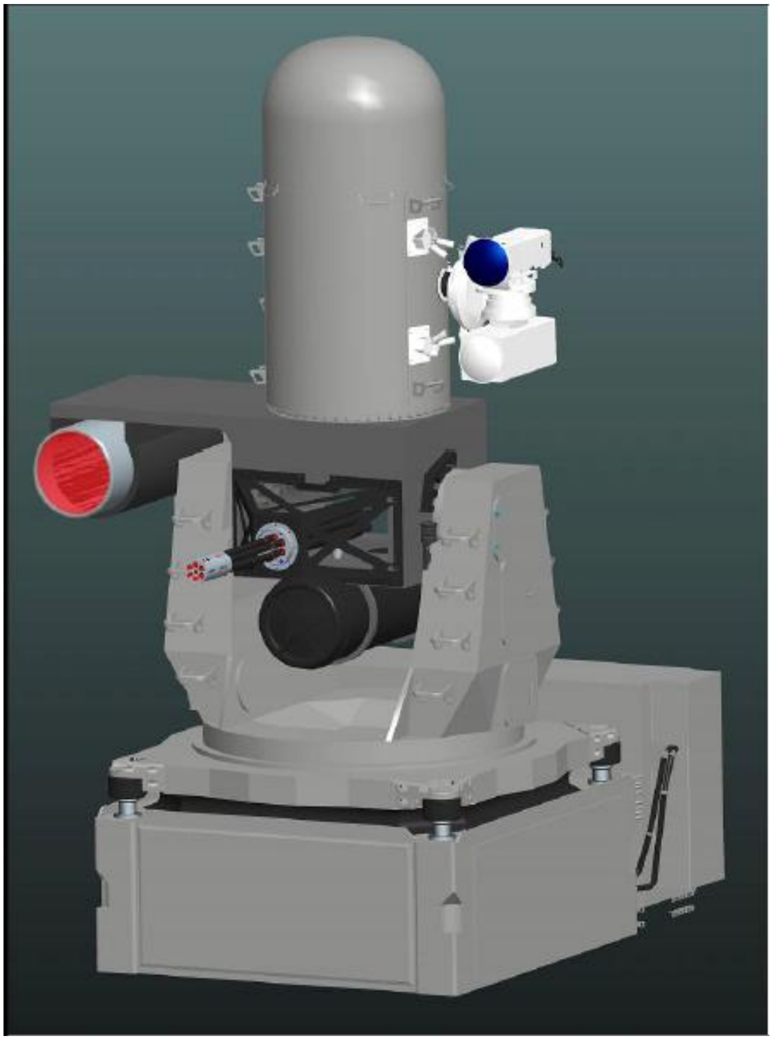


Figure 70. Rendering of LASER Weapon System (LaWS) Integrated on Close-In Weapon System (CIWS) Mount (from O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013)

LaWS is designed to be a “plug and play” system that integrates into a ship’s existing targeting technologies and power grids (Martinez 2013). LaWS can be directed onto targets from the radar track obtained from a MK 15 CIWS or other targeting source (Lundquist 2013). These functions are accomplished using the search/track radar system and the Phalanx Thermal Imager (PTI).

The LaWS will be remote operated by a console operator located in the ship's CIC. The optics that would be added for the LASER to detect and track targets in support of a LASER engagement would immediately contribute additional capabilities to the entire ship combat system even without operating the LASER (Staton and Pawlak 2012). The additional sensitivity and angle resolution provided by the LaWS optics would allow the identification, precision tracking, and "monitoring" (at high resolution) of potential threats or vehicles of interest at substantially greater ranges than could be achieved by the PTI alone (Staton and Pawlak 2012). The CIWS radar, or another source, would have to provide an initial, accurate cue to facilitate initial acquisition, but once acquired, the target could be examined and monitored with high resolution at range (Staton and Pawlak 2012).

e. Weapon Coverage

The actual weapon coverage of the LaWS system is assumed to be very similar to that of the CIWS since they share the same mount and therefore the same block zones. Figure 71 shows the approximate weapons cut-out of the forward and aft CIWS mounts.

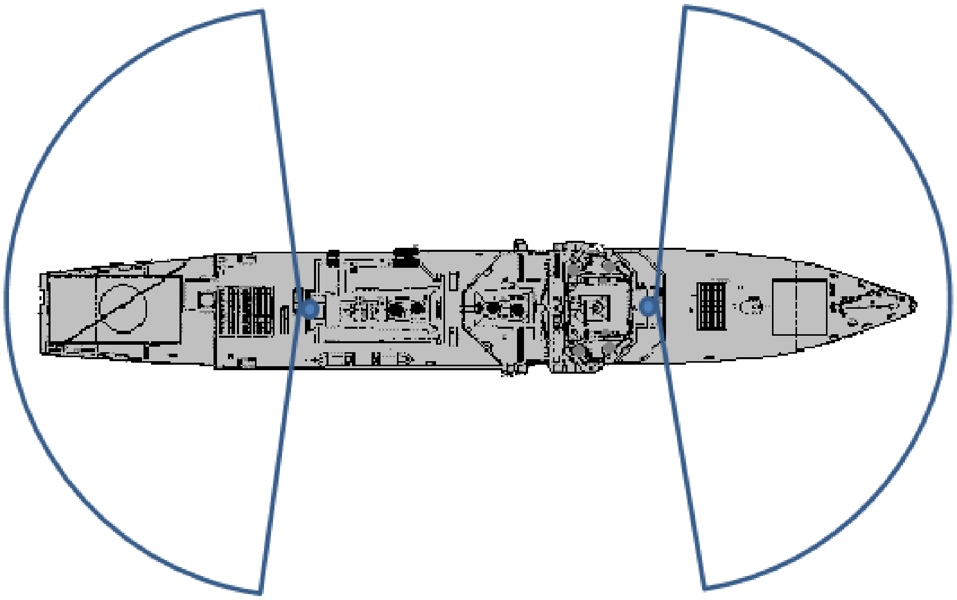


Figure 71. Close-In Weapon System (CIWS)/LASER Weapon System (LaWS) Weapons Coverage

Table 31 contains the CIWS mount traverse and elevation limitations as well as the mechanical speed in which the mount moves to engage a target.

Table 31. Close-In Weapon System (CIWS) Mount Cut-outs (from Navweaps.com 2010)

Elevation	-25 to +85 degrees
Speed in Elevation	115 degrees per second
Traverse	-150 to +150 degrees
Speed in Traverse	115 degrees per second

As in any shipboard weapon system, the weapons coverage limitations can be overcome by a vessel at sea through maneuver, and consideration must be given while at anchor or in port if the LaWS will be considered for ship defense in an Anti-Terrorism/Force Protection (AT/FP) role.

2. Maritime LASER Demonstration (MLD) Shipboard Considerations

The Maritime LASER Demonstration (MLD) coherently combines beams from multiple slab Solid State LASERs (SSLs) to create a 100kW high-power beam with good Beam Quality (BQ). The system comprises a tracking subsystem, a LASER subsystem to generate the LASER beam, a beam director with stabilizer through which the LASER is fired, and a fire control computer interface. The schematic of the MLD is shown in Figure 72.

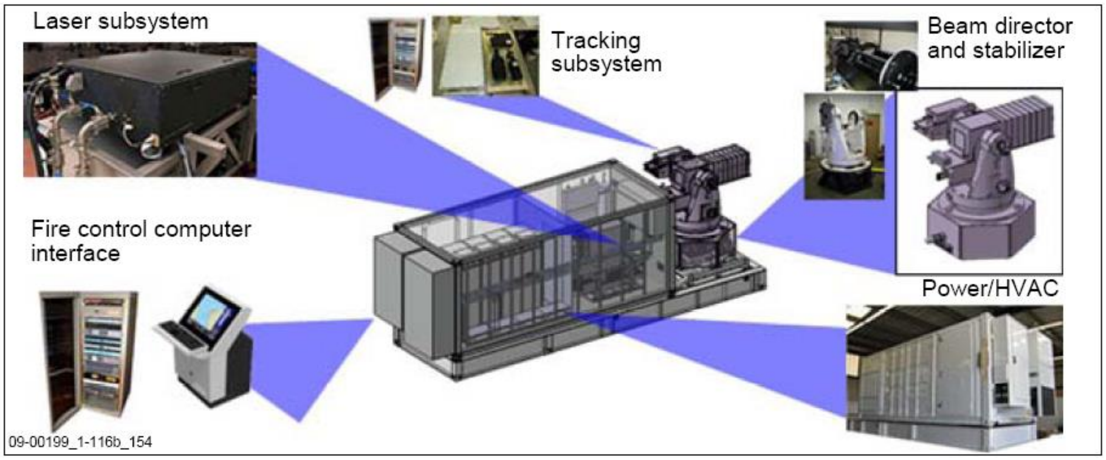


Figure 72. Schematic of Maritime LASER Demonstration (MLD) (from O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013)

A brief summary of the technical specifications for MLD is given in Table 32.

Table 32. Summary of Maritime LASER Demonstration (MLD) Technical Specifications (from O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013)

Wavelength	1.064 microns
Beam Quality (BQ)	< 3
Dimensions	A 15kW slab SSL ~ 1 ft. x 2 ft. x 3.5 ft.
Weight	~20 tons
Power Requirements	400–500 kW
Efficiency	20% - 25%

Tests in a maritime environment were performed in April 2011 by the Office of Naval Research (ONR), together with the main contractor Northrop Grumman. The system was installed on the Navy's Self Defense Test Ship, the ex-USS Paul F. Foster, and integrated with the ship's radar and navigation system. The high-energy LASER demonstration successfully tracked and defeated multiple moving small boat targets at operationally significant ranges, proving the potential for solid-state LASER weapons to defend Navy ships from small boat threats. MLD was also proven to withstand the challenging maritime environment of rain and fog, with waves up to eight feet and winds up to 25 knots (Northrop Grumman 2012).

a. Size, Weight, and Power (SWaP) Constraints

MLD is physically the largest of the four systems being considered for shipboard installation. The current MLD system is comprised of a tracking subsystem, a LASER subsystem to generate the LASER beam, a beam director with stabilizer through which the LASER is fired, and a fire control computer interface. MLD also includes a containerized unit that houses power and HVAC requirements for the system. In its current configuration, the entire MLD system is capable of being operated and transported by truck and trailer. The MLD requires more space, adds more weight, and requires slightly more power than the other three systems that were considered for addition to the DDG-51 platform.

(1) Size and Weight. The size and space of the MLD standalone prototype can be reduced through shipboard integration. Reduced requirements can be achieved by eliminating the need for the containerized power generator and HVAC cooling system. The required 'hotel services' can be provided by the DDG-51 platform. Similar to the LaWS, the MLD concept is to combine smaller LASERs to achieve the desired output power. This "stacking" is done in 15 kW increments. Each 15 kW slab SSL is housed in a Line Replaceable Unit (LRU) measuring about 1 foot by 2 feet by 3.5 feet. It is estimated that a below-deck space measuring

roughly 4.5 feet by 8 feet by 12 feet might be required for a SSL with a total power of 300 kW (O’Rourke, Navy DDG-51 and DDG-1000 Destroyer Programs: Background and Issues for Congress 2013). The fire control interface module will most likely be installed in CIC.

The combined weight of the MLD system is estimated at 20 tons. Since the actual weight could not be obtained through open source references, the weight of the MLD was estimated based on the maximum cargo weight of international intermodal containers for transport on the U.S. highway system. This assumption was based on the fact that the MLD in its self-sufficient containerized configuration is capable of transport by a single truck and trailer and is most likely a high estimation (www.ocema.org 2013). It is assumed that this weight can be reduced by half by eliminating the Power/HVAC module and by utilizing the ship’s generators and AC plants to provide the power and cooling requirements for the MLD. As a result, an estimated 20,000 pounds will be added to the ship by the LASER mount and associated equipment. Again by utilizing the DDG-51 hydro spreadsheet, with the same assumptions as described earlier, and based on an estimate that all the weight would be placed on the ship’s centerline at 32’ above the keel, the additional weight of the MLD will result in an increase in draft of .1996 inches and a decrease in the ship’s metacentric height of .0018, or .18%. Given this relatively small increase in total shipboard weight by the addition of the MLD, the impact to the stability of the ship will be essentially zero.

(2) Power. The selection of a large platform such as DDG-51 provides the advantage of sufficient power to support the high power requirements of the MLD. The power efficiency of the MLD is currently between 20–25%, but may increase to 30% in future (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013). If we assume the worst case of 20% efficiency, at least 520kW of power would be required to produce a 105 kW output beam.

Similarly to the LaWS power requirements already discussed, there is essentially 2500 kW of unused power on a DDG-51 during normal operations that could be utilized by additional systems. The MLD system would represent a load increase of 10.5% to the current shipboard electrical power plant and would be able to easily support this requirement for a single MLD. Like with LaWS, current load shed procedures may need to be revised to account for the increase in shipboard power requirements in the event of a generator casualty.

b. Cooling

An important consideration for the MLD is the utilization of the ship's cooling capacity through shipboard integration in order to minimize equipment damage caused by overheating. The MLD must dissipate any excess heat that is generated by the LASER. Based on the worst case with 20% efficiency, the total power needed to operate a 105 kW system is 525 kW and the resulting waste thermal energy generated would be approximately 420 kW.

A FLT IIA Arleigh Burke class destroyer currently has five 200T Air Conditioning and Refrigeration (AC&R) units located in various engineering main spaces. Two of these units are online at any given time to provide the ship with cooling for equipment and personnel. The current shipboard load requirement for the Flight IIA DDG-51 is approximately 170 tons (Vandroff 2013). Approximately 120 tons of cooling would be required to remove the 420 kW of excess heat generated. Therefore, sufficient cooling for a 105 kW MLD system can easily be supported by the current DDG-51 platform.

c. System Placement

There are several potential options when considering the installation of the MLD system. One installation option would be to remove either the forward or aft CIWS mount in order to facilitate the placement of the MLD and associated equipment. Another would be to keep both CIWS systems in place and add the LASER as a new addition to the ship. There are definitely some trade-offs to consider with either approach, but for the purpose of this project, consideration will be given to installing the MLD on its own mount rather than replacing an existing CIWS mount with the intention of potentially increasing the overall capability of the ship.

Figure 73 depicts the notional shipboard installation of the MLD beam director and stabilizer located on the ship's centerline, aft of the current aft CIWS mount and Vertical Launch System (VLS). The elevated mount would provide additional storage space for the LASER subsystems as well as the cooling and power piping and wiring necessary for system installation. The fire control computer interface is likely to be co-located with other fire control system interfaces in CIC.

Figure 73. Notional Shipboard Installation of Maritime LASER Demonstration (MLD) (from Northrop Grumman 2012)

d. Combat Systems Considerations

In addition to the ship's power and cooling systems, the MLD will require several inputs from the ship's Combat Systems suite to perform the target detection, identification, and tracking functions. Initial tracking of high speed, remotely operated and maneuverable small boat surface targets would be provided by the ship's complement of existing radars, and then passively and actively tracked by the beam director cameras through varying environmental conditions up to sea state three (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013). The MLD would have to be integrated with the ship’s radar and navigation system to take in inputs from the system.

Active engagement of the target would be controlled by fire controllers located in CIC. A fire control network would be required to enable the engagement. Additionally, high resolution images provided by the stabilized, optical pointing and tracking system yield an extremely effective, multi-mission capability for situational awareness and intelligence, surveillance and reconnaissance missions at long ranges (Northrop Grumman 2012).

e. Weapon Coverage

With the installation of the MLD directly above the ship’s helicopter hangars, the weapon system will have similar weapons coverage to that of the aft CIWS mount. Assuming that the beam director is fully rotatable around its base, the weapon coverage on each side would be at least 180°, providing weapon coverage for the aft portion of the ship (Figure 74). Weapon cut-outs based on the ship’s structure would need to be established to determine the minimum engagement range of the small boat threat.

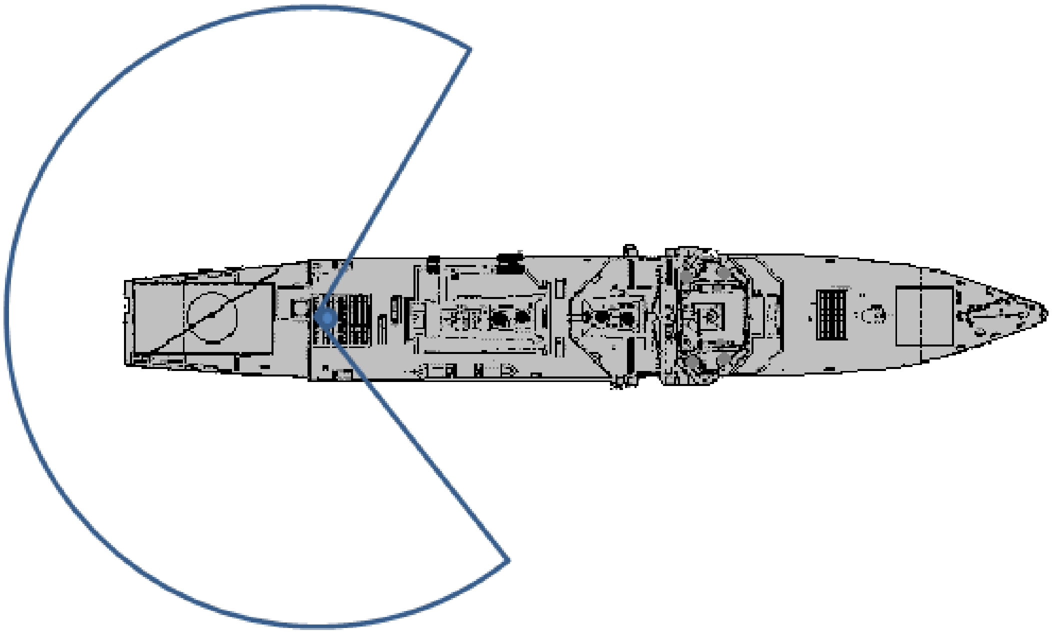


Figure 74. Potential Weapon Coverage of Maritime LASER Demonstration (MLD)

3. Tactical LASER System (TLS) Shipboard Considerations

BAE Systems and Boeing have partnered to develop a system known as the MK 38 Tactical LASER System (TLS) based around a 10kW industrial fiber LASER. This tactical LASER weapon is integrated as a side-car add-on to the MK 38 MOD 2 Machine Gun System (MGS), retaining the full capability of the machine gun system and the single operator philosophy of the MK 38 weapon (Sohm, et al. 2012). The system shown in Figure 75 combines both kinetic and directed energy weapons on a single mount to offer the war fighter with additional options with minimal impact to the current shipboard configuration. The addition of the LASER weapon module will provide high-precision accuracy against surface and air targets such as small boats and UAVs (Reed 2011). To date, 182 MK 38 Mod 2s have been delivered to the USN and have been deployed on twelve different ship classes (Sohm, et al. 2012). The primary advantage of the TLS is that it only requires minor alterations to the current ship configuration to complete the upgrade and that when deployed in pairs on U.S. Navy vessels will provide nearly 360 degrees of coverage against smaller asymmetric threats. This section will consider the additional requirements in adding a Tactical LASER System to the current DDG-51 configuration only.

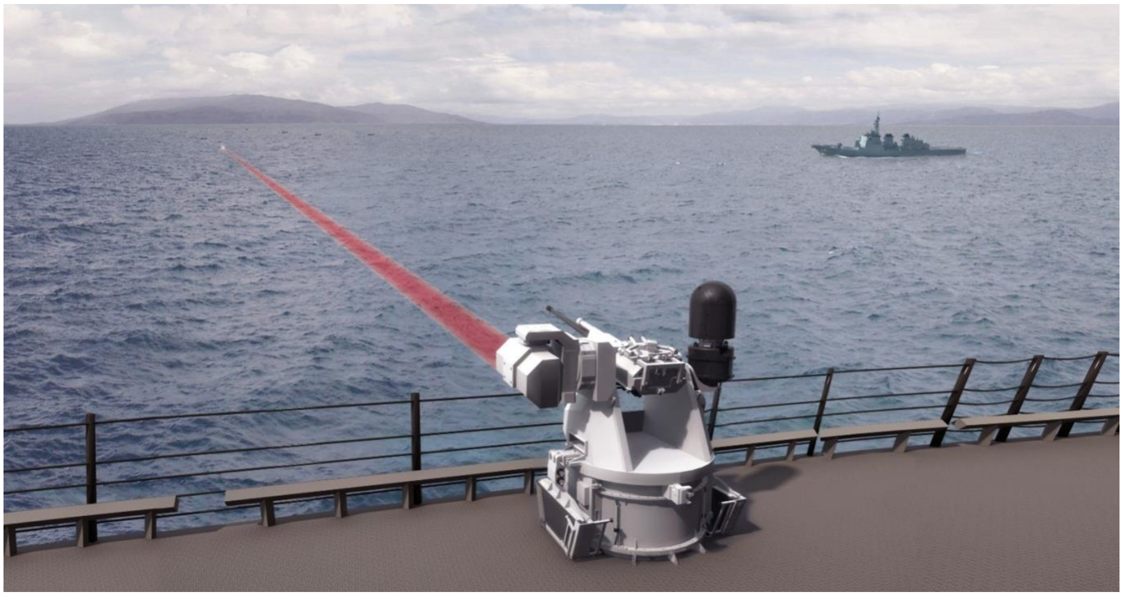


Figure 75. Artist impression of Tactical LASER System (TLS) (from Naval Open Source Intelligence: BAE Systems Completes Successful Test of Mk 38 Tactical LASER System Concept 2011)

a. Size, Weight, and Power (SWaP) Constraints

Another advantage of TLS over many other types of directed energy weapons is that it does not require much more additional space, weight, or power over the current conventional weapon being employed. As an upgrade to an existing weapon system, the TLS provides an improved capability without the typical trade-offs associated with adding or replacing a shipboard weapon.

(1) Size and Weight . While big in capability, TLS is compact in size. The TLS adds a Beam Director (BD) on the side opposite of the MK38 Electro Optical System (EOS) and houses the 10kW fiber LASER, thermal, and power management systems, which in one packaging concept, is underneath the gun mount in an environmental enclosure. The system still maintains the same deck space as the original MK38 MOD 2 (Sohm, et al. 2012). The BD is shown on the right side of the 25mm barrel in Figure 76. Also shown is the mount packaging concept in which all of the necessary equipment to operate the LASER is co-located directly under the weapon mount. The remote operating station for each system (port and starboard) will most likely be installed in the ship's bridge.

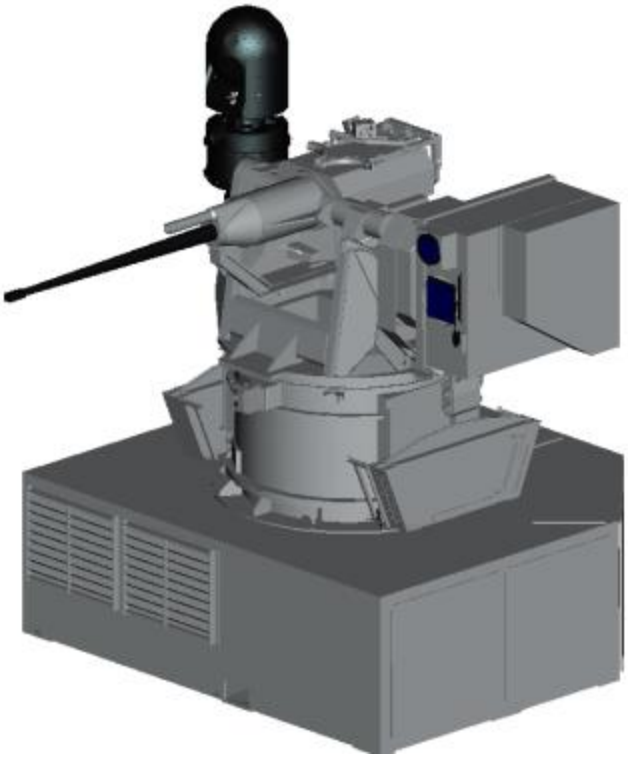


Figure 76. MK38 Tactical LASER System (TLS) under Mount Packaging Concept (from Sohm, et al. 2012)

While the actual weight increase of the TLS upgrade to the MK 38 MOD 2 system was unavailable through open source research, the system weight can be estimated based on its dimensions and components. By estimating the dimensions of the equipment package shown in Figure 76 to be approximately 2m x 2m x .5m, the total dimension is 2m^3. If the assumption that 1m^3 of equipment weighs approximately 100kg is acceptable, then the total weight of the TLS equipment is estimated to be 200 kg or 441 lbs. (Ang 2012). The TOPLITE electro-optical fire control system that is part of the MK 38 Mod 2 system weighs 59kg (130 lbs.) (www.rafael.co.il 2013). We estimate that the TLS optics based on its apparent size will weigh at least twice that of the MK 38 optics adding an addition 260 lbs. to the system. The actual weight of the current MK 38 Mod 2 system is 2300 lbs. (BAE Systems 2011). The addition of the TLS will add an additional 700 lbs. to the MK 38 Mod 2 resulting in an overall system weight of 3000 lbs. Therefore, it is a safe assumption that this increase in weight to an Arleigh Burke Class Destroyer will be inconsequential to the overall stability of the ship.

(2) Power. The power requirement from the DDG-51 will consist of the combined power requirement for the MK 38 MOD 2 system and the TLS. Due to the unavailability of open source power requirement data for the MK 38 MOD 2 MGS, the power required was estimated by using an analogous system. The system that most closely resembled the MK 38 was the MK 96 (an automated gun system on the PC-1 CYCLONE class) which resulted in an estimate of approximately 0.81 kW per system in addition to the TLS requirements (IHS Jane's 2012).

The TLS is about 30% efficient, meaning 34 kW of power is needed to operate the 10 kW LASER and the remaining 24 kW are converted into thermal energy that must be removed from the system (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013). Additionally, the TLS provides power distribution and cooling systems in the self-contained environmental enclosure. The total power requirement from the ship would be approximately 75 kW to operate the LASER, power management, and currently installed/designed thermal management systems (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013).

Based on the estimates, the combined power required from the ship for one system is 75.81 kW (0.81 kW from MK 38 MOD 2 and 75kW from TLS). The total power required for two systems (port and starboard) would be 151.62kW. Comparing the required power against the ship's generated power; both systems combined will only require 3% of the total power produced during normal operations. Therefore, sufficient power is available to support the integration of the TLS system on a DDG-51 platform.

b. Cooling

TLS currently utilizes its own cooling system and operates independent of any shipboard cooling systems. The Thermal Management System (TMS) provides the environmental conditioning to the power electronics and LASER components including the beam director and is completely packaged in the environmental enclosure (Sohm, et al. 2012). It is an advantage with respect to efficiency of the fiber LASER technology used in the TLS over other solid-state LASER technologies that allow for the reductions in thermal management system weight, volume, and power. Another benefit of this LASER source is that due to the construction of the LASER, the system can be directly cooled with a propylene glycol water mixture, thus special liquids such as de-ionized water and specific cold weather start up procedures are not required (Sohm, et al. 2012). Since the MK38 TLS is designed for minimal ship impact, the TMS requires only electrical power. Additional engineering would be required to configure the TLS to utilize the ships cooling systems, though this modification would result in an unnecessary increase in cost to modify the ship.

c. *System Placement*

The installation location of the TLS will be the same as the MK 38 MOD 1 and MOD 2 installs. The arrow in Figure 77 shows the physical location of the starboard system on the O-3 level amidships. The second system is located in the same area on the port side of the ship. As discussed above, all the associated equipment will be installed in the environmental enclosure as part of the weapon system foundation resulting in a similar shipboard footprint as the current MK 38 MOD 2 system. Other packaging configurations are being investigated such as an environmental enclosure that is next to the MK38 MOD 2 mount and the possibility of installing the LASER components below deck (Sohm, et al. 2012).

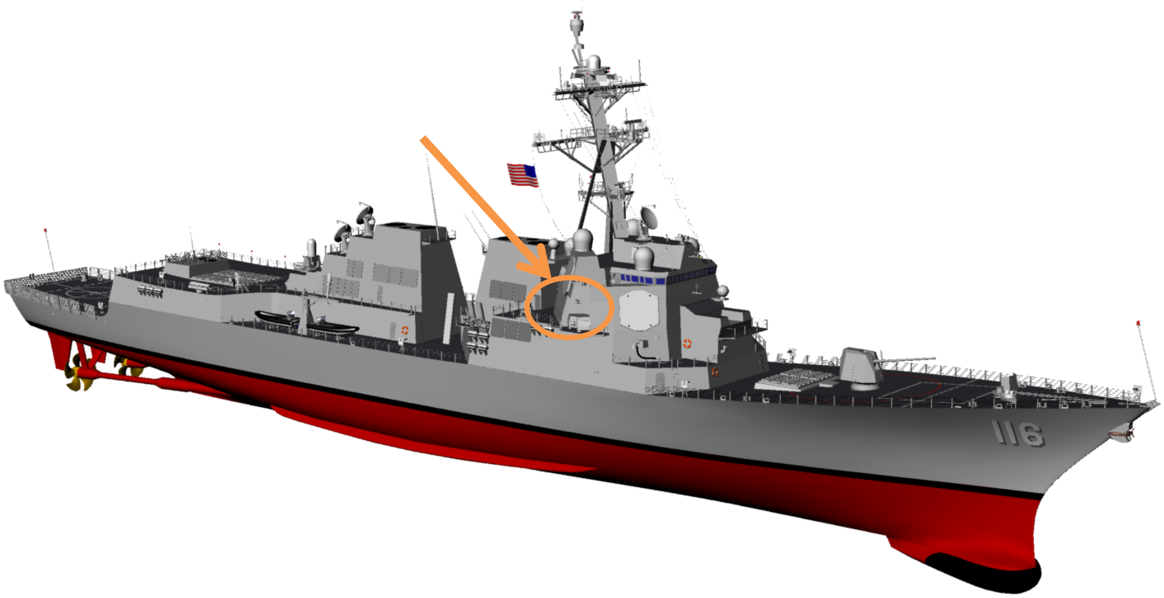


Figure 77. Location of Tactical LASER System (TLS) Installation (after Vandroff 2013)

d. *Combat Systems Considerations*

The integration approach to the ship is to keep the MK38 TLS interface similar to that of the MK38 MOD 2, which currently requires a mechanical interface (weapon station foundation), and electrical power and communication/data lines (Sohm, et al. 2012). The TLS will rely on its installed equipment and operator to complete the Detect-to-Engage sequence and will not be part of the AEGIS Combat System. Initial detection may originate from the ship's information networks, radars, or visually through the shipboard Optical Sight System (OSS) or MGS Electro-Optical System (EOS), and relayed to the TLS operators. After initial detection, the MK 38 TLS operator will perform the sensing and pointing with the MGS Electro-Optical System to track and engage the target. This dedicated sensor package includes a day-use electro-optical magnified camera, forward-looking infrared camera and eye safe LASER rangefinder. These sights help to ensure nearly 360-degree coverage for surface contact identification, night vision and periscope detection.

The TLS will be remote operated and the consoles will be located on the ship's bridge. Each system will have its own console operator that fires the MGS, and controls and fires the LASER with the ability to shift between systems as the tactical situation dictates. Independent drives allow the TLS to make azimuth corrections faster and point beyond the elevation limits of the MGS (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013). The current intent is to let the MGS Electro-Optical Sight (EOS) hand over track to the TLS. Recent field testing demonstrated a capability to identify and classify hostile targets and provide rapid hand-off to Mobile Active Targeting Resource for Integrated Experiment (MATRIX) system for interdiction (Selinger 2011).

The MK38 TLS is a fully integrated system that provides substantial capability enhancements to the current MK38 MOD 2 MGS. It has the capability to independently search, detect and track targets, assign targets to the TLS and the 25-mm gun, conduct live fire LASER weapon and gun engagements, and monitor weapon effectiveness against both air and surface targets (Sohm, et al. 2012). The BD module provides all of the optical, electro-optical, mechanical, and electrical components required to perform precision beam control for the complete High Energy LASER target engagement. The BD includes independent elevation and azimuth drives that articulate the BD with respect to the MK38 traversing mass. The independent drives are required to inertially stabilize the BD to levels not achievable by the MK38. The BD includes Near Infrared (NIR) and Midwave Infrared (MWIR) tracking capabilities. (Sohm, et al. 2012)

e. Weapon Coverage

The TLS weapon coverage will be nearly the same as the existing MK 38 MOD 2 system. Figure 78 depicts the approximate cut-outs for each system.

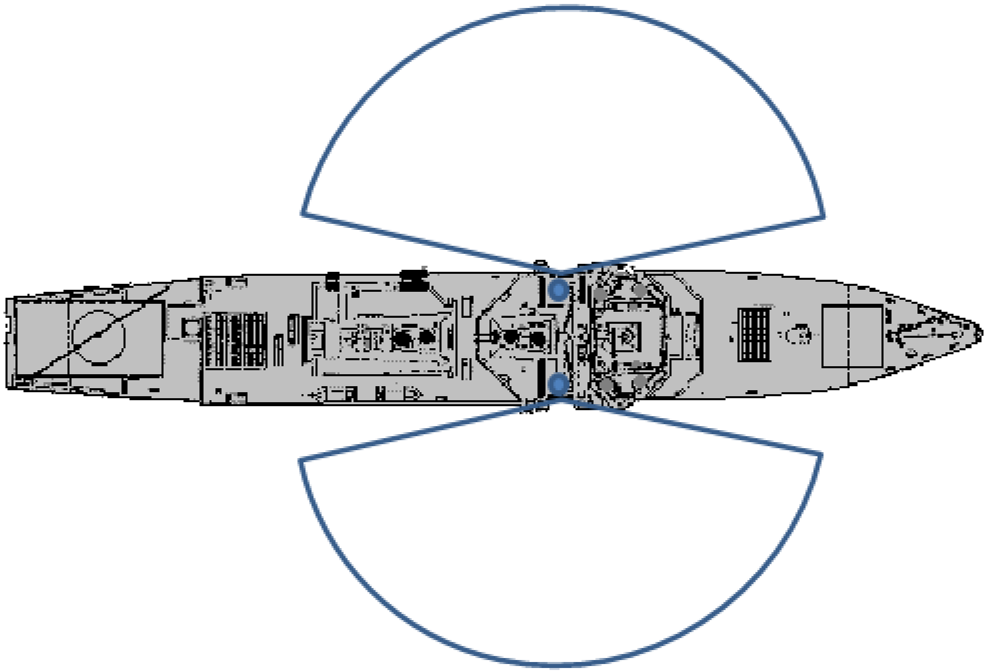


Figure 78. Tactical LASER System (TLS) Weapon Coverage

The placement of the TLS system provides coverage primarily to the ships beam and can train between +/- 15° to +/- 165° with an elevation range of -20° to +40° (www.seaforces.org 2013). However, each system can be unmasked to engage threats outside the engagement zones by maneuvering the ship.

4. Active Denial System (ADS) Shipboard Considerations

In order to maximize the coverage of the system when installed, the addition of two systems will be considered. One system will be installed on the port side of the ship while the other will be installed on the starboard. Both systems will be placed amidships. While alternative design concepts are currently being explored for the ADS with respect to improved cooling methods and transition to solid state, these concepts will not be addressed here as we are only concerned with the current system configuration for the purpose of the project. These improvements will only further facilitate the installation and integration of the system for a maritime application in the future.

a. Size, Weight, and Power (SWaP) Constraints

There are currently three system design configurations of the ADS, each varying in size, weight, and power. The first ADS configuration consisted of a conex shipping container housing the necessary components, with the antenna mounted on the roof. This system, known simply as System 0, allowed for proof of concept testing that led to the ADS Advanced Concept Technology Demonstration (ACTD) (LeVine 2009). For demonstration and warfighter assessment purposes, the ADS ACTD first integrated the millimeter wave beam into a hybrid-electric version of the Highly Mobile Multi-Wheeled Vehicle (HMMWV), popularly known as a “Humvee” (LeVine 2009). This specific ADS variant is known as System 1. System 2 is armored, environmentally sealed, and designed to operate between 0 and 125 degrees Fahrenheit. System 2 is a containerized design composed of two boxes that can be transported by, or operated from, a variety of tactical trucks. It is a modified version of this system that will be considered for shipboard integration due to it increased power and range.

(1) Size and Weight. The ADS System 2 in its current configuration consists of two sealed conex boxes per system as shown in Figure 79. The four main system components are the power generation/storage/conditioning, thermal management, beam source and antenna and are contained within the two boxes

(Hambling, Pain Beam to Get Tougher, Smaller, More Powerful 2009). One box contains the components necessary to produce the directed energy beam. The second box is a self-contained power generator unit and operator station (LeVine 2009). Shipboard space must be identified for the remaining equipment and system components to facilitate system installation. This space requirement will be addressed in the system placement section.

Figure 79. Active Denial System (ADS) System 2 (from Miller, NATO NAVAL ARMAMENTS GROUP 2009)

Each system will require separate components such as the transmitter and antenna. The transmitter produces the millimeter wave energy which when directed to an antenna will project the energy beam. The approximate size of the component conex box is 9’ x 4’ x 4’ which when dispersed and installed onboard the destroyer will require a minimum volume of 144 cubic feet of available space. The generator and operator box is approximately 8’ x 4’ x 4’ in dimension requiring approximately 128 cubic feet of available space. However, due to the availability of ship's power and the likely placement of the operator station in CIC, the generator/operator box may be eliminated.

Each antenna (Figure 80) is 86 inches when measured diagonally and is made up of 25 separate subreflectors. The antenna receives the output from the gyrotron through a beam conditioner that is focused on the small subreflector plate located in front of the main antenna. The subreflector then broadens the beam to evenly illuminate the main antenna reflector array, which then sends the millimeter wave beam down range (LeVine 2009).

Figure 80. Active Denail System (ADS) Antenna (from Miller, NATO NAVAL ARMAMENTS GROUP 2009)

When installing any new equipment or system onboard a naval vessel, considerations must be given to the amount of weight that is added and the effects of that weight on ship stability. The approximate weight of the self-contained ADS system 2 is 20,000 lbs. (Robinson 2012). As discussed earlier, this weight can be reduced by nearly half and distributed by utilizing the ships generators to provide power and by moving the operator stations to CIC. It can also be assumed that the system weight can be reduced by using the current ships armor in place of the protective armor provided by the self-contained system package.

Since we are considering the installation of two separate systems, the result is an increase in weight to the ship of approximately 20,000 lbs. to the aft superstructure on the ships centerline. Based on an estimate that all the weight would be placed on the ship's centerline at 68' above the keel, the additional weight of both ADSs will result in an increase in draft of .205 inches and a decrease in the ship's metacentric height of .0113, or 1.13%. Due to the increased height of the ADS system, this results in the largest delta in the metacentric height. However, at a slightly greater than 1 percent increase, the impact of adding the ADS to a DDG-51 is minimal.

(2) Power. The current ADS have a power output of 100 kW (Hambling, Pain Beam to Get Tougher, Smaller, More Powerful 2009). One of the major advantages of selecting the DDG-51 as a potential platform for the ADS is the ship's ability to provide sufficient power to the system. As discussed previously, this aids in reducing the size and weight of the system while providing a reliable source of input power. The DDG-51 electrical plant consists of three Gas Turbine Generator Sets (GTGs) rated at 2500 kW each. While the DDG 51 Class peace time ship electrical load is typically less than the generator rating (currently 2500kW), the practice is to have a minimum of two GTGs on line at all times to ensure continuity of service should there be a system fault, or casualty to one of the GTGs (Mahoney, et al. 2010). The output power of the ADS is 100 kW and has an efficiency of approximately 50%. Therefore, each system requires 200 kW to operate which equates to approximately 8% of the total available power provided by the ship. Both ADS arrays will be capable of being energized and operated simultaneously under normal steaming conditions with little to no impact to the ship's electrical system.

In addition to the alternating current provided by the ships electrical plant, the Active Denial System requires a separate high voltage direct current power supply. The system will utilize a lithium ion battery bank to supply dynamic direct current (DC) power to the energy transmitter. This uninterrupted power supply is required to energize the superconducting magnet in turn generating the 95 GHz radiation.

Lithium-ion batteries with high energy densities provide significant benefits in weight, volume, and extended mission durations as well as provide excellent cycle and calendar life with a lower self-discharge rate (Banner and Winchester 2011). There are however several legitimate hazards and concerns with the use and approval of lithium ion batteries for shipboard use. Among these are the release of thionyl chloride, bromine, chlorine dioxide, hydrochloric acid, sulfur dioxide and sulfuryl chloride gasses (Banner and Winchester 2011). Also, the electrolyte contained in lithium cells can cause severe irritation to the respiratory tract, eyes, and skin. Perhaps the greatest concern with lithium ion batteries is its propensity to start or further complicate a shipboard fire. This hazard is primarily caused by the batteries releasing internal pressure through venting, and through this process, flammable gasses are produced and could potentially ignite (Banner and Winchester 2011). Lithium will burn in a normal atmosphere and reacts explosively with water to form hydrogen. The presence of minute amounts of water may ignite the material and the hydrogen gas. Use of lithium cells will require specialized training and equipment for shipboard firefighters. These hazards can be mitigated to a manageable level of risk through the proper storage and care of the batteries in a dry, well-ventilated area onboard the ship.

To assure that the risks associated with all lithium batteries fielded in Navy applications have been characterized and accepted appropriately, the Navy employs a structured and tailored lithium battery safety program (Banner and Winchester 2011). This safety program requires the system to meet the concurrence requirements for specific platform carriage and use prior to shipboard integration which states: For any program whose system contains a lithium battery system to be deployed, transported, or recharged on a surface ship, aircraft, or submarine; specific concurrence from the technical authority for the platform in question must be secured prior to the issuance of a lithium battery approval by the Naval Ordinance Safety and Security Activity (NOSSA) (Banner and Winchester 2011). In this case, the approval authority currently resides with Code N84 of the NOSSA, under the auspices of the Explosive Safety Office for Naval Systems (Banner and Winchester 2011).

b. Cooling

One of the major technical challenges of the Active Denial System is in the reduction of the considerable amount of heat that is generated by the system components. The source developed for ADS achieved record breaking levels of power conversion efficiency for this type of device, in excess of 50 percent, and at output power levels of approximately 100 kilowatts (LeVine 2009). To reach this level of efficiency the system utilized a gyrotron which requires very high magnetic fields that are achieved by a superconducting magnet operating at approximately 4 degrees Kelvin (LeVine 2009). The process required to cool the superconducting magnet to 4 degrees Kelvin takes about 16 hours in its current configuration (Fortin 2012). From an operational standpoint, the system will need to be energized to its standby state well in advance of any weapon employment requirement.

In its self-contained form, the ADS requirement for supercooling is accomplished with a liquid helium cryocompressor. Liquid helium was chosen due to its lower boiling point of 4 Kelvin (-268.93 Celsius) when compared to liquid nitrogen which boils at 77.36 Kelvin (-195.8 Celsius) (Warner 2004). Due to this need for supercooling, the shipboard chill water and sea water cooling systems will most likely not be employed with the current configuration of the system to perform the thermal management function. In addition to the extensive use of liquid cooling loops, radiators and fans will be required to dissipate the excess heat.

Since the boiling point of helium is so low, special care must be taken to prevent injury when handling it in its liquid form. Because helium is a nonflammable gas, its inert characteristics allow it to be stored with flammable or oxidizing gases. However, since these nonflammable gases will not support respiration (a sufficient concentration in a closed space will cause asphyxiation), they must be stowed on the weather deck or in other well-ventilated spaces (Integrated Publishing 2013).

c. System Placement

In order to integrate the ADS onto a DDG-51 ship, it is first necessary to identify the potential location of its associated equipment. Figure 81 below depicts the probable location of each ADS antenna on the aft superstructure. The port antenna is shown in the figure, and the starboard antenna would be located in the same position on the opposite side.

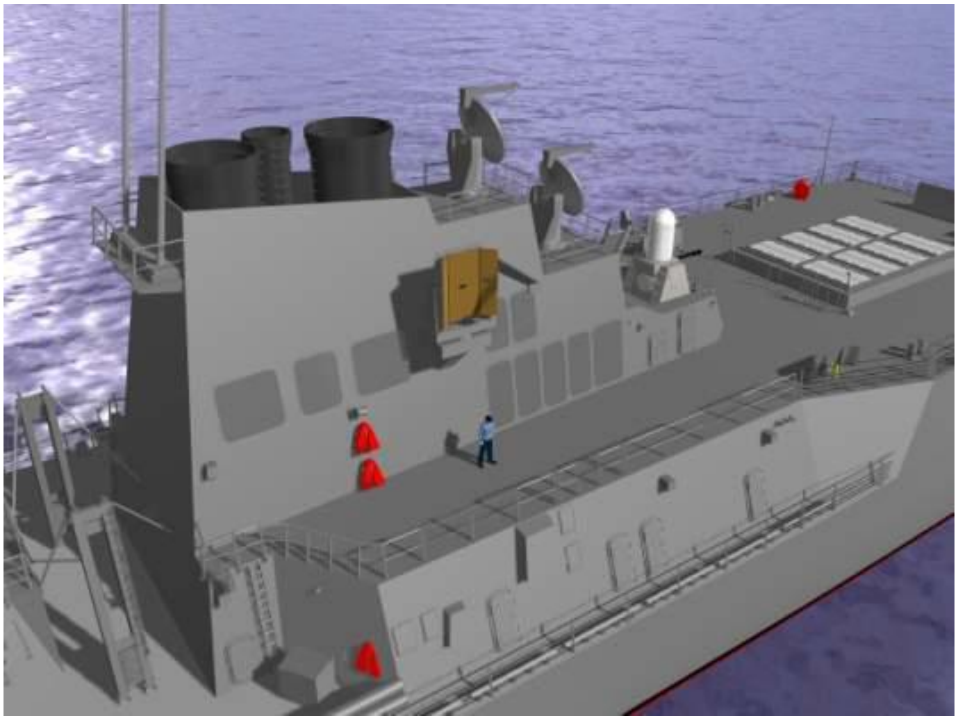


Figure 81. Active Denial System (ADS) Antenna Placement (from Miller, NATO NAVAL ARMAMENTS GROUP 2009)

For the most part, the 20,000 lbs. of equipment described earlier will be located in the vicinity of the antennas in the ships director equipment rooms just aft of the antennas. The red boxes in Figure 82 highlight the #2 and #3 director equipment rooms. These areas will also house the liquid helium cooling systems associated with each system. A plan prior to installation to cross-connect the two systems will provide some redundancy and flexibility and improve the overall system performance. Also included with the ADS equipment in one equipment room will be the lithium ion battery bank which will require the installation of proper ventilation.

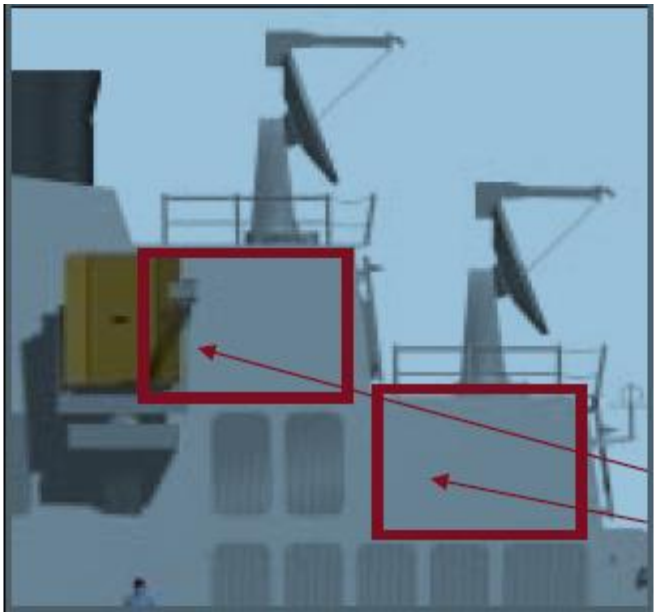


Figure 82. DDG-51 Director Equipment Rooms (from Miller, NATO NAVAL ARMAMENTS GROUP 2009)

Finally, the operator systems for each ADS will be located in CIC. Two separate consoles will be required to provide the shipboard operators with the ability to simultaneously control both systems.

d. Combat Systems Considerations

An important consideration for the installation of the ADS is how it will integrate with the current shipboard Combat Systems. The system will rely on the current shipboard methods of detection although the ADS will not be directly integrated into the shipboard combat systems. Targets will be detected via the ships information networks, radars, or visually through its optical sight system (OSS) and relayed to the ADS operators. The operators who will be located in the ships CIC can then take manual control of each antenna system to conduct the tracking and engagement. Each ADS system will require its own operating console (Figure 83) which provides the operator with a joystick to control the antenna movement and employment of the weapon, as well as a video display to view the antenna camera to track and engage the potential threat. A LASER range finder has also been installed in the antenna to provide operators with the target range in order determine the required amount of power.

Figure 83. Active Denial System (ADS) Operator Console (from Defense Update 2007)

A trained operator will interface with the system from the console by utilizing the optics system that is installed in the center of each antenna. The optics consists of a video camera for day operations and an infrared camera for night operations.

This optical system allows the system operator to aim and fire the system using the joystick while seeing exactly where the energy is directed as well as observing the reaction of the target on a display panel. Figure 84 shows the operator display/control panel. The display/control panel is a touch screen that enables the operator to select the system's output power and firing time based on the distance to the target. The ADS LASER rangefinder will assist the operator in the determination of these settings prior to engagement to prevent the accidental overexposure of this non-lethal system. The control pane allows the operator to select four power levels, from 25 to 100 percent, and six different time settings (Penn State 2008).

Shot duration 1.2 sec

Power level 74%

Faults cleared by operator.

Figure 84. Active Denial System (ADS) System 1 Operator Display (from Reilly 2012)

It is essential to have a stable beam directed at the target. Given the nature of the sea environment, the ADS would be subjected to the ship's motion, which would affect the ability of the HPM to sustain the energy on a single spot. A stabilization subsystem, similar to that of existing shipboard radar stabilization systems, should be installed to mitigate the effect of the ship’s motion, and to prevent the need for operators to make gross corrections while maintaining target tracking and engagements.

e. Weapon Coverage

The addition of two Active Denial Systems to the ship provides a significant standoff capability bridging the gap between shout and shoot while providing nearly 360 degrees of coverage. The ADS weapon coverage area is shown below in Figure 85. The areas at the ship’s bow and stern are masked by the ship’s superstructure. Like other systems onboard the ship this can be overcome by a vessel at sea through maneuver. Consideration must also be given to a ship at anchor or in port to effectively employ the weapon while understanding the potential limitations of weapons coverage.

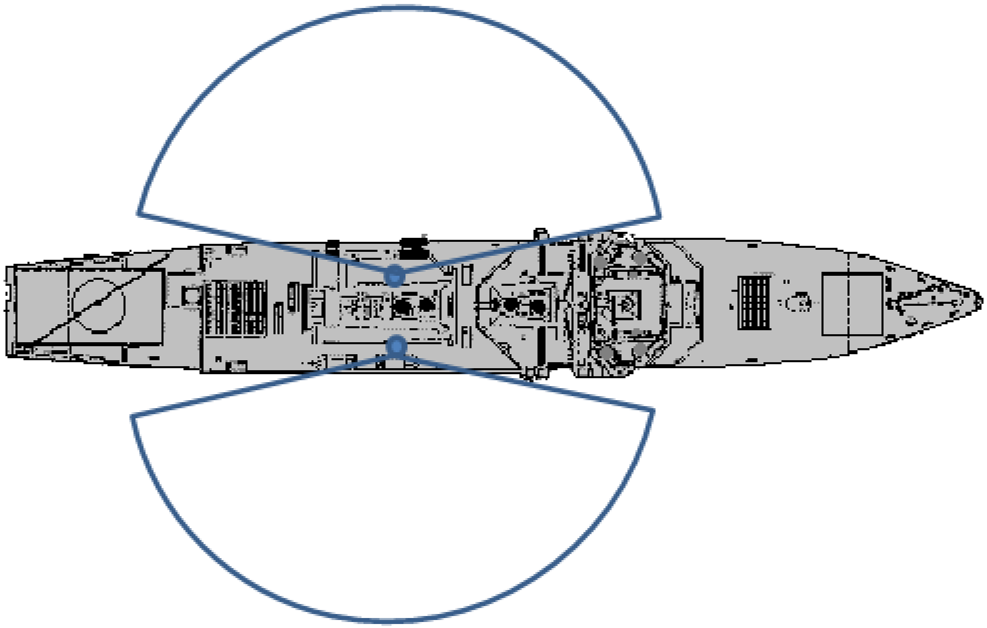


Figure 85. Active Denial System (ADS) Weapon Coverage

5. Summary

As the Navy proceeds with the procurement and installation of LASER weapons and high powered microwaves, the Navy will be faced with many integration challenges to its existing platforms. Competition among DEW and future combat systems additions with respect to topside real estate, weight, power, and cooling will have a major effect on which systems decision makers choose to further pursue. Table 33 below contains a summary of the shipboard integration section. Due to the likelihood that the TLS and ADS will be installed as pairs, the combined values are shown in the table for a dual system installation.

Table 33. Shipboard Integration Summary

	(2)TLS	LaWS	MLD	(2) ADS
Weight	2000 lbs.	10,000 lbs.	20,000 lbs.	20,000 lbs.
Input Power	151.62 kW	400 kW	520 kW	400 kW
Cooling	Self-Contained	86 Tons	120 Tons	Self-Contained
Coverage	Nearly 360°	180°	180°	Nearly 360°
Combat Systems	No	Yes	No	Yes

The MLD is by far the largest of the four systems with respect to weight and size. At an estimated 20,000 lbs., it is nearly as heavy as the two unit active denial system. While the LaWS will add an additional 10,000 lbs. to the ship, the addition of the TLS as an upgrade to each MK 38 GWS will have essentially zero impact on the overall stability of the ship. Both the LaWS and the TLS are installations to existing shipboard weapon systems and therefore require limited additional deck space. Conversely, the MLD and the ADS will be standalone systems that can take up potentially significant deck space.

The MLD, LaWS, and ADS each require approximately 400 kW to 500 kW of electrical power provided by the ship, while both TLS systems operated simultaneously will only require approximately 150 kW. The cooling requirements for the ADS and the TLS are part of their self-contained systems and are operated by the ships electrical system. The MLD and LaWS will require 120T and 86T of cooling respectively that is provided by the ship's chill water system.

The TLS and ADS by nature of their dual installations will provide the ship with nearly 360 degrees of coverage while the single MLD and LaWS systems installed either forward or aft will provide approximately 180 degrees of coverage. Both the MLD and LaWS will require inputs from the ship's combat systems, thus increasing the complexity of the installation, while the ADS and TLS will be installed as standalone systems.

The current DDG-51 platform can support each of the four systems with respect to SWaP constraints, cooling requirements, and combat systems integration. However, from a purely shipboard integration perspective, the TLS appears to be the best option as it minimizes the total impact to the ship. Additionally, although the current AEGIS destroyer can support a 100 kW LASER, a quick analysis of the current capability showed that as the power levels of these LASERs are increased in the future, the DDG-51 platform must also be upgraded to account for the additional power and cooling requirements.

B. SUSTAINMENT

Sustainment is "the supportability of fielded systems and their subsequent life cycle product support - from initial procurement to supply chain management (including maintenance) to reutilization and disposal" (Defense Acquisition University 2003). That is, sustainment is supporting an operational system throughout the time it is being used until its ultimate disposal. Sustainment involves the materials (parts and units of the system), the management of these materials to include procurement and distribution, sustaining engineering, operational unit support, and removal from the fleet.

1. Overview

The sustainment graph (Figure 86) was taken from an interview with Dr. Gary Langford, a professor and recognized subject matter expert of directed energy technologies (Langford, Sustainment 2013). It depicts the time to have useable output energy as it relates to the integration of the DEW systems. As time progresses, the systems may take considerably less and less time to produce the desired output beam. At the initial stage, the systems will take some considerable amount of time prior to being ready to fire. Experts are on site overseeing the startup. At the integrated stage, the system is activated and formulating acceptable beams faster than at the initial stage as it begins to be incorporated on the ship. The optimized stage represents when the systems are going through the final stages of integration and are performing at a level conducive to operational requirements in a military environment (able to come "online" within seconds of activation).

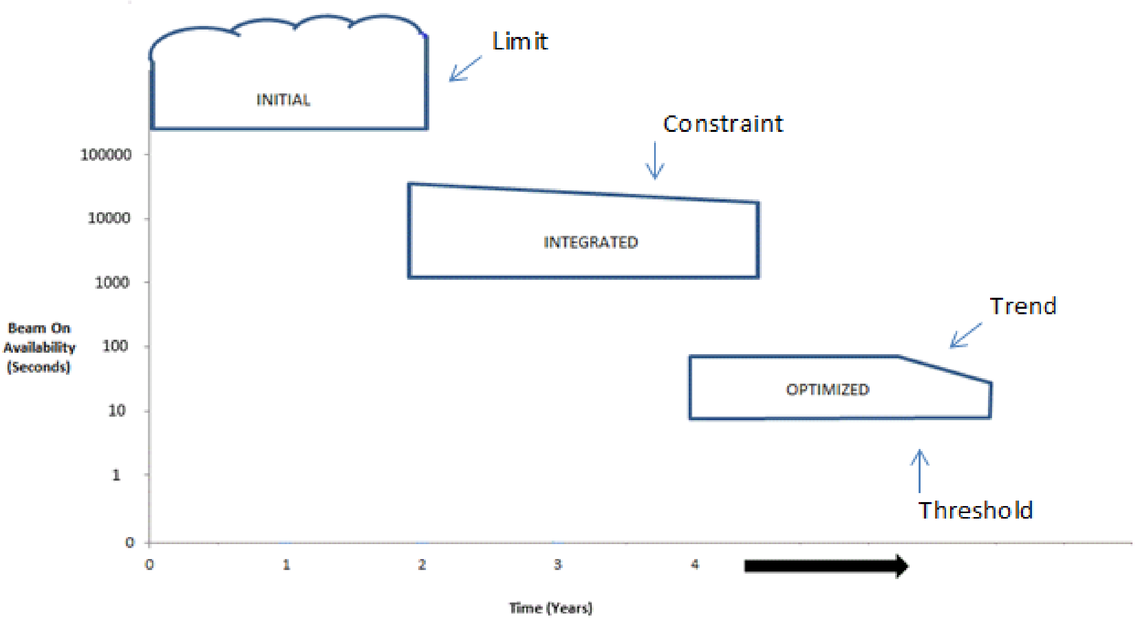


Figure 86. Sustainment Overview (from Langford, Sustainment 2013)

Curves of the initial phase indicate that throughout this period there may be some moments of significant progress in decreasing beam availability time along with some setbacks. Near the end of the initial phase the integration portion will commence. Throughout the integration phase a steady decline in beam availability time may occur as a result of the systems becoming more and more incorporated onto the platform. Moreover, there may be some overlap between the integrated phase and optimized phase. The optimized phase indicate that at some point there will be consistency in the amount of time to get the beam on; however, this steady rate may drop as the technology matures.

2. Methodology and Approach

The basis and intent of sustainment is to do what it takes to keep systems operational throughout their life cycles (Defense Acquisition University 2003). The scheduling of routine preventative maintenance activities to keep systems available for use, assessing systems to ensure proper operation, reviewing operational logs for indications of system wide issues, and satisfying supportability requirements of the system from its inception to ultimate disposal all are life cycle issues (Defense Acquisition University 2003). These steps are based on an approach to sustainment that is centered on addressing issues relevant to maintaining the continuous operation of systems.

Our approach to sustainment involves addressing the decision making considerations for materials, safety, supply chain management, operational unit support, and disposal of the systems. Materials involve developing supply requirements, storing components needed for repair and replacement, and providing personnel for warehouse functions. Safety concerns are those considerations that ensure equipment is operated properly while avoiding harm to personnel. Supply chain management includes the procurement and distribution of materials and services (Defense Acquisition University 2012). Operational unit support is providing a Point of Contact (POC) for supply support concerns and feedback. Sustaining engineering relates to performing technical tasks to ensure continued operation of a system (depot level support). Disposal involves the decision calculus of when, where, and how to get rid of or convert the system (Defense Acquisition University 2012).

3. Materials

Due to the lack of required specific open source data on LaWS, TLS, and MLD, addressing specific concerns of each DEW system and more importantly, differentiating between the systems is impossible. Therefore, all three will be grouped for the sustainment analysis.

a. Solid State LASER (SSL)

The number of SSL systems acquired will be based on the number of DDGs available in addition to the budget. In the case of the TLS, the number of MK 38 Mod 2 mounts that will be upgraded will be dependent on the number of DDG platforms identified to receive the system. In addition, installation will occur during each ship's preplanned availability period. Major components of SSL systems include the medium, optical equipment, flash pumps or diodes, and amplifiers. Considerations of components operating in a marine environment have to be made. For example, in order to function properly, optical equipment has to be extremely clean. Contaminants on optical equipment could absorb LASER energy, resulting in damage to the optical coating or the optical material. Maintaining clean optical equipment could pose a challenge at sea where the system may be exposed to saltwater, particulate laden aerosols (smoke), and high humidity. This requirement for the operational equipment requires those handling the optical equipment to wear gloves and clean the lens with a dedicated set of rags (e.g., microfiber), brushes (e.g., camel hair), and solutions. This requirement also includes having equipment available to handle extremely large optics. It should be noted that this reliance on large optics is not the case for the fiber SSLs since they use fiber optics. Although the MLD is more complex (MLD is a slab LASER as opposed to LaWS which is a fiber LASER), it could be more easily maintained since it uses sealed line replaceable units (LRUs) (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013). These LRUs can be stored onboard ship as ready spares, allowing personnel to replace faulty equipment instead of requiring depot level maintenance. Furthermore, coverings will have to be provided to protect the system from exposure to the elements when not in use. Coverings can be in the form of an enclosed shell that shields the system or thick drapes to protect hardware and exposed wiring. Stabilizers must be in place to keep the system steady in the dynamic maritime environment which causes the ship to be in continuous motion. Mechanical components of the systems must be periodically lubricated. For this reason, the specific oil or grease must be stocked and available for routine and corrective maintenance.

b. Active Denial System (ADS)

The number of ADS units to be procured for future installation will be determined by the number of available platforms and naturally budgetary constraints. Installation will occur during a ship's preplanned maintenance period. In addition to installed units, there will also have to be parts support. The ADS is composed of a variety of electrical and mechanical components which require considerations to be made when placing them on naval vessels. Naval vessels tend to have higher maneuver capabilities and differing operational profiles than typical commercial vessels (Kuseian 2013). For this reason, structures will have to be in place to provide stabilization for the system while the ship is the dynamic environment of the sea. Furthermore, lubricants and seals will have to be used in order to guard against the ill effects of metal being in humid surroundings. Moreover, the system having as many line replaceable units as possible may assist in repair due to the modularity; however, there are some key components which may require off ship storage. These components are mainly used for power generation and wave production. Key components for power generation include a hybrid electric plant composed of batteries and a diesel generator (LeVine 2009). Upon shipboard integration, ADS will operate using the ship's power grid. Gyrotons, a vacuum tube device, and a superconductor magnet operating at 4 degrees Kelvin are used for wave production and must have on-hand replacements depending on the failure rate (LeVine 2009).

The operational success of a DEW depends on availability. Having test equipment to determine which part failed (or is failing) and parts onboard for repair and replacement is vital. However, some components require high levels of expertise, are extremely sensitive, or large in size discouraging storage onboard a ship. Examples of these types of components include a liquid helium cryocompressor used for cooling the superconducting magnet and the antenna which focuses the beam (LeVine 2009). Parts such as these will have to be housed at depot level facilities. Minor components such as the batteries will require onboard storage. Extra materials may be needed such as coverings for the system which will be stored onboard the ship. These coverings are necessary to protect the system from the harsh maritime environment considering the ADS was developed in conjunction with the Army.

4. Safety

Markings and signs around the location of the system will be required to alert personnel of the possible dangers inherent to DEWs. Visual and audible alarms will be required to indicate when the systems have been activated (as is common with current weapon and electronic systems). These signs and alarms are necessary to inform personnel of possible exposure to harmful beams and the necessary protective measures required in the area. Personal protective gear will be provided to protect operators of the system from exposure to eyes and skin. Eyewear will be appropriate for wavelength and optical density for the system in use. Moreover, warning labels on systems will be necessary to alert personnel of potential dangers. For example, connected optical fiber systems are enclosed; however, if they are disconnected then there’s a possibility of harmful exposure (University of Maryland 2012). Kill switches will be in place to disengage the system in an emergency situation. Flat and polished surfaces can act as hazardous secondary reflectors (University of Iowa 2013). Therefore, removal of these materials around the system will prevent unwanted exposures to the beams. Safety training and training manuals must be provided to system operators. The training and manuals will outline procedures conducive to proper operation and avoidance of injury to personnel. Supplies for signs, warning labels, and protective gear will be based upon number of units and manning requirements.

5. Supply Chain Management

Supply chain management involves the “cross-functional approach to procuring, producing, and delivering products and services to customers” (Defense Acquisition University 2012). Navy Supply Systems Command Weapon Systems Support (NAVSUP WSS) is responsible for providing weapons support to Naval Forces (Naval Supply Services Command 2011). Procuring parts necessary for repair or replacement will be handled through current ship requisition computer programs. Moreover, a ship’s need for extensive repairs will be made known through casualty reporting (CASREP) procedures that indicate the type of damage and any technical information needed to conduct repairs. Personnel performing preventative and corrective maintenance requirements must have specialized training of the system. Logistical considerations for parts, software upgrades, and technical support will have to involve a mixture of forecast and agility. This forecast will ensure that there are economic quantities of resources (e.g., parts and fuel) available based upon anticipation of customer needs (e.g., scheduled underway replenishments and maintenance periods) along with rapid responses to operational crises (e.g., emergency repairs) and available upgrades to software.

6. Operational Unit Support

Operational unit support involves providing shipboard personnel with a point of contact to resolve any type of supportability issues. Operational requirements may prevent ships from travelling to a depot level facility whenever a problem arises. For this reason, there has to be a mechanism in place to address issues without jeopardizing the ship’s mission. To facilitate this support, ships will have call centers they can contact in order to troubleshooting and repair these DEW systems. Call centers will be composed of technical experts with an in-depth knowledge of the repair, maintenance, and operation of the systems. There may be situations that phone consultations cannot rectify. At this point, technicians may be required to travel directly to the ship for further investigation. This travel can be accomplished through scheduled underway replenishments or private means funded by the company as outlined in the contract.

7. Sustaining Engineering

Sustaining engineering is “those technical tasks (engineering and logistics investigations and analyses) to ensure continued operation and maintenance of a system with managed (i.e., known) risk” (Defense Acquisition University 2012). Due to the high technical aspect of the equipment in the system along with storage restrictions onboard ships, major repairs will be conducted at depot facilities. Depot level support involves the repairing, testing, analyzing, and upgrading (to include software) of equipment at highly sophisticated shop facilities. Depot support entails providing personnel of high technical expertise for not only repairs but also for consultation in regards to maintenance (Defense Acquisition University 2011).

Part of ensuring that a system continues to operate involves having performance standards and analysis for continued use in place. These standards will be used to indicate whether or not there are fleet wide system faults causing discontinued use of the units. This situation is similar to how fighter jets are grounded when there are problems like cracks in engine components. These performance standards will be evaluated not only at depot facilities but also during routine ship inspections from outside personnel like the Board of Inspection and Survey (INSURV), a group of recognized experts under the direction of the Secretary of the Navy (SECNAV) and Chief of Naval Operations (CNO) to periodically examine vessels to determine fitness for further service (Board of Inspection and Survey 2011). Part of the examination process would be periodic firings of systems. During these firings, mechanisms must be in place to determine whether or not the output beams are hitting the desired targets. For example, possible mechanisms include positioning a sensor on the target to detect the firings of the testing LASER. In addition, built in test equipment (BITE) can assist in determining the proper firing and operation of the system.

8. Disposal

Disposal involves removing the system from operational service at the end of its lifespan. Getting rid of the system may involve transferring, redistributing, selling, or complete destruction of system materials (Defense Acquisition University 2012). Considerations have to be made involving the impact to the environment, storage or destruction of materials, and redistribution of any salvageable items. Options for disposal include donating systems to other organizations such as educational institutes (e.g., NPS), reselling materials back to the manufacturer, disabling the systems electrically, preventing reactivation, or completely destroying the systems through alterations of design (University of Iowa 2013). In all cases, legal and regulatory requirements must be adhered to as outlined by the DoD. Plans will have to include salvaging of exotic metals and removal of hazardous materials. Timing of disposal is a major consideration and will have to be done in a manner conducive to the operational requirements of the ship. Disposal schedules will inform operators of when and where to get rid of systems and what may have to be done prior in preparation for disposal. Disposal will involve close interaction with naval shipyards which traditionally handle disposal (Naval Sea Systems Command 2009). In addition, plans will include measures that have to be taken in cases where there is a replacement system that will be installed.

C. TRAINING AND MANNING

In a dynamic global environment where threats to national interests fall along the full spectrum of warfare, military forces must be properly organized, equipped, and trained to employ the most technologically advanced equipment, tactics, and procedures at an instant notice. Doctrine and National policy must provide the necessary framework to ensure that troops are properly organized, trained and equipped, and that available systems provide the required capabilities and effects on the battlefield (Lincoln 2004). To ensure readiness and efficiency in threat engagements, operators must be well versed in the deployed systems, tactics and procedures to facilitate time and cost effectiveness during operation. Readiness and efficiency can be achieved through proper manning and training of personnel operating the system.

1. Manning

The establishment of adequate manning for a system is of critical importance, but there is also a need to consider the tradeoffs. Vice Admiral William Burke, Deputy Chief of Naval Operations for Warfare Systems said that the Navy is looking for ways to reduce crew size by using labor-saving technology, but he said that it is necessary to look at the trade-offs. In his statement, he mentioned "I'm not for taking existing ships and looking to take people off" (Burgess 2013), commenting on "optimal manning" initiatives over the last decade to reduce crew size on some ships, something he said the fleet sardonically called "suboptimal manning" (Burgess 2013). The point to note here is to maximize the throughput with lean manning, but yet maintain the performance required for the mission. Alternative approaches like looking at automation of process and capitalizing on proficiency of individual skills may compensate for the decrease in labor size.

With respect to crew manning requirements and operations, smart systems to control and monitor energy consumption, as well as the health of critical systems, can support both manning and resource conservation. Effective training and reliable man-to-machine interfaces will allow for more effective use of platform resources and potentially reduced operational cost or an expanded operational capability (Office of Naval Research 2009).

2. Training

Readiness and efficiency are directly impacted by the established training plan. The importance of an effective training program brings about personnel development as well as operator’s proficiency in systems which are vital in time critical mission (Expert 2010). The impacts of an effective training program can be seen as follows.

Training helps in optimizing the utilization of human resources that further help to align individuals in achieving the organizational goals as well as their individual goals and provides an opportunity and broad structure for the development of human resources technical and behavioral skills in an organization. Technical competence is vital during operations when the operator’s proficiency in systems play an important role in time critical missions, increased system knowledge will also determine the level of safety and maintenance during operation.

Training helps in improving upon the quality of work and improves the safety of the organization thus preventing a standstill in organization strength at a low level of proficiency. An effective training program demonstrates a commitment to keeping individuals on the cutting edge of knowledge and practice. (Hub 2012).

Notwithstanding the common importance of training described above, it should be noted that relevance in training pertaining to application is equally important to ensure that whatever the operators are trained in, it is logical and applicable. For example, personnel need to be educated specifically concerning the weapon system they support and generally about DE technical concepts such as generation, attenuation, and propagation. Understanding how the atmosphere affects DEW platforms is necessary for those who support DEW systems and operators to maximize employment (Narcisse 2007). Concepts such as temperature, pressure, and other considerations such as optical turbulence affecting range employed are areas where operators should be trained to ensure that they are proficient when using such a high end system. Having discussed the importance of training, there is an imminent need to be mindful that training does affect the life cycle costs of a system. Consideration should be taken early in the capabilities development process beginning with the analyses that support development of the Initial Capabilities Document (ICD). The ICD can facilitate and ensure that projected training requirements and associated costs are appropriately addressed across the program life cycle.

3. Life cycle Costs of Training and Manning for a System

To ensure naval forces continue to maintain global dominance, future platforms and combat systems must be affordable to acquire, operate and maintain over their entire life cycle. This affordability can be achieved with the reduction in Total Ownership Cost (TOC) by developing and aiding the insertion of technology to reduce platform acquisition cost, reduce life cycle and sustainment costs, and achieve crew manning requirements. Total Ownership Cost includes all costs associated with the research, development, procurement, operation, training and disposal of platforms.

Training is one of the elements that have a very high return on investment (Defense Acquisition University 2011). Training is often considered a cost to the program and requires the trainees to be absent from their daily duties for a period of time. This investment in skills improvement is a long term investment - often short term needs preclude the training (Defense Acquisition University 2011).

Specific examples of the return on investment by integrating training include:

- Many maintenance failures are due to operational error, a good operator training program will reduce equipment failure, reduce accidents, and allow for higher system availability at reduced cost (cost avoidance in this case) (Defense Acquisition University 2011).
- The skill level of the maintainer is critical to a quick and effective repair process (Defense Acquisition University 2011).
- Item managers and procurement specialists need to be trained on the automated supply systems (often part of an enterprise resource program) in order to correctly enter information, understand reports, and be able to diagnose supply deficiencies. Even minor errors or misunderstanding of

the system can result in significant spare part shortages, incorrect items ordered, or mismanagement of the supply base (Defense Acquisition University 2011).

- Design engineers should be trained on product support approaches and how system design influences (both positively and negatively) the availability, reliability and ownership cost of the weapon system (Defense Acquisition University 2011).

Training costs impact the O&S cost in the overall TOC. If training is not realistically planned and accounted for in the early phase, it may incur an increase cost for the program and not achieve its objectives.

4. Projected Training and Manning Requirements for a Directed Energy Weapon (DEW) System

In the following sections, the project training and manning requirements for the respective DEW systems will be discussed. Notwithstanding, there is limited information on the requirements for some of the DEW systems.

a. LASER Weapon System (LaWS)

The LASER is designed to integrate with the Navy’s existing shipboard Combat Systems, where a single operator can control the system. The operator will require specialized training, similar to the instruction that Navy crews receive for the MK 15 Phalanx Close-in Weapon System or the MK 45 lightweight gun. With this training, the Sailors will be able to maintain the LASER at an organizational level (Jean 2010).

b. Maritime LASER Demonstration (MLD)

The MLD is a solid state, directed energy system previously installed and tested on a decommissioned Spruance class destroyer. MLD is also the first LASER system to be integrated with a ship’s radar and navigation system. Given the maturity of LASER systems, it will not be long for the LASER to operate synergistically with kinetic energy weapons for ship defense optimization (Northrop Grumman 2011). Hence, the number of operators required to man the system could just be the same as those already operating the current kinetic energy weapon systems.

c. Tactical LASER System (TLS)

TLS is paired with the MK 38 Mod 2 Machine Gun System (MGS), sharing the initial sensing and pointing systems operator control console. As such, the same operator that remotely controls and fires the MGS, also controls and fires the LASER with the ability to shift between systems as the tactical situation dictates (Merida 2012).

Due to this operational concept, similar to the LaWS and MLD, the operator manning the gun system (installed with the LASER system) will only be required to complete the specialized weapon training as part of their Navy training term during the Gun System Operation Training (applicable to LaWS, MLD, and TLS).

d. Active Denial System (ADS)

Based on the land based deployment of ADS, the estimated number of crews required is between 3–4 personnel (LeVine 2009). The required crew for a land system can be used as an estimation for crew personnel operating the ADS mounted on the naval vessel. Currently, two units of ADS will be mounted onboard the Navy vessels (DDG-51 Destroyers) and could possibly require around two operators (Miller, NATO NAVAL ARMAMENTS GROUP 2009).

5. Conclusion

To date, the training and manning requirements for the DEW systems researched suggest that they do not require the commitment of significant additional manpower resources. The development of DEW systems thus far showed that the DEW are intended to integrate with main gun system installation onboard the existing Navy ships. As such, the manning of the DEW systems is concurrent with the existing weapon systems. Table 34 summarizes the training and manning requirements for each potential DEW system.

Table 34. Training and Manning Requirements Summary

	Training		Manning	
Types	**Projected Requirements**	**Comments**	**Projected Requirements**	**Comments**
LaWS LaWS+	Similar to MK 15 Phalanx	Similar to the MK 15 Phalanx close-in weapon system or MK 45 lightweight gun	1–2 operators	The laser is designed to tie into the Navy’s existing shipboard combat system
TLS	Based on LaWS training requirement, it is assumed that the same format of training will take place for TLS, MLD and ADS.		1–2 operators	The laser system is paired with the MK 38 Mod II gun system
MLD			2–3 operators	Operates in tandem with kinetic energy weapons
ADS			3–4 operators	Shipboard ADS

With the LASER system installed as part of the main gun system/vehicular platforms, there is no requirement for the operator to go through LASER system training. Depending on the deployment of the LASER system, the training for the system and personnel may vary.

D. COST ESTIMATION

The bottom line truth with respect to cost estimation of future DE projects is that there are a lot of unknowns, perhaps more so than any other acquisition project in existence today. Despite that directed energy projects have been around for decades, the associated technologies are still in their infancy in terms of practical application, as well as acceptance by military leadership. As a result, it is not known with any degree of certainty which systems the Navy will ultimately attempt to acquire, what quantity will be purchased, or even what specific surface ship platforms the systems will be integrated with.

> Although the Navy is developing LASER technologies and prototypes of potential shipboard LASERs, and has a generalized vision for shipboard LASERs, the Navy currently does not have a program of record for procuring a production version of a shipboard LASER, or a roadmap that calls for installing LASERs on specific surface ships by specific dates.

> (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013)

This type of situation makes the job of a cost estimator extremely difficult due to the abnormally high degree of uncertainty associated with any potential calculation attempt. The best alternative option is to begin by creating a set of assumptions about prospective systems based on current U.S. Navy trends. It is necessary to recognize that all assumptions must not only be consistent with, but more importantly physically possible given the stringent constraints imposed by the SEA-19B Capstone Project guidance. Several of the perceived trends are outlined below:

> The Navy and DoD have conducted development work on three principal types of LASERs for potential use on Navy surface ships—fiber solid state LASERs (SSLs), slab SSLs, and free electron LASERs (FELs). One fiber SSL prototype demonstrator developed by the Navy was the LASER Weapon System (LaWS); another Navy fiber SSL effort is called the Tactical LASER System (TLS). Among DoD's multiple efforts to develop slab SSLs for military use was the Maritime LASER Demonstration (MLD), a prototype LASER weapon developed as a rapid demonstration project. (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013)

This guidance was utilized as the basis for the project's directed energy technology cost estimating methodology. All estimates are calculated by analogy.

1. External Source Data

- **Electronics Standard Factors Handbook (Schmit and Hicks 1999).** This document consist of the statistical analysis on the historical data of Government support costs obtained from previous Navy budgets, which will aid us in the determination of the Work Breakdown Structure (WBS) in deriving the cost estimation.
- **Joint Inflation Calculator** (Naval Center for Cost Analysis 2013). This document generates inflation rates and indices for Navy and Marine Corps appropriations and cost elements which can be used to prepare for future fiscal-year budgets.

2. Methodology

The first, and arguably most difficult, task was to determine the details of the cost estimate. What "exactly" were we tasked with costing? The group's initial hunch was to attempt to derive a total life cycle cost; however, due to the high degree of uncertainty associated with this type of technology the idea was dismissed. An estimated total life cycle cost would offer little value to the Navy given the large number of assumptions it would inevitably have to be based upon. Instead, the objective became to determine and estimate the integration, as well as implementation, cost of select directed energy technologies deemed relevant by the Navy, and suitable for shipboard use by our project group. The selected objective is based on several assumptions outlined in a subsequent section of the report.

Although directed energy technologies share many similarities, they are also quite different in terms of the specific components required to make them function. Since component, research and development (R&D), test and evaluation (T&E), and shipboard integration cost can vary significantly from project to project (even in projects that appear similar in premise), it was determined that individual custom tailored cost estimates for each of the selected technologies would be preferential to a single gross DEW estimate.

A cost estimate was done for each of the four systems considered for shipboard integration, MLD, LaWS, TLS, and ADS. Cost estimate scenarios (vignettes) were written for each of the selected systems and are shown in Table 35.

Table 35. Cost Estimate Scenarios

System	Integration Design Reqd.	Additional R&D Reqd.	Cost Objective
Active Denial System (ADS)	Yes	Minimal	To derive the cost estimate of deploying two units of Active Denial System (ADS) onboard a DDG-51 class ship.
LASER Weapon System (LaWS)	No	Power scaling upgrade; T&E	To determine and estimate the upgrade and shipboard installation cost of the LASER Weapon System (LaWS) from its current 33kW output to 150 kW.
Maritime LASER Demonstration (MLD)	Yes	Power scaling upgrade, BQ upgrade, T&E	To derive the cost estimate of integration and installation of the Maritime LASER Demonstration (MLD) onboard DDG-51 class ships.
Tactical LASER System (TLS)	Minimal	Minimal	To determine the estimated single unit cost of installing and deploying the Tactical LASER System (TLS) on DDG-51 class ships.

Since much of the financial data for these scenarios is proprietary, and therefore not accessible to the project group, the next step was to obtain some type of baseline costs from trusted published references. Table 36 depicts both the actual figures and data sources utilized to obtain the data.

Table 36. Baseline Costing Figures

System	Baseline Figure	Remarks	Company
Active Denial System (ADS)	$7.5M	Cost plus award fee contract to design, fabricate, and test	Raytheon
LASER Weapon System (LaWS)	$17M	Per mount cost with CIWS integration once upgraded; TRL 7 upgrade estimated at $150M	Raytheon
Maritime LASER Demonstration (MLD)	$98M	Indefinite delivery/indefinite quantity contract ceiling value	Northrop
Tactical LASER System (TLS)	$2.8M	Prototype development contract	BAE

In order to facilitate organization, the project cost estimate work scope was decomposed into smaller discrete components, meaning that all required WBS sub-elements were identified. The items on the WBS generally consisted of the following: design, hardware, contractor support, government support, software and integration.They were derived using an Engineering & Manufacturing Development (EMD) table applicable to surface ships from a document of Standard Factors (Naval Center for Cost Analysis 1999).”DoD policies require that a WBS be established to provide a framework for program and technical planning, cost estimating, resource allocation, performance measurement, and status reporting.” In addition, “the top three levels are the minimum recommended any program or contract needs for reporting purposes unless the items identified are high cost or high risk. Then, and only then, is it critical to define the product at a lower level of WBS detail” (Defense Acquisition University 2012). Maximum effort was made to ensure the project cost estimate WBS is compliant with DoD policies.

For all systems, the cost estimate is calculated by analogy, and based on a cost factors approach. The Analogy method is most appropriate to use early in the program life cycle when the system is not yet well defined (Williams and Barber 2011). Due to the unavailability of costing data for comparable/similar systems, the project group considered multiple cost factor combinations from various projects. The goal was to determine a best fit, and minimize uncertainty. "A cost factor is derived from cost-to-cost relationships between two similar systems. To derive a cost factor, one must select analogous tasks or products that represent a cost-to-cost relationship." Also, "uncertainty in a cost estimate using analogy is due to subjective evaluations made by the technical staff and cost estimators in their determination of the cost impacts of the differences between the old and new systems" (Williams and Barber 2011). Utilizing Naval Postgraduate School (NPS) faculty as technical staff it was agreed that cost factors derived from historical EMD ships data would be sufficient and adequate for analogous comparison. Specific factor ratios are provided in Figure 87.

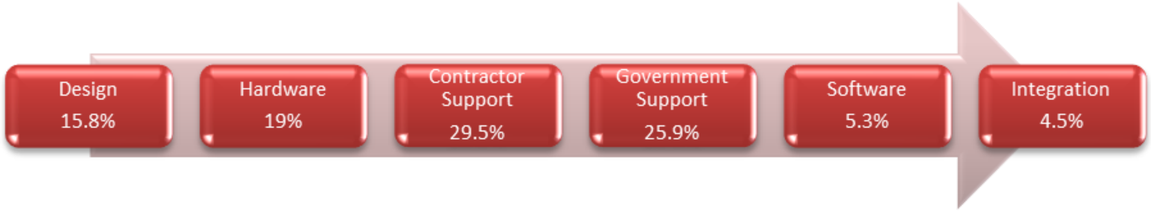


Figure 87. Cost Factors

For comparative consistency, the group utilized a cumulative inflation approach to calculate the projected inflated cost for FY13. Inflation rates were obtained from the Joint Inflation Calculator. Even a cursory examination of Table 36 shows the baseline figures selected to be quite different in nature. In order to be of value, the baseline figures need to be normalized in some way such that an actual "apples to apples" comparison could be made. The group reconciled the actual cost figures with respect to the various cost factors identified with a more detailed summary of the normalization/reconciliation process for each system is provided in its specific methodology section.

Taking the cost estimates' high degree of uncertainty into consideration, sensitivity analysis was conducted for each of the respective systems. The analysis was conducted on the various cost factors to establish a range of estimated cost. The

Electronics Standard Factors Handbook provides Coefficient of Variance (C_V) data for each cost factors. This C_V value is used to calculate the standard deviation from the mean value, and subsequently used to derive the 95% confidence interval (CI) in accordance with the following equation:

$$C_v = \left(\frac{\sigma}{\mu}\right)100 \rightarrow \sigma = \frac{\mu C_v}{100}$$

Equation 39. Standard Deviation from the mean value

$$95\%\ CI = CE \pm 1.96\sigma$$

Equation 40. 95% Confidence Interval

3. Assumptions

- Total Life cycle Cost Estimate would be a waste of time due to high degree of uncertainty.
- Estimating an implementation cost of a single unit is feasible.
- Federal dollars expended to date are “sunk.”
- DDG-51 class integration assumed due to short time requirement.
- Sufficient power, cooling, weight, and space are available on the DDG-51.
- Total hardware cost is proportional to LASER power (linear fit assumed for hardware).
- Cost factors for aggregate shipboard electronics distributions are applicable to DEW.

4. Tactical LASER System (TLS)

a. Objective

To derive the cost estimate of deploying two units of the Tactical LASER System (TLS) on DDG-51 class ships.

b. Facts

- TLS is a fiber Solid State LASER (SSL) with a LASER with a beam power of 10 kW that is designed to be added to the Mk 38 25 mm machine guns currently installed on some DDG-51 ship class decks (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013).

- In March 2011 the Navy awarded a $2.8 million contract to BAE to develop a prototype of the TLS. Boeing is collaborating with BAE on the project (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013).
- The LASER weapon consists of a Boeing 10kW fiber-LASER developed by International Photonic Group (IPG), coupled with the Air Force Research Lab (AFRL) Mobile Active Targeting Resource for Integrated Experiments (MATRIX) system, a mobile beam control and fire control solution also developed by Boeing (Defense Update 2011).
- Field testing of the major components in the summer of 2012 at Eglin Air Force Base in Florida showed the system could distinguish between friendly and enemy activities in both daytime and nighttime environments (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013).
- The TLS is about 30% efficient, meaning 34 kW of power is needed to operate the 10 kW LASER (U.S. Navy 2011).
- Currently, the TLS will utilizes its own power distribution and cooling systems; the power requirement from a ship would be approximately 75 kW to run the LASER, power management, and currently installed/designed thermal management systems (U.S. Navy 2011).

c. Ground Rules and Assumptions

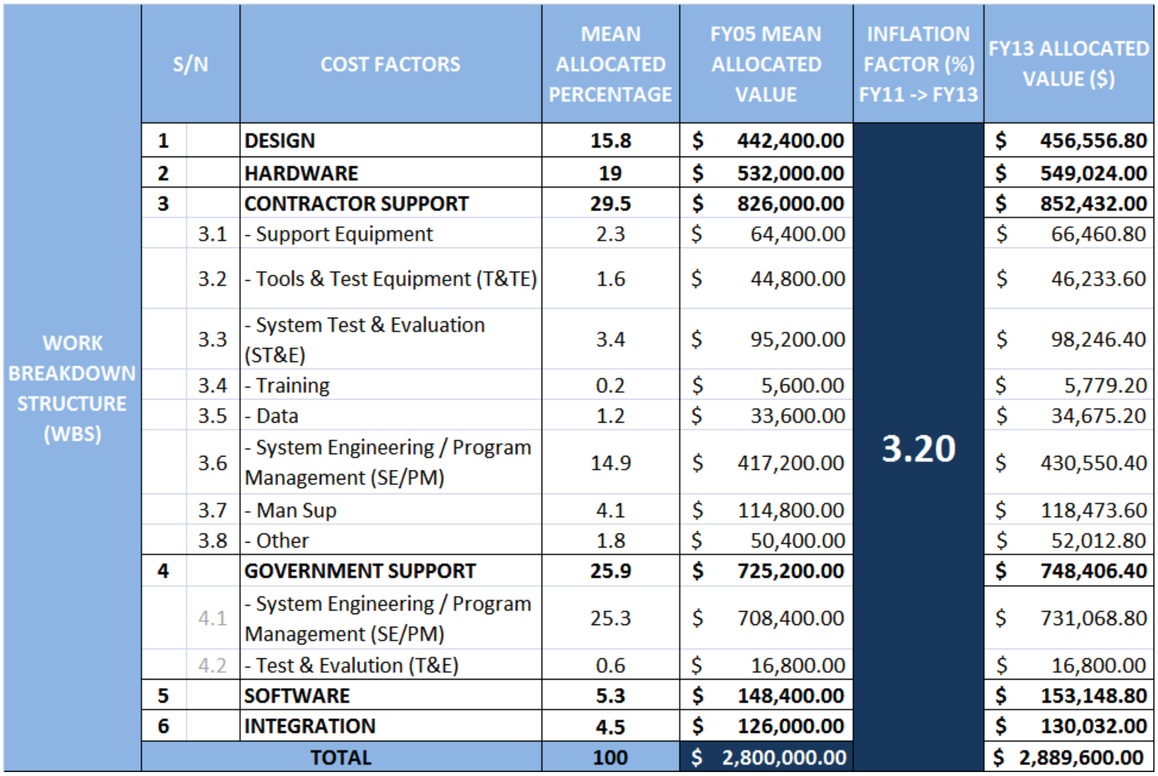
- Two TLS units would be required per ship; the units would likely be installed on the main deck, one port, and one starboard.
- The weapon system would likely be operated from a standalone console installed on the bridge.
- Since the proposed system is equipped with independent search, tracking, beam, and fire control; integration with currently installed shipboard combat systems would not be required.
- The $2.8M contract awarded to BAE included funding for required additional R&D, design, prototype hardware, as well as T&E.

- Additional engineering development (design) would be required for actual shipboard integration and use; cost of additional development will be included in the final objective based cost estimate and be equivalent to approximately 15% of the total design cost.

d. Cost Summary

The deployment cost of TLS on DDG-51 class will primarily consist of the sum of the per unit hardware cost multiplied by two, the hardware integration cost, as well as some minimal costs associated with training and contractor support. Unfortunately, the $2.8M contract base figure obtained by the project group is not indicative of the sum of these costs since, as stated in the assumptions, it includes funding for R&D, design, and T&E. With one exception, these latter items are excluded from the cost estimate objective. However, it is first necessary to decompose the baseline contract amount into its respective discrete components, and identify the WBS sub-elements shown in Table 37.

Table 37. Tactical LASER System (TLS) Work Breakdown Structure (WBS)

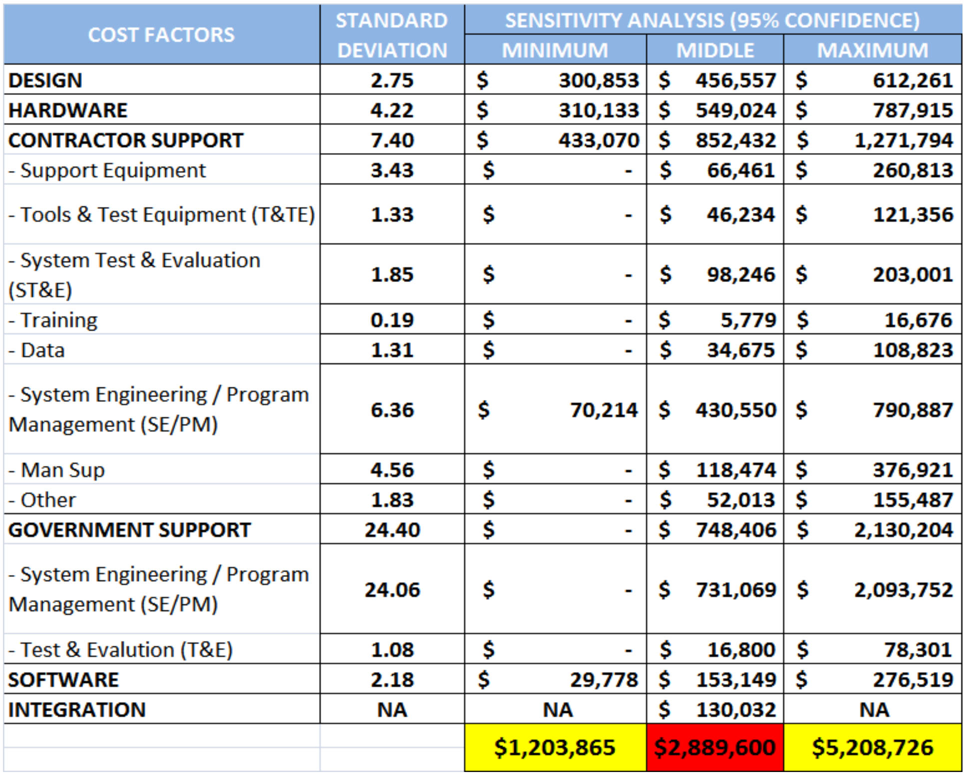


WORK BREAKDOWN STRUCTURE (WBS)	S/N		COST FACTORS	MEAN ALLOCATED PERCENTAGE	FY05 MEAN ALLOCATED VALUE	INFLATION FACTOR (%) FY11 -> FY13	FY13 ALLOCATED VALUE ($)
WORK BREAKDOWN STRUCTURE (WBS)	**1**		**DESIGN**	**15.8**	**$ 442,400.00**	3.20	**$ 456,556.80**
	2		**HARDWARE**	**19**	**$ 532,000.00**		**$ 549,024.00**
	3		**CONTRACTOR SUPPORT**	**29.5**	**$ 826,000.00**		**$ 852,432.00**
		3.1	- Support Equipment	2.3	$ 64,400.00		$ 66,460.80
		3.2	- Tools & Test Equipment (T&TE)	1.6	$ 44,800.00		$ 46,233.60
		3.3	- System Test & Evaluation (ST&E)	3.4	$ 95,200.00		$ 98,246.40
		3.4	- Training	0.2	$ 5,600.00		$ 5,779.20
		3.5	- Data	1.2	$ 33,600.00		$ 34,675.20
		3.6	- System Engineering / Program Management (SE/PM)	14.9	$ 417,200.00		$ 430,550.40
		3.7	- Man Sup	4.1	$ 114,800.00		$ 118,473.60
		3.8	- Other	1.8	$ 50,400.00		$ 52,012.80
	4		**GOVERNMENT SUPPORT**	**25.9**	**$ 725,200.00**		**$ 748,406.40**
		4.1	- System Engineering / Program Management (SE/PM)	25.3	$ 708,400.00		$ 731,068.80
		4.2	- Test & Evalution (T&E)	0.6	$ 16,800.00		$ 16,800.00
	5		**SOFTWARE**	**5.3**	**$ 148,400.00**		**$ 153,148.80**
	6		**INTEGRATION**	**4.5**	**$ 126,000.00**		**$ 130,032.00**
			TOTAL	**100**	**$ 2,800,000.00**		**$ 2,889,600.00**

After the total contract is decomposed, the discrete components are adjusted for inflation. In this case, the adjustment from FY11 to FY13 yields an inflation factor of 3.20%. At this point, the sensitivity analysis is conducted. The total system cost calculation provides us with a 95% confidence interval from $1.2M to $5.2M FY13.

Table 38 provides a start to finish estimate for TLS which includes design, prototype hardware assembly, as well as T&E. In accordance with project methodology, it is now necessary to factor out of the total cost estimate all elements not pertaining to the objective of estimating the single unit cost of installing and deploying the Tactical LASER System (TLS) on DDG-51 class ships. These elements include: 85% of the design cost, ST&E, Contractor SE/PM, MAN SUP, and T&E.

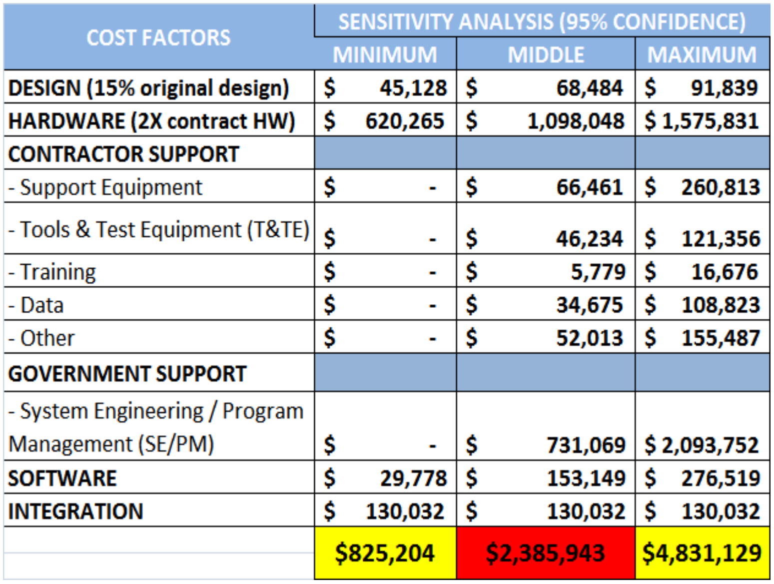
Table 38. Tactical LASER System (TLS) Sensitivity Analysis



COST FACTORS	STANDARD DEVIATION	SENSITIVITY ANALYSIS (95% CONFIDENCE) MINIMUM	MIDDLE	MAXIMUM
DESIGN	2.75	$ 300,853	$ 456,557	$ 612,261
HARDWARE	4.22	$ 310,133	$ 549,024	$ 787,915
CONTRACTOR SUPPORT	7.40	$ 433,070	$ 852,432	$ 1,271,794
- Support Equipment	3.43	$ -	$ 66,461	$ 260,813
- Tools & Test Equipment (T&TE)	1.33	$ -	$ 46,234	$ 121,356
- System Test & Evaluation (ST&E)	1.85	$ -	$ 98,246	$ 203,001
- Training	0.19	$ -	$ 5,779	$ 16,676
- Data	1.31	$ -	$ 34,675	$ 108,823
- System Engineering / Program Management (SE/PM)	6.36	$ 70,214	$ 430,550	$ 790,887
- Man Sup	4.56	$ -	$ 118,474	$ 376,921
- Other	1.83	$ -	$ 52,013	$ 155,487
GOVERNMENT SUPPORT	24.40	$ -	$ 748,406	$ 2,130,204
- System Engineering / Program Management (SE/PM)	24.06	$ -	$ 731,069	$ 2,093,752
- Test & Evalution (T&E)	1.08	$ -	$ 16,800	$ 78,301
SOFTWARE	2.18	$ 29,778	$ 153,149	$ 276,519
INTEGRATION	NA	NA	$ 130,032	NA
		$1,203,865	$2,889,600	$5,208,726

The sum of the remaining items, including two times the cost of hardware, will constitute a cost estimate consistent with the objective statement shown in Table 39.

Table 39. Tactical LASER System (TLS) Objective Cost Estimate



COST FACTORS	SENSITIVITY ANALYSIS (95% CONFIDENCE)		
	MINIMUM	MIDDLE	MAXIMUM
DESIGN (15% original design)	$ 45,128	$ 68,484	$ 91,839
HARDWARE (2X contract HW)	$ 620,265	$ 1,098,048	$ 1,575,831
CONTRACTOR SUPPORT			
- Support Equipment	$ -	$ 66,461	$ 260,813
- Tools & Test Equipment (T&TE)	$ -	$ 46,234	$ 121,356
- Training	$ -	$ 5,779	$ 16,676
- Data	$ -	$ 34,675	$ 108,823
- Other	$ -	$ 52,013	$ 155,487
GOVERNMENT SUPPORT			
- System Engineering / Program Management (SE/PM)	$ -	$ 731,069	$ 2,093,752
SOFTWARE	$ 29,778	$ 153,149	$ 276,519
INTEGRATION	$ 130,032	$ 130,032	$ 130,032
	$825,204	**$2,385,943**	**$4,831,129**

Given the objective cost estimate (Equation 41), the project group is 95% confident that the cost of installing and deploying a two TLS on a single DDG-51 class ship will be between $825K and $4.8M FY13.

$$15\%\ \text{Design} + 2\left(\text{Contract HW}\right) + \text{Applicable CS \& GS Elements} + \text{Software} + \text{Integration}$$

Equation 41. Objective Cost Estimate

5. Active Denial System (ADS)

a. Objective

To derive the cost estimate of deploying two units of Active Denial System (ADS) onboard a DDG-51 class ship.

b. Facts

- The Active Denial System (ADS) has a Technology Readiness Level (TRL) of 7, meaning that prototypes have been created and tested in the field (O'Rourke, Navy Shipboard LASERs for

Surface, Air, and Missile Defense: Background and Issues for Congress 2013).

- Raytheon Missile Systems has been awarded a $7,549,715 cost-plus award-fee contract. The purpose of this contract program is to design, fabricate, test, and rapidly field a fixed ADS referred to as System 2 and ADS2 (U.S. Department of Defense 2005).

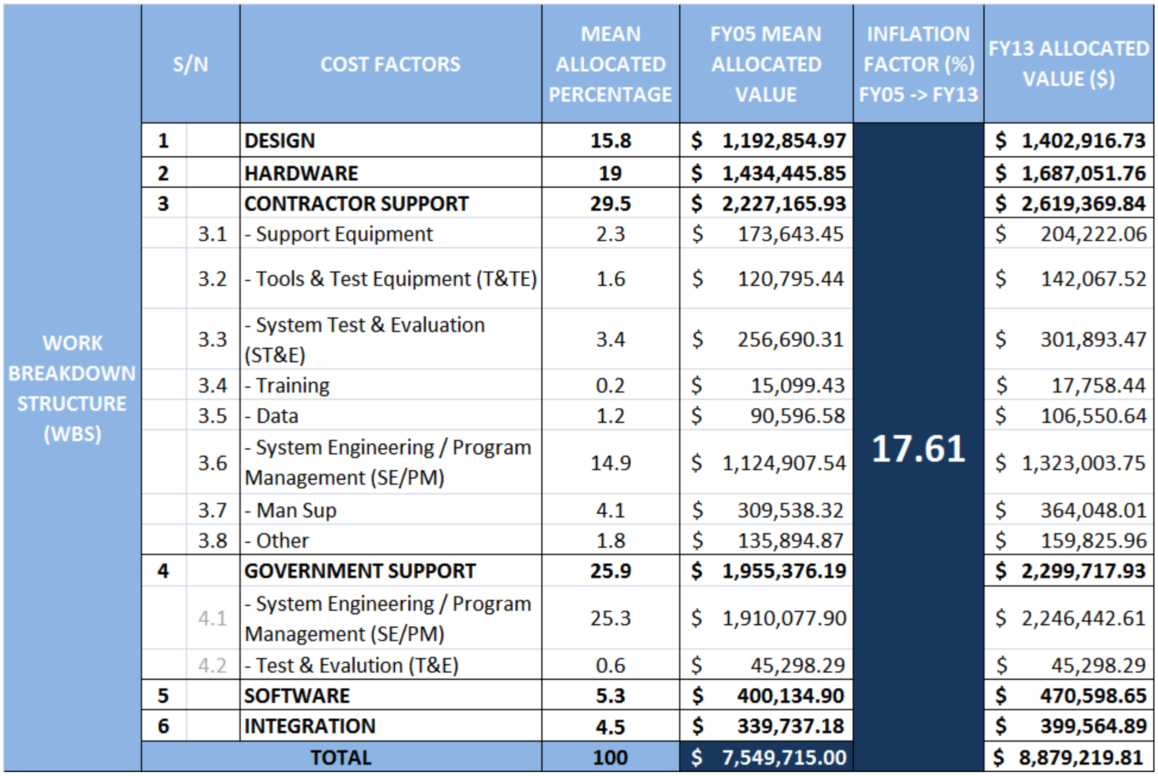
c. Ground Rules and Assumptions

- The ADS has a physical dimension of 36 cubic meters (6m long x 3m wide x 2m tall). As mentioned earlier on, the ADS will be able to fit on-board the DDG-51 class ship.
- Shipboard organic power will be adequate to support the operation of the ADS.
- The cost estimation will focus on the production, integration, and installation cost for one unit on one platform only, rather than total life cycle cost.
- ADS is not "plug and play"; some physical modifications will be required to the DDG-51 class ship in order to accommodate the ADS.

d. Cost Summary

The initial goal was to approach the vendor to obtain the total cost of designing and manufacturing a single unit of the ADS. However, due to the sensitivity of the product no vendor was willing to reveal the cost figure. Therefore, an alternate approach relying on trusted published articles from web based sources was selected. Through research, a contract figure of $7,549,715 published by U.S. Department of Defense was discovered. The initial WBS decomposition is shown in Table 40.

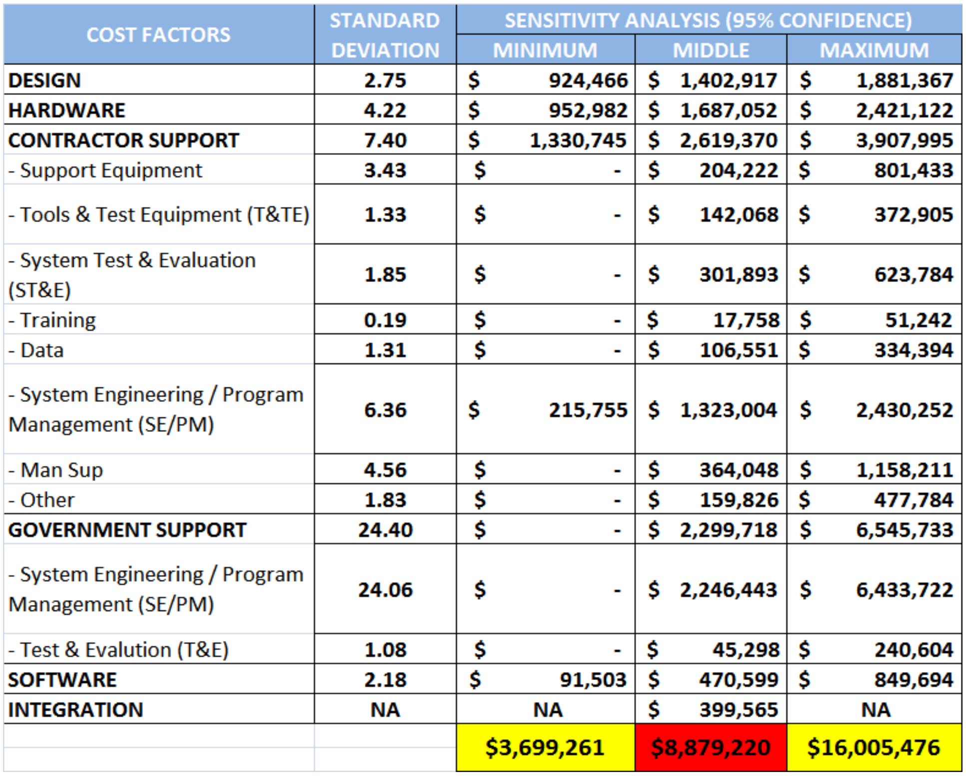
Table 40. Active Denial System (ADS) Work Breakdown Structure (WBS)



WORK BREAKDOWN STRUCTURE (WBS)	S/N		COST FACTORS	MEAN ALLOCATED PERCENTAGE	FY05 MEAN ALLOCATED VALUE	INFLATION FACTOR (%) FY05 -> FY13	FY13 ALLOCATED VALUE ($)
WORK BREAKDOWN STRUCTURE (WBS)	**1**		**DESIGN**	**15.8**	**$ 1,192,854.97**	17.61	**$ 1,402,916.73**
	2		**HARDWARE**	**19**	**$ 1,434,445.85**		**$ 1,687,051.76**
	3		**CONTRACTOR SUPPORT**	**29.5**	**$ 2,227,165.93**		**$ 2,619,369.84**
		3.1	- Support Equipment	2.3	$ 173,643.45		$ 204,222.06
		3.2	- Tools & Test Equipment (T&TE)	1.6	$ 120,795.44		$ 142,067.52
		3.3	- System Test & Evaluation (ST&E)	3.4	$ 256,690.31		$ 301,893.47
		3.4	- Training	0.2	$ 15,099.43		$ 17,758.44
		3.5	- Data	1.2	$ 90,596.58		$ 106,550.64
		3.6	- System Engineering / Program Management (SE/PM)	14.9	$ 1,124,907.54		$ 1,323,003.75
		3.7	- Man Sup	4.1	$ 309,538.32		$ 364,048.01
		3.8	- Other	1.8	$ 135,894.87		$ 159,825.96
	4		**GOVERNMENT SUPPORT**	**25.9**	**$ 1,955,376.19**		**$ 2,299,717.93**
		4.1	- System Engineering / Program Management (SE/PM)	25.3	$ 1,910,077.90		$ 2,246,442.61
		4.2	- Test & Evalution (T&E)	0.6	$ 45,298.29		$ 45,298.29
	5		**SOFTWARE**	**5.3**	**$ 400,134.90**		**$ 470,598.65**
	6		**INTEGRATION**	**4.5**	**$ 339,737.18**		**$ 399,564.89**
			TOTAL	**100**	**$ 7,549,715.00**		**$ 8,879,219.81**

As the contract was awarded in Fiscal Year (FY) 2005, there was a need to include the inflation rate incurred until FY2013 for present reference. The inflation rate was obtained from the Joint Inflation Calculator. The next step was to conduct a sensitivity analysis on the various cost factors to establish a range of estimated total cost. The total system calculation provides us with a 95% confidence interval from $3.7M to $16M FY13 as shown in Table 41.

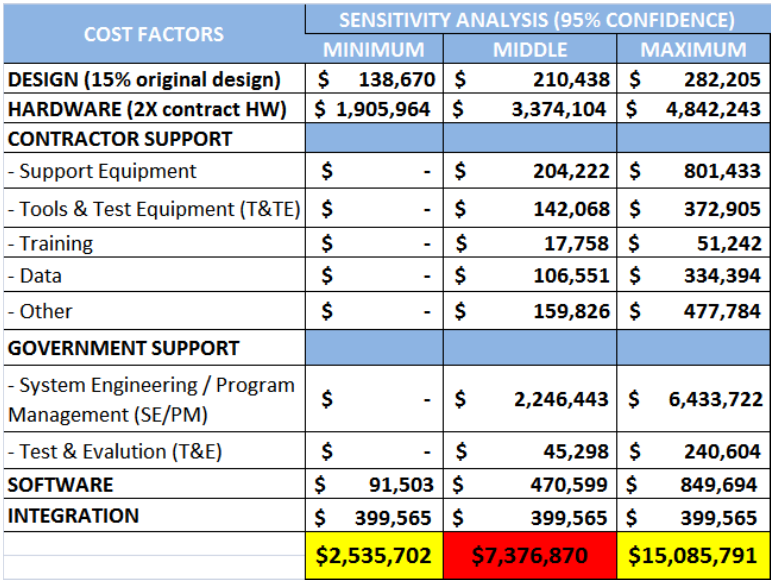
Table 41. Active Denial System (ADS) Sensitivity Analysis



COST FACTORS	STANDARD DEVIATION	SENSITIVITY ANALYSIS (95% CONFIDENCE)		
		MINIMUM	MIDDLE	MAXIMUM
DESIGN	2.75	$ 924,466	$ 1,402,917	$ 1,881,367
HARDWARE	4.22	$ 952,982	$ 1,687,052	$ 2,421,122
CONTRACTOR SUPPORT	7.40	$ 1,330,745	$ 2,619,370	$ 3,907,995
- Support Equipment	3.43	$ -	$ 204,222	$ 801,433
- Tools & Test Equipment (T&TE)	1.33	$ -	$ 142,068	$ 372,905
- System Test & Evaluation (ST&E)	1.85	$ -	$ 301,893	$ 623,784
- Training	0.19	$ -	$ 17,758	$ 51,242
- Data	1.31	$ -	$ 106,551	$ 334,394
- System Engineering / Program Management (SE/PM)	6.36	$ 215,755	$ 1,323,004	$ 2,430,252
- Man Sup	4.56	$ -	$ 364,048	$ 1,158,211
- Other	1.83	$ -	$ 159,826	$ 477,784
GOVERNMENT SUPPORT	24.40	$ -	$ 2,299,718	$ 6,545,733
- System Engineering / Program Management (SE/PM)	24.06	$ -	$ 2,246,443	$ 6,433,722
- Test & Evalution (T&E)	1.08	$ -	$ 45,298	$ 240,604
SOFTWARE	2.18	$ 91,503	$ 470,599	$ 849,694
INTEGRATION	NA	NA	$ 399,565	NA
		$3,699,261	$8,879,220	$16,005,476

Table 41 provides a start to finish estimate for ADS which includes design, prototype hardware assembly, as well as T&E. In accordance with project methodology, it is now necessary to factor out of the total cost estimate all elements not pertaining to the objective of deploying one unit of ADS within a DDG-51 class ship. The objective cost estimate equation will be similar to that of TLS provided in the preceding section; however, since ADS has not undergone T&E in a maritime environment, the cost of government supported T&E is added to the equation as shown in Table 42.

Table 42. Active Denial System (ADS) Objective Cost Estimate



COST FACTORS	SENSITIVITY ANALYSIS (95% CONFIDENCE)		
	MINIMUM	MIDDLE	MAXIMUM
DESIGN (15% original design)	**$ 138,670**	**$ 210,438**	**$ 282,205**
HARDWARE (2X contract HW)	**$ 1,905,964**	**$ 3,374,104**	**$ 4,842,243**
CONTRACTOR SUPPORT			
- Support Equipment	**$ -**	**$ 204,222**	**$ 801,433**
- Tools & Test Equipment (T&TE)	**$ -**	**$ 142,068**	**$ 372,905**
- Training	**$ -**	**$ 17,758**	**$ 51,242**
- Data	**$ -**	**$ 106,551**	**$ 334,394**
- Other	**$ -**	**$ 159,826**	**$ 477,784**
GOVERNMENT SUPPORT			
- System Engineering / Program Management (SE/PM)	**$ -**	**$ 2,246,443**	**$ 6,433,722**
- Test & Evalution (T&E)	**$ -**	**$ 45,298**	**$ 240,604**
SOFTWARE	**$ 91,503**	**$ 470,599**	**$ 849,694**
INTEGRATION	**$ 399,565**	**$ 399,565**	**$ 399,565**
	$2,535,702	**$7,376,870**	**$15,085,791**

The project group is 95% confident that the cost of installing and deploying two ADS on a single DDG-51 class ship will be between $2.5M and $15.1M FY13.

6. LASER Weapon System (LaWS)

a. Objective

To determine and estimate the upgrade and shipboard installation cost of the LASER Weapon System (LaWS) from its current 33kW output to 150 kW.

b. Facts

- The cost apportioned for the development cost of the LaWS was obtained from CRS report for Congress (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2011). The yearly breakdown for the "Funding for LaWS development" is shown in Table 43 for reference.

Table 43. Funding for LASER Weapon System (LaWS) Development

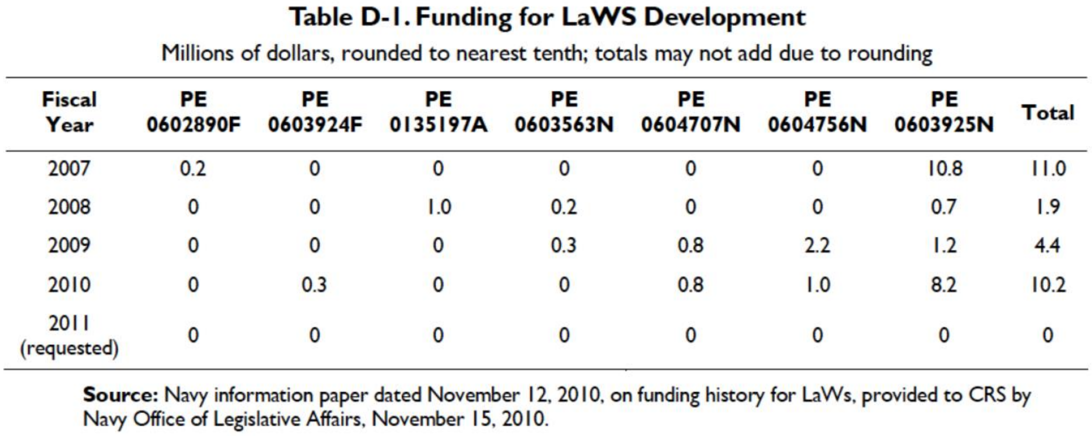


Table D-1. Funding for LaWS Development

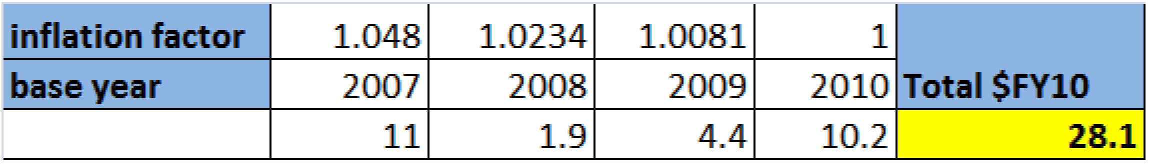
Millions of dollars, rounded to nearest tenth; totals may not add due to rounding

Fiscal Year	PE 0602890F	PE 0603924F	PE 0135197A	PE 0603563N	PE 0604707N	PE 0604756N	PE 0603925N	Total
2007	0.2	0	0	0	0	0	10.8	11.0
2008	0	0	1.0	0.2	0	0	0.7	1.9
2009	0	0	0	0.3	0.8	2.2	1.2	4.4
2010	0	0.3	0	0	0.8	1.0	8.2	10.2
2011 (requested)	0	0	0	0	0	0	0	0

Source: Navy information paper dated November 12, 2010, on funding history for LaWs, provided to CRS by Navy Office of Legislative Affairs, November 15, 2010.

- Funding for each year is projected from that year to a base reference year 2010. The inflation rates used for the calculation are obtained from the Joint Inflation Calculator and presented in Table 44.
- The LaWS prototype incoherently combines light beams from six fiber SSLs (commercial, off-the-shelf welding LASERs, each with a power of 5.5 kW) to create a LASER with a total power of 33 kW and a BQ of 17 (Taylor 2010).

Table 44. LASER Weapon System (LaWS) Base Costing Inflation Adjusted Totals



inflation factor	1.048	1.0234	1.0081	1	**Total $FY10**
base year	2007	2008	2009	2010	
	11	1.9	4.4	10.2	**28.1**

c. Ground Rules and Assumptions

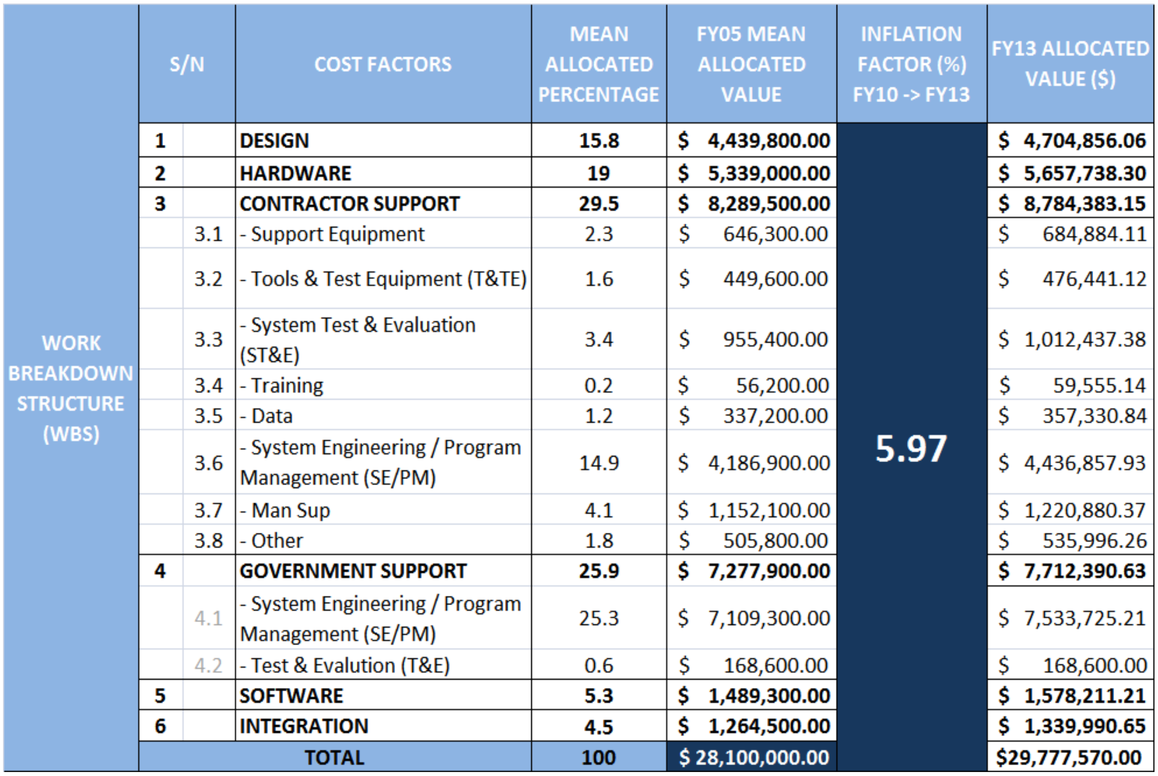
- It is observed that Congress has requested no funding for LaWS in 2011. From this cut in funding, we infer that from 2011 and onwards, there is no further funding to LaWS development.

- The funding for LaWS development includes all items in the WBS, encompassing the hardware components required to deliver the current 33kW output.
- The cost of improved hardware components is scaled according to its power output (150kW from 33kW); assuming that the cost is linearly proportional to the output power. This would increase the hardware cost by a factor of 4.5 (approximate).
- No further engineering development (design) is suspected to be required for actual shipboard integration and use; although the upgraded 150kW weapon variant is not believed to have been built, it is assumed the blueprints exist.
- Additional T&E will be required for the upgraded 150kW variant; cost of T&E will be included in the objective estimate calculation.
- Cost estimate assumes hybrid option (Phalanx CIWS) is also included.

d. Cost Summary

The deployment cost of LaWS on DDG-51 class will primarily consist of the scaled hardware improvement cost, the hardware integration cost, as well as the cost of additional T&E associated with the upgrade. No further design is required, and therefore a design cost estimate was not conducted. Given the $28.1M initial investment figure calculated by the project group it is first necessary to decompose the baseline amount into its respective discrete components, and identify the WBS sub-elements shown in Table 45.

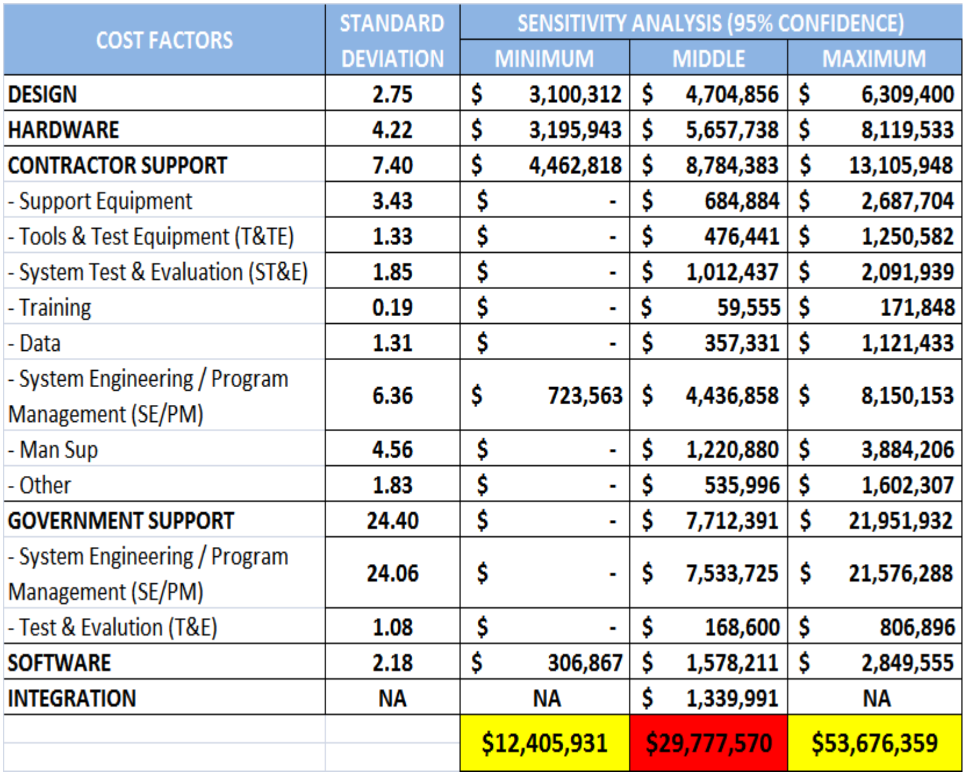
Table 45. LASER Weapon System (LaWS) Work Breakdown Structure (WBS)



WORK BREAKDOWN STRUCTURE (WBS)	S/N		COST FACTORS	MEAN ALLOCATED PERCENTAGE	FY05 MEAN ALLOCATED VALUE	INFLATION FACTOR (%) FY10 -> FY13	FY13 ALLOCATED VALUE ($)
WORK BREAKDOWN STRUCTURE (WBS)	**1**		**DESIGN**	**15.8**	**$ 4,439,800.00**	5.97	**$ 4,704,856.06**
	2		**HARDWARE**	**19**	**$ 5,339,000.00**		**$ 5,657,738.30**
	3		**CONTRACTOR SUPPORT**	**29.5**	**$ 8,289,500.00**		**$ 8,784,383.15**
		3.1	- Support Equipment	2.3	$ 646,300.00		$ 684,884.11
		3.2	- Tools & Test Equipment (T&TE)	1.6	$ 449,600.00		$ 476,441.12
		3.3	- System Test & Evaluation (ST&E)	3.4	$ 955,400.00		$ 1,012,437.38
		3.4	- Training	0.2	$ 56,200.00		$ 59,555.14
		3.5	- Data	1.2	$ 337,200.00		$ 357,330.84
		3.6	- System Engineering / Program Management (SE/PM)	14.9	$ 4,186,900.00		$ 4,436,857.93
		3.7	- Man Sup	4.1	$ 1,152,100.00		$ 1,220,880.37
		3.8	- Other	1.8	$ 505,800.00		$ 535,996.26
	4		**GOVERNMENT SUPPORT**	**25.9**	**$ 7,277,900.00**		**$ 7,712,390.63**
		4.1	- System Engineering / Program Management (SE/PM)	25.3	$ 7,109,300.00		$ 7,533,725.21
		4.2	- Test & Evalution (T&E)	0.6	$ 168,600.00		$ 168,600.00
	5		**SOFTWARE**	**5.3**	**$ 1,489,300.00**		**$ 1,578,211.21**
	6		**INTEGRATION**	**4.5**	**$ 1,264,500.00**		**$ 1,339,990.65**
			TOTAL	**100**	**$ 28,100,000.00**		**$29,777,570.00**

As the contract was awarded in Fiscal Year (FY) 2010, there was a need to include the inflation rate incurred until FY2013 for present reference. The inflation rate was obtained from the Joint Inflation Calculator. The next step was to conduct a sensitivity analysis on the various cost factors to establish a range of estimated total cost. The total system cost calculation provides us with a 95% confidence interval from \$12.4M to \$53.7M FY13 as shown in Table 46.

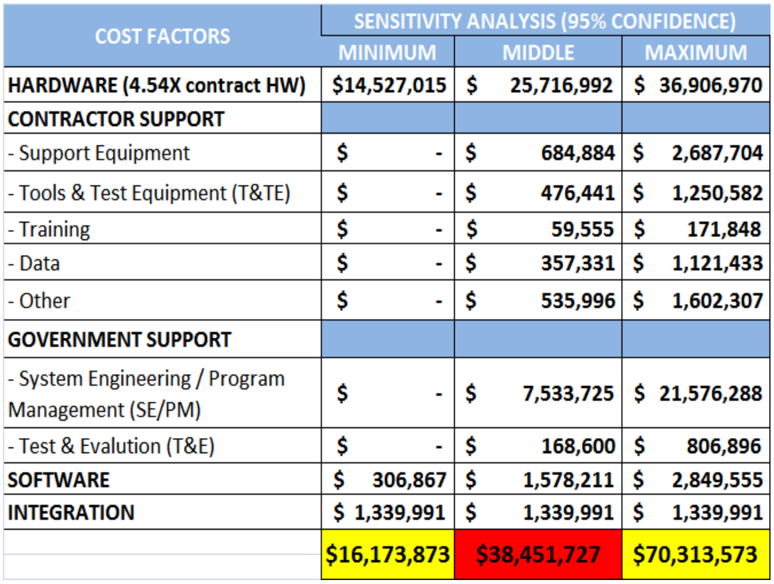
Table 46. LASER Weapon System (LaWS) Sensitivity Analysis



COST FACTORS	STANDARD DEVIATION	SENSITIVITY ANALYSIS (95% CONFIDENCE)		
		MINIMUM	MIDDLE	MAXIMUM
DESIGN	2.75	$ 3,100,312	$ 4,704,856	$ 6,309,400
HARDWARE	4.22	$ 3,195,943	$ 5,657,738	$ 8,119,533
CONTRACTOR SUPPORT	7.40	$ 4,462,818	$ 8,784,383	$ 13,105,948
- Support Equipment	3.43	$ -	$ 684,884	$ 2,687,704
- Tools & Test Equipment (T&TE)	1.33	$ -	$ 476,441	$ 1,250,582
- System Test & Evaluation (ST&E)	1.85	$ -	$ 1,012,437	$ 2,091,939
- Training	0.19	$ -	$ 59,555	$ 171,848
- Data	1.31	$ -	$ 357,331	$ 1,121,433
- System Engineering / Program Management (SE/PM)	6.36	$ 723,563	$ 4,436,858	$ 8,150,153
- Man Sup	4.56	$ -	$ 1,220,880	$ 3,884,206
- Other	1.83	$ -	$ 535,996	$ 1,602,307
GOVERNMENT SUPPORT	24.40	$ -	$ 7,712,391	$ 21,951,932
- System Engineering / Program Management (SE/PM)	24.06	$ -	$ 7,533,725	$ 21,576,288
- Test & Evalution (T&E)	1.08	$ -	$ 168,600	$ 806,896
SOFTWARE	2.18	$ 306,867	$ 1,578,211	$ 2,849,555
INTEGRATION	NA	NA	$ 1,339,991	NA
		$12,405,931	$29,777,570	$53,676,359

Table 46 provides a start to finish estimate for LaWS which includes design, prototype hardware assembly, as well as T&E. In accordance with project methodology, it is now necessary to factor out of the total cost estimate all elements not pertaining to the objective of determining and estimating the upgrade and shipboard installation cost of the LASER Weapon System (LaWS) from its current 33kW output to 150 kW. The objective cost estimate equation will be similar to those provided in the preceding sections; however, since LaWS requires a technology upgrade, the hardware cost estimate has been adjusted accordingly as shown in Table 47.

Table 47. LASER Weapon System (LaWS) Objective Cost Estimate



COST FACTORS	SENSITIVITY ANALYSIS (95% CONFIDENCE)		
	MINIMUM	MIDDLE	MAXIMUM
HARDWARE (4.54X contract HW)	**$14,527,015**	**$ 25,716,992**	**$ 36,906,970**
CONTRACTOR SUPPORT			
- Support Equipment	**$ -**	**$ 684,884**	**$ 2,687,704**
- Tools & Test Equipment (T&TE)	**$ -**	**$ 476,441**	**$ 1,250,582**
- Training	**$ -**	**$ 59,555**	**$ 171,848**
- Data	**$ -**	**$ 357,331**	**$ 1,121,433**
- Other	**$ -**	**$ 535,996**	**$ 1,602,307**
GOVERNMENT SUPPORT			
- System Engineering / Program Management (SE/PM)	**$ -**	**$ 7,533,725**	**$ 21,576,288**
- Test & Evalution (T&E)	**$ -**	**$ 168,600**	**$ 806,896**
SOFTWARE	**$ 306,867**	**$ 1,578,211**	**$ 2,849,555**
INTEGRATION	**$ 1,339,991**	**$ 1,339,991**	**$ 1,339,991**
	$16,173,873	**$38,451,727**	**$70,313,573**

The project group is 95% confident that the upgrade and shipboard installation cost of the LASER Weapon System (LaWS) from its current 33kW output to 150 kW will be between $16.2M and $70.3M FY13 per unit.

7. Maritime LASER Demonstration (MLD)

a. Objective

To derive the cost estimate of integration and installation of the Maritime LASER Demonstration (MLD) onboard DDG-51 class ships.

b. Facts

- The contract award for the development of the first MLD unit is $98M (Department of the Navy 2009); the original scope of work includes assembling, integration and demonstration of the MLD (Optics.org 2011).
- In March 2009, Northrop Grumman (NG) demonstrated a version of MLD that coherently combined seven slab SSLs, each with a power of about 15 kW, to create a beam with a power of about 105

kW (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013).

- In 2011, MLD was the first LASER of that energy level to be put on a Navy ship, be powered from the ship, and counter a target at range in a maritime environment (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013).

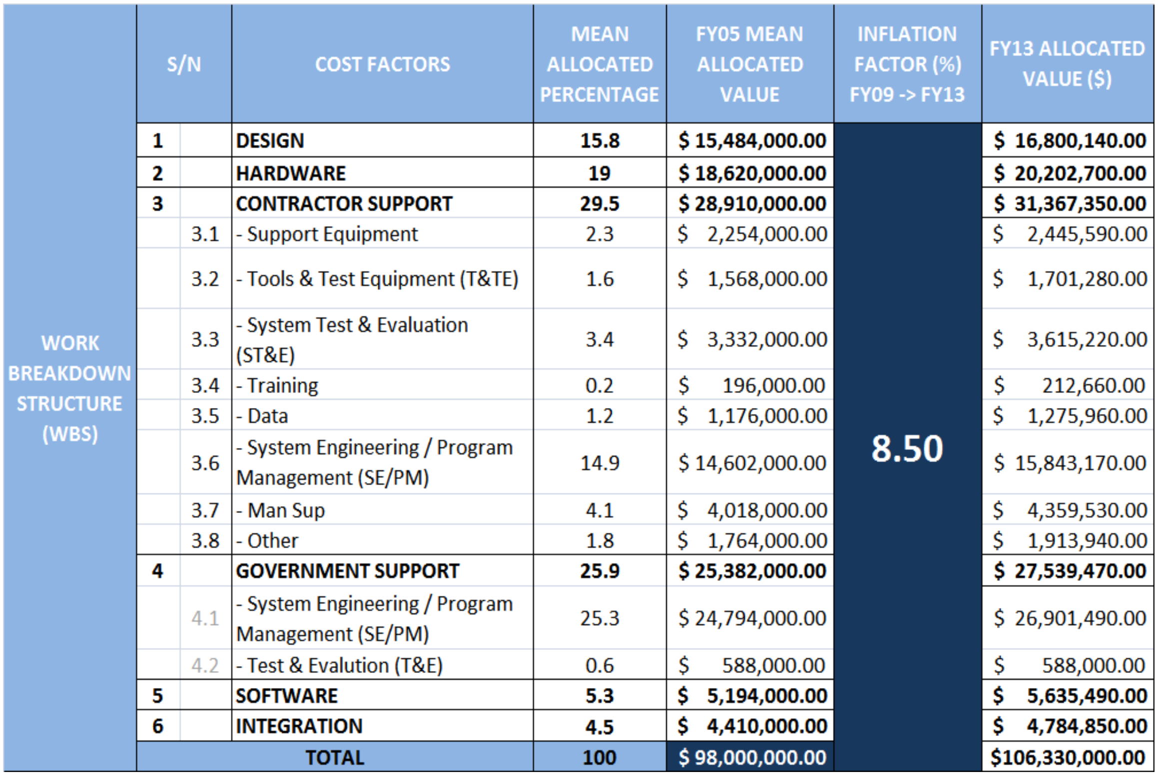
c. Ground Rules and Assumptions

- The $98M contract awarded to Northrop Grumman in 2009 includes the required funding for R&D, design, prototype hardware assembly, and T&E.
- No further engineering development (design) is required for actual shipboard integration and use.
- No additional hardware upgrade is required; the MLD is intended to operate at the originally designed 105kW power level.
- The original contract's high price tag (relative to other analyzed systems) is correlated to the MLD project's robustness and high technical readiness level (TRL).

d. Cost Summary

The deployment cost of MLD on DDG-51 class will primarily consist of the projected hardware cost and hardware integration cost. No further technology upgrade is required, and therefore an upgrade cost estimate was not conducted. No further design is required, and therefore a design cost estimate was not conducted. Given the high $98M initial contract figure obtained by the project group it is necessary not only to decompose the baseline amount into its respective discrete components, and identify the WBS sub-elements shown below, but also attempt to justify the additional expenditure.

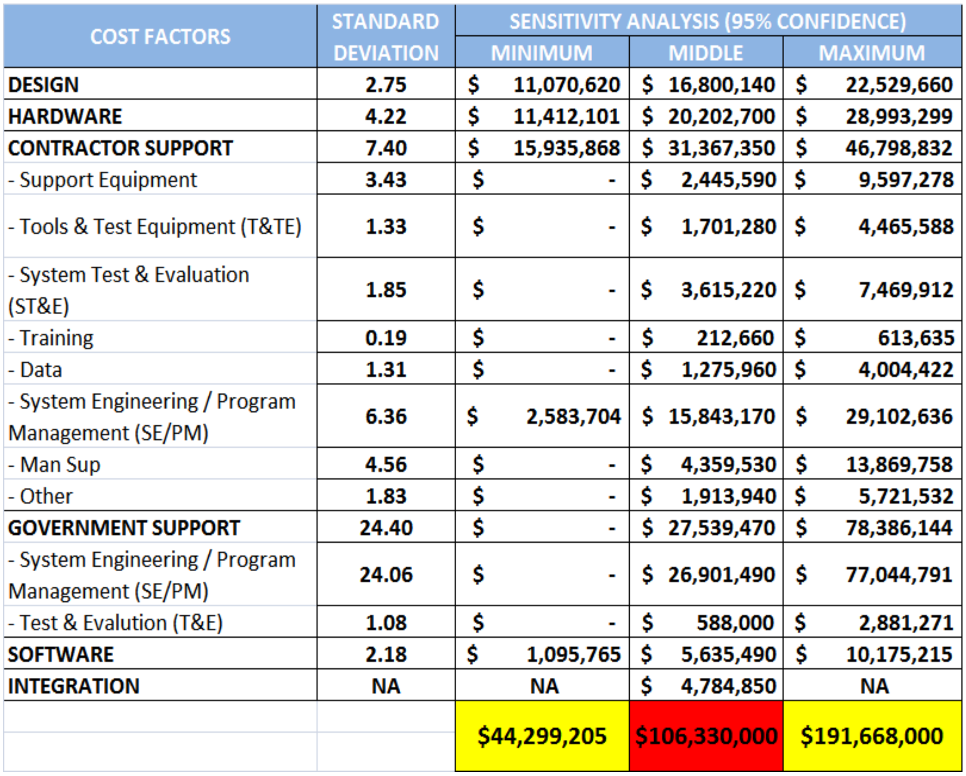
Table 48. Maritime LASER Demonstration (MLD) Work Breakdown Structure (WBS)



WORK BREAKDOWN STRUCTURE (WBS)	S/N		COST FACTORS	MEAN ALLOCATED PERCENTAGE	FY05 MEAN ALLOCATED VALUE	INFLATION FACTOR (%) FY09 -> FY13	FY13 ALLOCATED VALUE ($)
WORK BREAKDOWN STRUCTURE (WBS)	**1**		**DESIGN**	**15.8**	**$ 15,484,000.00**	**8.50**	**$ 16,800,140.00**
	2		**HARDWARE**	**19**	**$ 18,620,000.00**		**$ 20,202,700.00**
	3		**CONTRACTOR SUPPORT**	**29.5**	**$ 28,910,000.00**		**$ 31,367,350.00**
		3.1	- Support Equipment	2.3	$ 2,254,000.00		$ 2,445,590.00
		3.2	- Tools & Test Equipment (T&TE)	1.6	$ 1,568,000.00		$ 1,701,280.00
		3.3	- System Test & Evaluation (ST&E)	3.4	$ 3,332,000.00		$ 3,615,220.00
		3.4	- Training	0.2	$ 196,000.00		$ 212,660.00
		3.5	- Data	1.2	$ 1,176,000.00		$ 1,275,960.00
		3.6	- System Engineering / Program Management (SE/PM)	14.9	$ 14,602,000.00		$ 15,843,170.00
		3.7	- Man Sup	4.1	$ 4,018,000.00		$ 4,359,530.00
		3.8	- Other	1.8	$ 1,764,000.00		$ 1,913,940.00
	4		**GOVERNMENT SUPPORT**	**25.9**	**$ 25,382,000.00**		**$ 27,539,470.00**
		4.1	- System Engineering / Program Management (SE/PM)	25.3	$ 24,794,000.00		$ 26,901,490.00
		4.2	- Test & Evalution (T&E)	0.6	$ 588,000.00		$ 588,000.00
	5		**SOFTWARE**	**5.3**	**$ 5,194,000.00**		**$ 5,635,490.00**
	6		**INTEGRATION**	**4.5**	**$ 4,410,000.00**		**$ 4,784,850.00**
	TOTAL			**100**	**$ 98,000,000.00**		**$106,330,000.00**

As the contract was awarded in Fiscal Year (FY) 2009, there was a need to include the inflation rate incurred until FY2013 for present reference. The inflation rate was obtained from the Joint Inflation Calculator. The next step was to conduct a sensitivity analysis on the various cost factors to establish a range of estimated total cost. The total system cost calculation provides us with a 95% confidence interval from $44.3M to $191.7M FY13 as shown in Table 49.

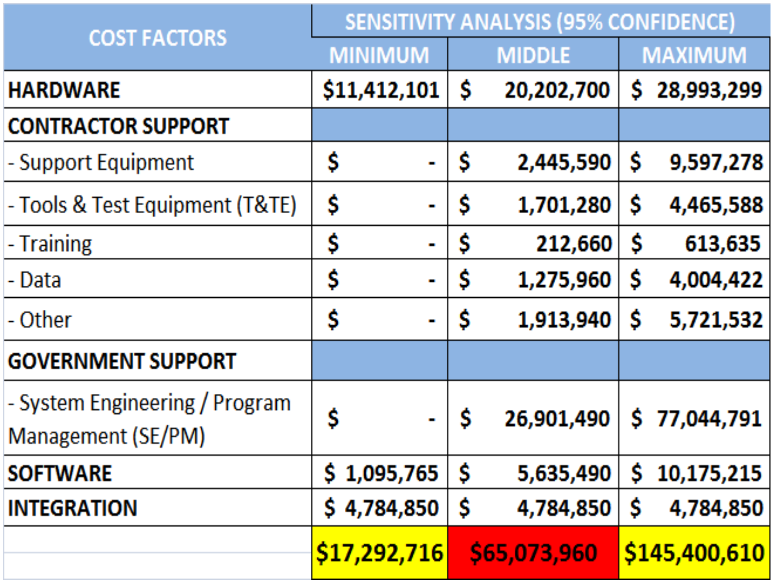
Table 49. Maritime LASER Demonstration (MLD) Sensitivity Analysis



COST FACTORS	STANDARD DEVIATION	SENSITIVITY ANALYSIS (95% CONFIDENCE)		
		MINIMUM	MIDDLE	MAXIMUM
DESIGN	**2.75**	**$ 11,070,620**	**$ 16,800,140**	**$ 22,529,660**
HARDWARE	**4.22**	**$ 11,412,101**	**$ 20,202,700**	**$ 28,993,299**
CONTRACTOR SUPPORT	**7.40**	**$ 15,935,868**	**$ 31,367,350**	**$ 46,798,832**
- Support Equipment	**3.43**	**$ -**	**$ 2,445,590**	**$ 9,597,278**
- Tools & Test Equipment (T&TE)	**1.33**	**$ -**	**$ 1,701,280**	**$ 4,465,588**
- System Test & Evaluation (ST&E)	**1.85**	**$ -**	**$ 3,615,220**	**$ 7,469,912**
- Training	**0.19**	**$ -**	**$ 212,660**	**$ 613,635**
- Data	**1.31**	**$ -**	**$ 1,275,960**	**$ 4,004,422**
- System Engineering / Program Management (SE/PM)	**6.36**	**$ 2,583,704**	**$ 15,843,170**	**$ 29,102,636**
- Man Sup	**4.56**	**$ -**	**$ 4,359,530**	**$ 13,869,758**
- Other	**1.83**	**$ -**	**$ 1,913,940**	**$ 5,721,532**
GOVERNMENT SUPPORT	**24.40**	**$ -**	**$ 27,539,470**	**$ 78,386,144**
- System Engineering / Program Management (SE/PM)	**24.06**	**$ -**	**$ 26,901,490**	**$ 77,044,791**
- Test & Evalution (T&E)	**1.08**	**$ -**	**$ 588,000**	**$ 2,881,271**
SOFTWARE	**2.18**	**$ 1,095,765**	**$ 5,635,490**	**$ 10,175,215**
INTEGRATION	**NA**	**NA**	**$ 4,784,850**	**NA**
		$44,299,205	**$106,330,000**	**$191,668,000**

Table 49 provides a start to finish estimate for MLD which includes design, prototype hardware assembly, as well as T&E. In accordance with project methodology, it is now necessary to factor out of the total cost estimate all elements not pertaining to the objective of deriving the cost estimate of integration and installation of the Maritime LASER Demonstration (MLD) onboard DDG-51 class ships. The objective cost estimate equation will be similar to those provided in the preceding sections. The calculation is presented in Table 50.

Table 50. Maritime LASER Demonstration (MLD) Objective Estimate



COST FACTORS	SENSITIVITY ANALYSIS (95% CONFIDENCE)		
	MINIMUM	MIDDLE	MAXIMUM
HARDWARE	$11,412,101	$ 20,202,700	$ 28,993,299
CONTRACTOR SUPPORT			
- Support Equipment	$ -	$ 2,445,590	$ 9,597,278
- Tools & Test Equipment (T&TE)	$ -	$ 1,701,280	$ 4,465,588
- Training	$ -	$ 212,660	$ 613,635
- Data	$ -	$ 1,275,960	$ 4,004,422
- Other	$ -	$ 1,913,940	$ 5,721,532
GOVERNMENT SUPPORT			
- System Engineering / Program Management (SE/PM)	$ -	$ 26,901,490	$ 77,044,791
SOFTWARE	$ 1,095,765	$ 5,635,490	$ 10,175,215
INTEGRATION	$ 4,784,850	$ 4,784,850	$ 4,784,850
	$17,292,716	$65,073,960	$145,400,610

The project group is 95% confident that the integration and installation of the Maritime LASER Demonstration (MLD) onboard DDG-51 class ships will be between $17.3M and $145.4M FY13 per unit.

8. Conclusion

It can be reasoned from the overall methodology that the selected costing approach presented is not ideal, primarily due to the “reverse-engineering” steps utilized in obtaining the various cost factors. A 95% confidence interval was calculated around the cost factors using each of the respective factors’ associated co-variance value. Even though both the cost factors and co-variance data are subject to the same bias that account for the primary sources of error, the wide range of estimates given by the high and low calculations should more than compensate for any weaknesses attributable to the bias. A preferred approach would have been to obtain the actual cost data associated with the respective cost factors, and subsequently derive the total cost in a forward manner. However, as mentioned earlier, the actual figures were not available to the project group.

As a result, the best alternative method was used which bases the calculations on historical data obtained from prior projects. The cost estimation project group had made every effort to ensure the validity and applicability of historical data used.

In addition, due to extreme scarcity of open source and unclassified contracting data, the baseline cost estimation figures are all mainly based on a single data point from a trusted published document pertaining to the programs development. Ideally, additional data points should have been used to verify, reinforce, or if necessary refine and adjust the final objective based cost estimate.

Although it is important to acknowledge that cost will only be one of many attributes evaluated when making final project recommendations, a cost as an independent variable (CAIV) assessment is provided as follows:

- Given today's budgetary constraints, the Tactical LASER System is selected as the optimal choice with respect to CAIV.
- With a middle objective estimate of less than \$2.4M, the TLS acquisition burden is projected to be an entire order of magnitude smaller than any other solid state LASER system.
- Acquisition of LaWS would cost approximately 16 times that of TLS.
- Acquisition of MLD would cost approximately 1.7 times that of LaWS, and 27 times that of TLS.

With a middle objective estimate of \$7.4M, the Active Denial System is considered to be a good investment based on the additional and unique capability the system has the potential to provide to the warfare commander.

E. OPERATIONAL AVAILABILITY

The project team attempted to include an analysis on the operational availability of the four selected systems (LaWS, ADS, TLS, MLD). This analysis was to include analyzing reliability and maintainability of the systems with a comparison to current conventional systems. As this project was conducted at the unclassified level, open source data on the specific parameters of current conventional and DEW prototypes was not available. The analysis should be conducted in the future once the data becomes available.

VI. ANALYSIS OF ALTERNATIVES

An Analysis of Alternatives (AOA) was conducted in order to provide an analytical comparison of the operational effectiveness of the various DEWs. The weapons were analyzed by performance, integration, schedule and cost criteria. Preference weightings for the four criteria were assigned based on perspective of the three stakeholders for the project (operator/user, exploratory developer, and system developer). For operators/users, the energy/power output and beam quality are essential performance parameters that are linked. These two parameters represent a trade-off in damage effects on targets at various distances, size and weight of the DEW device, and prime power conversion efficiencies. Secondary issues include reliability, maintainability, and potential hazards due to support and usage. The operator/user perspective is concerned about mission success which incorporates performance (0.50), cost (0.05), and schedule (0.25) for platform integration of the DEW (0.20). Contractors who perform engineering exploration of DEW candidates will have an initial focus on performance, in order to establish a competitive advantage over potential rivals and to establish themselves firmly as a premier provider of equipment, knowledge, and support. During the exploration phase of prototyping and demonstrating the DEW, the contractor(s) will have preference weighting similar to that of the user, reiterating the particular focus on performance factors. However, once sufficient damage on military relevant targets is demonstrated by the prototype DEW, the contractor's attention turns to developing the DEW that is designed for platform integration, now with particular emphasis on life cycle costs). During prototype development, the contract developer(s) has preference weightings focused on increased performance (0.55), life cycle costs (0.35), and schedule (0.10). During this development phase, the tradeoff between energy/power output and beam quality may favor one DEW design over another design. The cost factor becomes more dominant once the utility of DEW is recognized as militarily relevant. This project was focused on the military relevant stage of DEW development, i.e., what missions could be performed by prototype DEWs *if* the decision was made to integrate the best candidate(s) on ships. From this baseline of demonstrating minimal mission effectiveness, the development emphasizes achieving damage on similar targets at greater range. In other words, any improvement in performance (energy/power output and beam quality) is now on par with cost and schedule. All three are equal (0.33). Figure 88 shows the top level of the Analysis of Alternatives including the different stakeholders.

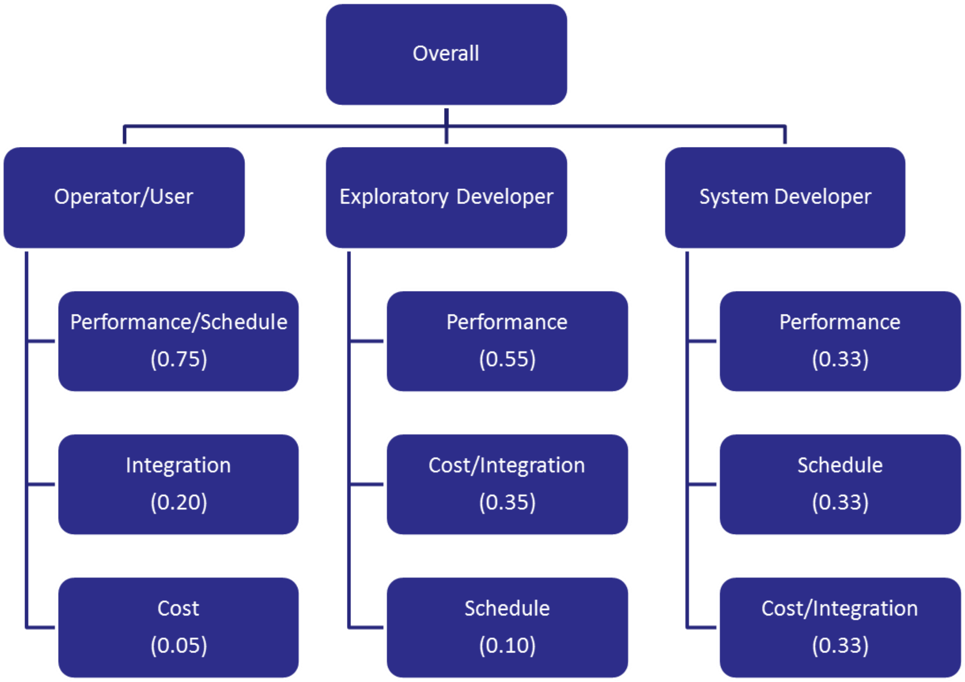


Figure 88. Analysis of Alternatives (AOA) Top Level

Each of the three criteria was evaluated based upon the factors pertaining to it discussed in Chapter 5 and summarized here. Within the performance criterion, considerations were given to how the weapons performed amongst the different mission areas along with average ranges to first Type I and Type II engagements. In evaluating integration, considerations were made to sustainment, training and manning, and shipboard integration. Sustainment was based on materials, safety, sustaining engineering, and disposal of the various weapons. Training and manning were evaluated based upon the additional personnel and work centers required for the various weapons. Shipboard integration involved evaluating factors such as weight, power requirements, cooling, coverage, and combat systems integration of the various weapons. The single unit procurement cost was the amount associated with each weapon system. The criteria were appropriated preference weights based on their respective value according to three stakeholder (Operator/User, Exploratory Developer, and System Developer) perspectives. Figure 89, Figure 90, and Figure 91 shows the AOA with the criteria and weights from the operator's perspective.

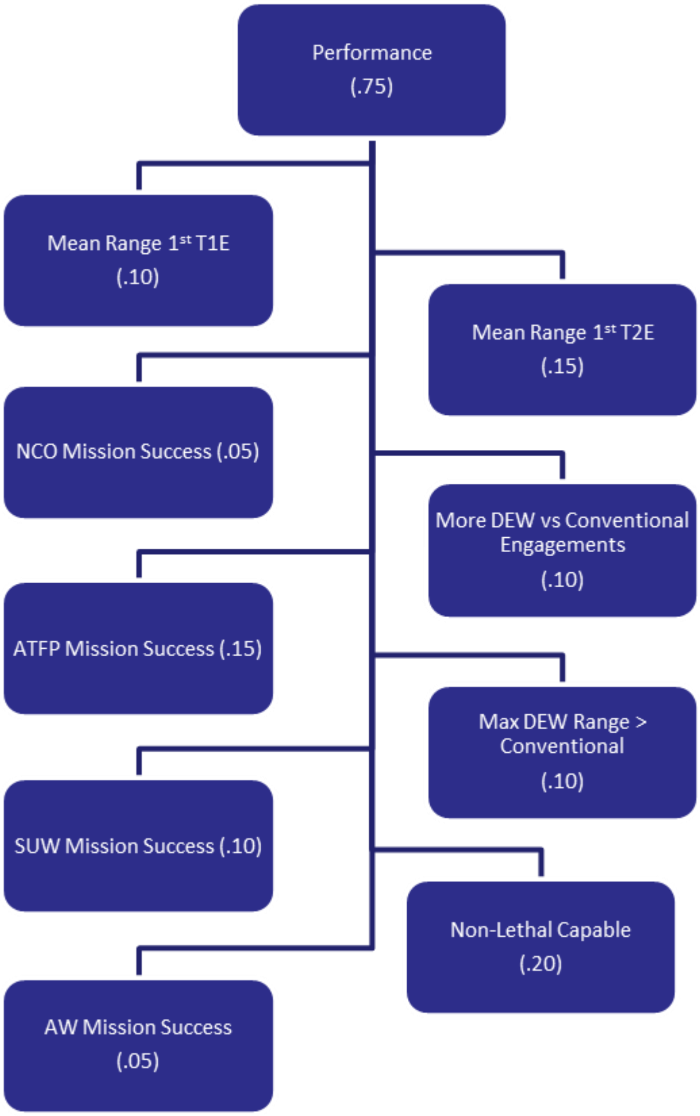


Figure 89. Operator Performance Analysis of Alternatives (AoA) Breakdown

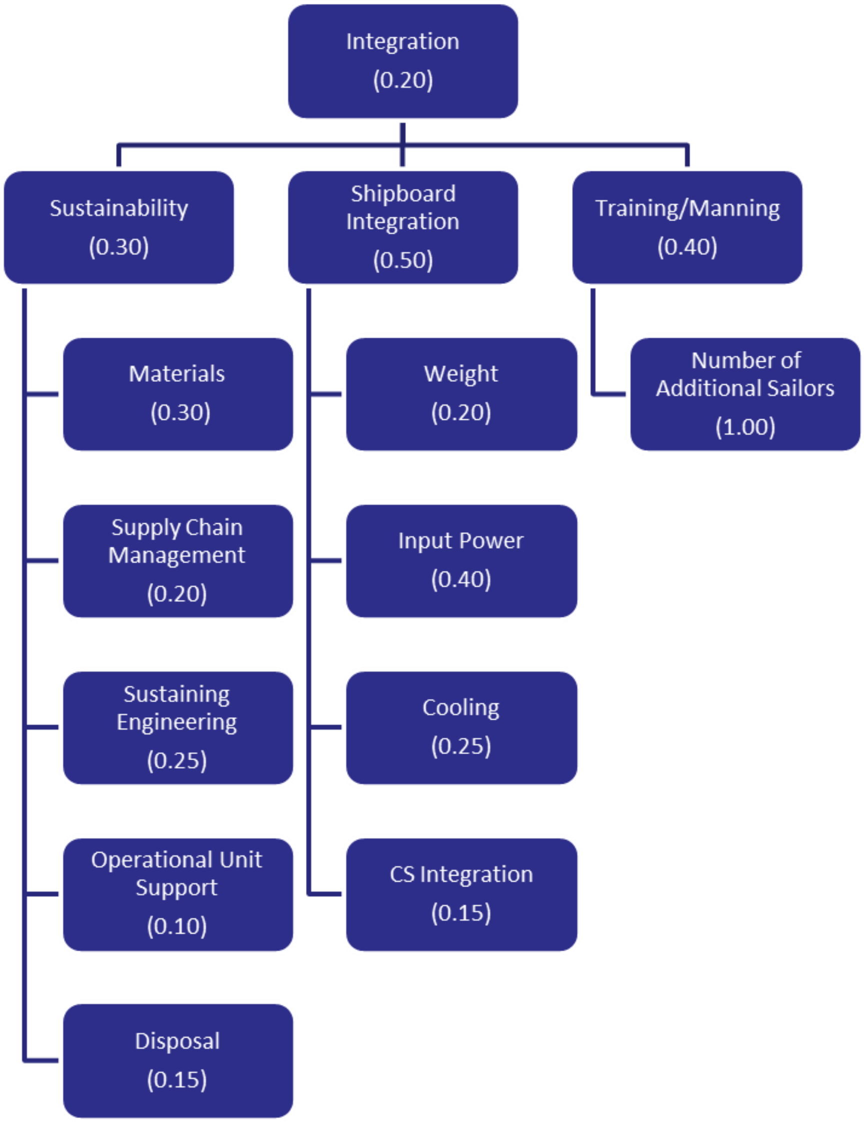


Figure 90. Operator Integration Analysis of Alternatives (AoA) Breakdown

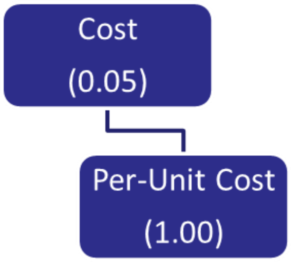


Figure 91. Operator Cost Analysis of Alternatives (AoA) Breakdown

Figure 92 displays the results of the AOA from the perspectives of the various stakeholders. For the operator, ADS is the best with a value of 0.66. An Exploratory Developer would find the TLS most satisfactorily with a score of 0.66. Like the Exploratory Developer, the TLS performed the best for an System Developer with a score of 0.70. On average, the TLS outperformed the other systems with a value of 0.62 whereas the LaWS had the lowest on average amongst the systems with a value of 0.20. Despite the LaWS being the lowest it should be noted that its score was pretty comparable to the LaWS+ and MLD which had scores of .27 and .31 respectively indicating that any additional considerations that may be needed in order to place the LaWS, LaWS+, or MLD onto a platform may not result in much added value. In addition, ADS was not too far from the TLS on average with a score of .57. Although these results give some indication of the value of each system, an analysis of cost versus performance is called for in order to provide further clarity on which of the systems should be chosen.

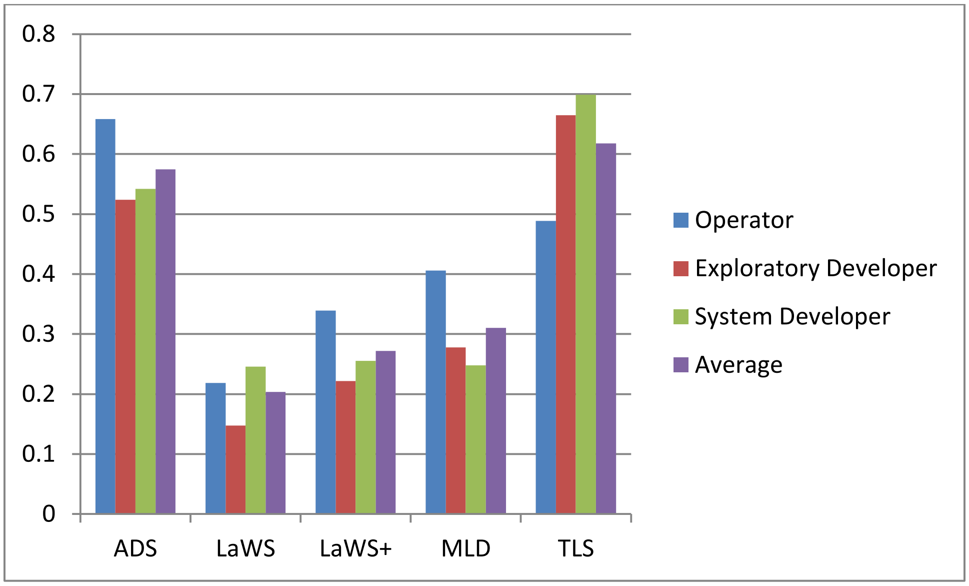


Figure 92. Analysis of Alternatives (AOA) Results

Figure 93 shows a Cost as an Independent Variable (CAIV) Analysis amongst the various stakeholders. When cost is not included in the total performance of the systems, ADS is the highest scoring weapon system. Moreover, it's one of the cheapest. Although the LaWS, LaWS+, and MLD have comparable performance scores across the board, their costs are quite different and tend to go up as performance goes up. LaWS, LaWS+, and MLD cost $18,392,473, $38,451,727, and $65,073,960 respectively. Both ADS and TLS perform at a similar level of MLD, but at far cheaper costs of $5,689,818 and $1,836,919 respectively.

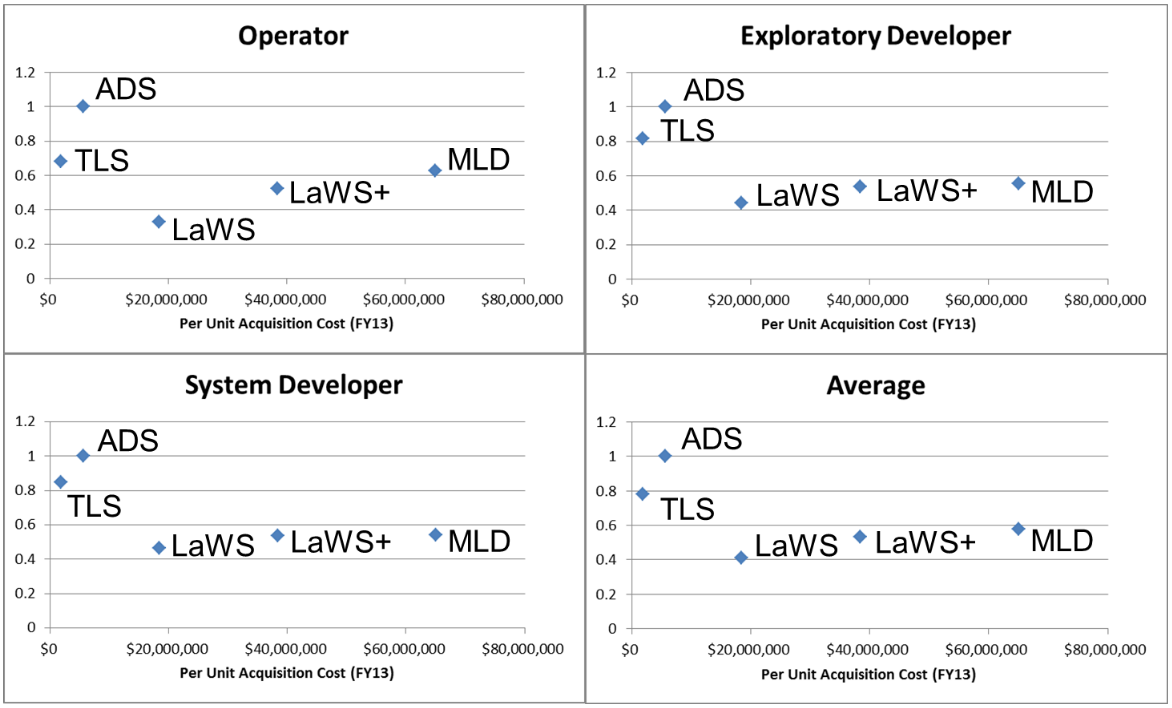


Figure 93. Cost as an Independent Variable (CAIV) Analysis

The AOA indicates that the most expensive option is not necessarily the 'best' option. When considering performance as the key contributing factor, the ADS system would be the best option (the operator's point of view). If considering both cost and performance, the TLS would be the best option (Exploratory and System Developers).

Since the key drivers for the Navy include cost and performance, we would recommend the TLS system as the most optimal system for integration onto the DDG-51 platform.

VII. CONCLUSION

This report conducted an in-depth analysis at the unclassified level of several promising DE technologies and specific DEW prototypes for integration onboard U.S. Navy ships.

A. METHODOLOGY

The methodology using GINA and other models to corroborate GINA results focused on what current prototypes are capable of as opposed to what DE could be in the future. The result of that methodology was to reveal a lower cost means of meeting current U.S. Navy missions requirements. Validation of the models was conducted against available test data to ensure that all model results were consistent with experimental data in operational environs. Missions, threats, and weapons were mapped to determine which weapons would be suitable for given mission and threat combinations. A cost analysis was also conducted to illustrate the available trade space between alternatives.

1. Mission Driven Analysis

An analysis was conducted on which missions of the U.S. Navy DE offers both current utility and potential for future uses. Using the UNTL, UJTL, and SFTM, a list of 81 missions and mission areas were identified. These missions could be completed by a DEW based strictly on the laws of physics and what is reasonable for a DEW (USW missions were not counted due to the high attenuation in seawater for example). There are other missions as well which a DEW could support but is not the prime factor in completing the mission, combat search and rescue (CSAR) is an example. Weapons are required for the protection of the CSAR aircraft, and a DEW has the potential to fill this requirement, but that is not the main purpose of CSAR, extracting personnel is.

2. Technology Driven Analysis

An analysis of what current DEW technology can achieve was then conducted. As those missions in which DE could play a part were already identified, this list was narrowed further. The list of 81 potential missions for DE was limited further by what current DEW prototypes have the potential to fulfill. Current DEW prototypes can potentially fulfill 29 of the previously identified 81 mission areas. Of these 29 missions, 21 are purely defensive in nature while the remaining eight have defensive elements. For example, ‘to engage surface ships could be offensive or defensive. No purely offensive mission was assessed as feasible by current DEW prototypes (e.g., naval surface fire support and strike warfare are two examples).

The defensive missions for which DEWs are suitable also suggests which systems are appropriate to compare DEW performance against. BMD, strike, air defense against ASCM and manned aircraft, and surface warfare against major combatants are not achievable by current DE prototypes. Since these mission areas are not possible DE missions, the 5-inch gun, Standard Missiles, Tomahawks, and Harpoons are not suitable to compare against DEW. CIWS, 25mm machine gun, and crew served weapons fulfill the same mission set as DEW have the potential to satisfy and this conventional set forms the appropriate weapons from which to compare DEWs. The expectation for the future is that DEWs will fulfill the BMD, strike, air defense, and surface warfare missions, but much greater power levels and beam quality must be achieved first. ABL was capable of BMD at a range of over 200km with a megawatt class laser (Cadena and Selinger 2009). Similar performance may be possible from a ship borne SSL in the future. The analyses beyond the four-year timeframe of this project suggest further analyses into alleviating the effects of atmospheric.

3. Model Validation

The model validation was presented in Chapter 4. The overall model had two separate components, the HPM component and LASER component. Both components had to be validated separately in order for the results to be accepted. Excel was the chosen tool to complete this validation.

a. HPM

Results of several tests conducted by the Army with ADS have been reported. These results were used to build the model as specific parameters of the system were not available. Figure 24 from Chapter 4 is reproduced here as Figure 94. From the tests performed by the Army at a range of 500 yards, it took about one second from the time that ADS was energized to when the people moved out of the beam (LeVine 2009). This time is similar to what the project team developed for the model as shown by the red line in Figure 94.

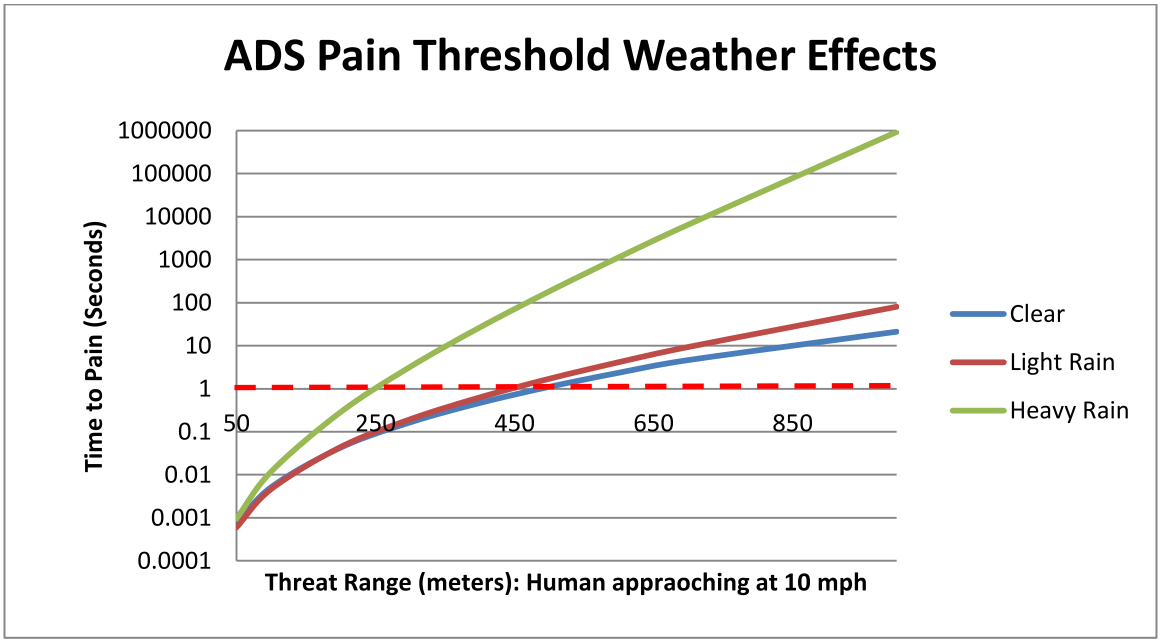


Figure 94. Active Denial System (ADS) Performance in Weather

b. LASER

Validation of the model depicting LASER performance was done similarly to that for HPM. The model was built and available data was input. Some assumptions had to be made and this is all detailed extensively in Chapter 4. Reproducing Figure 30 here as Figure 95, the performance of TLS is similar to that of LaWS+. A congressional report has said that TLS is on par with other LASER weapon systems despite the substantially lower power (O'Rourke, Navy Shipboard LASERs for Surface, Air, and Missile Defense: Background and Issues for Congress 2013).

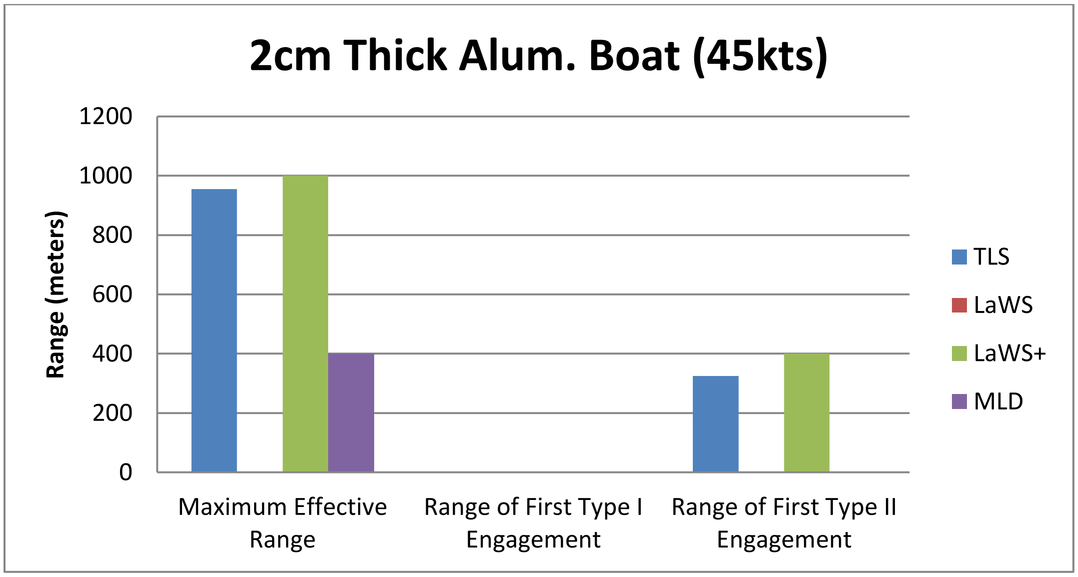


Figure 95. LASERs vs. Aluminum Boat, Clear Day

A second test case was done to additionally validate the LASER model. As opposed to targeting a boat, a LSF was used instead. Figure 31 is reproduced as Figure 96. Again, it should be noted that TLS performs similar to LaWS while MLD has an effective range over a mile. The range for MLD has been advertised as in the miles as opposed to yards (Brisbane Times 2011), and the model supports this claimed range of MLD.

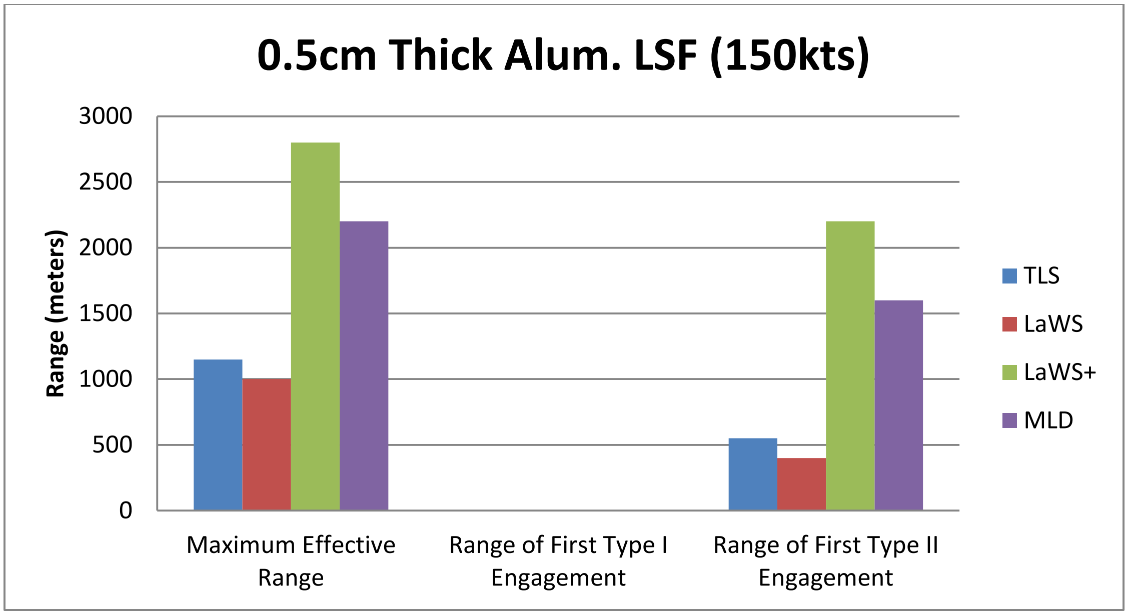


Figure 96. LASERs vs. Aluminum LSF, Clear Day

4. Mission Threat Mapping

Perhaps the most unique aspect of this student project was not attempting to put a DEW on a ship, or even to do it in a four year timespan, but the manner in which the missions were analyzed. GINA provided a very unique tool to combine missions, threats, weapons, and environments. Arguably, the analyses the project team conducted could have been done with Excel using manual inputs to gather atmospheric data from MODTRAN 5 and correlating the data to a successful mission or not. The issue would be adding or changing analysis criteria (for example, someone could determine that the environment does not matter but the color of the operator’s eyes does). This change in excel could prove to be very difficult depending on the level of complexity of the spreadsheet and the amount of documentation on the construction of the model. In GINA, changing an attribute or adding a new factor or set of data is accomplished by adding an additional X-Type for eye color and removing the one for environment. Using GINA, these modifications to are an expansion of the computer environment, but not the manner or means of sharing data and access to data..

As GINA has already been approved for use on DoD’s Secure Internet Protocol Router Network (SIPRNET), transferring the model and inputting classified data could provide more fidelity to the results reported here, (although such results will be the same on the gross level). The portability and tailorability of GINA could provide a unique analysis tool for determining interoperability for future systems, one part of which is the determination of effectiveness when two objects interact. This project demonstrated that changing threats, capabilities, environments, and other factors are readily implemented, thereby eliminating the need for extensive and expensive programming. The GINA interface is both intuitive and easy to use. Further, the GINA model could be modified for a non-DEW use altogether. Arguably, this project’s validation of GINA as a complex modeling tool for determining the feasibility of DEWs is the most significant output of the project.

5. Cost Analysis

Although specific cost data for operational DEW units do not exist, the cost estimation conducted in Chapter 5 provides great insight into comparative cost analyses in both collective as well as independent consideration of costs. Electrical distribution systems have been used for decades and several procurement programs have existed for developing, maintaining, and servicing these distribution systems. Comparing a DEW to such electrical distribution systems was done due to the lack of mature DEW systems. Fundamentally, electrical distribution systems and DEWs have similar complex electrical properties, traits, and attributes. Due to the covariance in each individual piece of data, the 95% confidence interval provides a substantial degree of likelihood for each prototype DEW. For the current embodiments of DEWs, ADS and TLS will cost approximately the same amount, LaWS+ and MLD will cost significantly more, and LaWS will be somewhere in the middle. Scaling the energy/power outputs to accommodate additional missions from the set of 81 potential missions will depend on the concept of operations. Of the two types considered in this report, multiple low power DE beams directed to strike a common point on a target simultaneously will outperform a single beam aimed at the same target point. The cost of multiple lower output DEWs is notably and significantly less than a single higher output DEW. Moreover, the volumetric coverage of defending against swarm- or single-attack is greater for multiple lower output DEWs. And finally, a large number of multiple lower output DEWs is inherently more survivable. If one ship is sunk or otherwise rendered inoperable, the remaining ships will still be functional rendering the fleet still operational just at a degraded capability.

The biggest takeaway from the cost analysis is that two each of TLS and ADS could be installed on a DDG-51 for less than any single unit of the other three systems. This would provide a tremendous added capability to current ships. TLS would be able to augment current kinetic weapons. Either TLS could be used exclusively against unarmored targets like small boats or UAVS or TLS could be used in conjunction with kinetic weapons to possibly reduce the conventional ammunition expended. ADS could be used for those AT/FP missions which currently do not have an adequate nonlethal option. Current tactics of using fire hoses, beanbags, or rubber bullets are not adequate against a determined adversary. ADS would provide a nonlethal option with a significant standoff range of over 200 meters.

B. LASER

Of the three LASER prototypes (TLS, LaWS/LaWS+, and MLD) analyzed for this project, the 10 kW TLS consistently performed as well or better than the other more powerful LASERs. The integration of TLS will be much less disruptive compared to significant modifications required for any of the other systems as the majority of the TLS equipment is in a box to be placed under existing 25mm machine gun mounts as shown in Chapter 5. This would facilitate quick installation as it could be done pier side as opposed to requiring a dry dock. The consistent high performance of TLS (compared to the other LASERs) and significantly lower cost made it the clear winner. If the trend of LaWS, LaWS+, and MLD was followed for TLS, the cost would be around $90 Million as opposed to the $2 Million as estimated.

C. HIGH POWER MICROWAVE (HPM)

At the onset of the project, most of the team though ADS would be useless for the Navy (considering the Navy has not considered it for use onboard ships). Although the integration requirements are similar to MLD, the complexity is similar to a basic radar which can be very inexpensive. The greatest advantage to ADS is the identified gap of a nonlethal standoff weapon. Similar to TLS, the high performance and low cost of ADS is disproportionate compared to the other three options. If the trend of LaWS, LaWS+, and MLD was followed for ADS, the cost would be around $130 Million as opposed to the $7 Million as estimated.

D. CONCEPT OF OPERATIONS (CONOPS)

Some general Concepts of Operation (CONOPS) were generated for the use of DEW. TLS, being similar in effect of a conventional weapon, could easily be used with existing tactics for use of the 25mm machine gun. ADS on the other hand does not have a current conventional analog, but would easily be integrated to force protection tactics with the limited avenues of approach to a ship.

There is one distinct use for the TLS (or similarly low-powered LASER) compared to one of the other higher powered alternatives. As discussed previously, the Hughes' Salvo Equations show that several smaller, less capable vessels are preferred over a few large, powerful ships (Hughes 2000). Current development of weapons for the Navy leans towards the later, a high-tech fleet with large (compared to other fleets) and expensive ships. Putting a LASER on this kind of ship would result in Figure 97, a single ship with a large laser targeting a single threat. This concept is acceptable as long as the ship is not destroyed or incapacitated (by damage or equipment casualty).

Figure 97. Single High-Powered LASER

An alternative concept is shown in Figure 98, several ships with a single (or multiple) low-powered LASERs each. The aggregate power on the target from the multiple LASERs could equal that of the single large laser, but the system is more survivable. In the event one of the ships is destroyed or incapacitated, the remaining ships still offer the same ability, although in a degraded capacity. Arguably, it would be just as complicated developing a targeting system able to put multiple lasers onto the same aim point as it would be to develop the mirror/lens system of a large laser that can focus a single high-power beam.

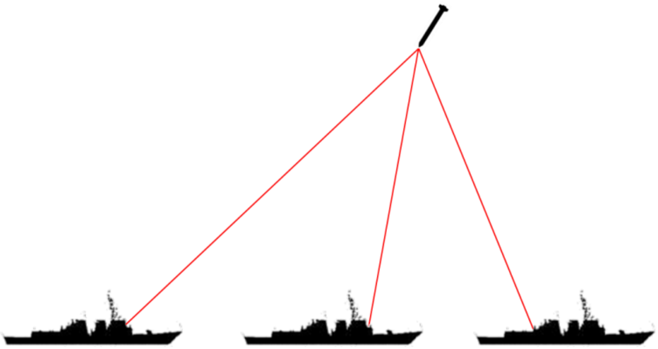


Figure 98. Multiple Low-Powered LASERs

E. FINAL THOUGHTS

Any of the potential prototypes would offer a unique (although limited) capability to the U.S. Navy compared to any other navy. The announcement of installing LaWS on

PONCE for an operational deployment is a step in the direction of incorporating DEW into the fleet as a whole, but there is much work to be done. A significant amount of time and money has been spent pursuing DEW for the military with varied results. Sometimes cutting your losses may be the right answer; however, the project research indicates that this is not one of those times. DE is on the cusp of being an operational weapon and the “game changer” politicians and researchers have been striving for since Townes and Schawlow designed the first LASER in 1957 and Maiman built it in 1960.

VIII. RECOMMENDATIONS

This project used the Systems Engineering Process to examine how mature directed energy technologies can provide mission-essential performance across multiple warfare area domains and mission sub-sets for the U.S. Navy. While we achieved our goals of identifying and characterizing the capability gaps and providing a coherent vision of naval missions that could incorporate DEWs, the project team acknowledged that additional research and analysis could be conducted as a continuation of this project to provide even greater fidelity in the feasibility of 'stacking' TLS modules and comparing it to the scalability of LaWS and MLD, the feasibility of integrating DEW onto ship borne aircraft, applying GINA across mission domains to determine future requirements, expanding GINA to include a cost X-Type, an improved combat model to compare DEWs and conventional weapons, and modeling the anticipated operational availability of a DEW.

Perhaps the most applicable future study would be on the scalability of TLS and comparing TLS against a single 10 kW module of the LaWS or 15kW LRU of the MLD. If TLS is limited by either the inability to add more units like LaWS and MLD, or to increase the number of paths through the medium to increase power, the future potential of TLS is limited. The future capabilities and upgradability is an aspect of the DEW systems which was not considered but is important for the selection of a system. TLS may perform better now, but if LaWS or MLD is easier to upgrade, that could be a key selling point. This study would require significant depth on the three systems, the method in which the beam is created, and the optics of the system.

Although the tasking statement tasked the project team to explore DEW for the Navy, the project team scoped the project to surface ships only. This was done for several reasons detailed in Chapter 1, but there is still the potential for DEW onboard aircraft as shown by the ABL. The C-2 and decommissioned S-3 are the largest aircraft flown from ships, so the integration would likely be easiest on one of those platforms (although the

MV-22 and CH-53 are large and may be other possibilities). Adding a DEW to an aircraft would extend the reach of the ship and be a low cost and precise option of strike warfare. TLS being relatively small would be a likely candidate to integrate to an aircraft, but the power requirements may be an issue. A study on the capabilities of these platforms and the ability to integrate a DEW could potentially benefit from much of what was done with the ABL program, specifically with the optics and fire control systems.

Expanding on the GINA model is another area which should be explored. Our project focused on what the Navy is currently required to do, what current DEWs can do, and how that could integrate. Expanding upon the missions and threats already input into GINA could lead to what future weapon requirements should be to counter these threats. This would require analyzing current and projected missions, threats, and environments. This analysis could help focus future R&D efforts for not only weapon systems, but platforms these systems would integrate with. If a megawatt class SSL was to be put on a ship, that ship would have to be specifically designed for the cooling and power loads required to fire the LASER.

GINA also could be modified to include a cost X-Type. This would allow a variation on the current CAIV analysis. The project team was able to judge the overall performance of a system and then compare that to the cost of a system. Putting cost into GINA would allow the analysis of the cost of a specific mission based on the weapon used. This could give more fidelity to the sustainment costs of each system and a more accurate ‘per round’ comparison to conventional weapons.

The conventional weapon comparison was simplified to distil the engagement equation outputs to values that had cross-domain relevance. An actual combat model validated against contextually significant data should be used to evaluate the conventional weapon performance. Using actual weapon parameters to account for sources of weapon failure, the effects of weather could be captured in a deterministic model at the unclassified level.

The final area for further study is an analysis on the operational availability of potential DEW systems. To truly determine the operational availability, the Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR) for the system needs to be known. Analyzing the MTBF and MTTR of major components would be more useful as it would give insight to which parts are more likely to fail or take a long time to repair. Initially, this analysis can be done with a two-state homogeneous Continuous Time Markov Chain. This analysis still would require some form of failure rate which the project team was unable to acquire. Once the LaWS has completed the deployment on PONCE, MTBF and MTTR data may become available to facilitate such an analysis.

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APPENDIX A. THREAT AND WEAPON MAPPING

Mission Threat Map (From GINA Model DEWAnalysisSEA19B, at p4ie.nps.edu)

Mission ID	Mission Description	Threat DESIG	Threat Name
ATFP 12	Pier Demonstration/Passive Protest Exercise	Person	Running 5 mph
ATFP 15	Nighttime Small Boat Attack at Anchor	FIAC	Fiberglass Boat
ATFP 4	Entry Control Point (ECP)Threat	Person	Running 5 mph
ATFP 8	Pierside Small Boat Attack Exercise	FIAC	Fiberglass Boat
ATFP 9	Terrorist A/C Attack Exercise	Cessna	Cessna 150
ATFP 9	Terrorist A/C Attack Exercise	Iranian UAV	Ghods Ababil Ababil-T
AW 1.1	Provide area defense for a strike group	C-802	Saccade
AW 1.1	Provide area defense for a strike group	AS-11	Kilter
AW 1.1	Provide area defense for a strike group	F-14	Tomcat
AW 1.1	Provide area defense for a strike group	MiG-19	Fulcrum
AW 1.1	Provide area defense for a strike group	Iranian UAV	Ghods Ababil Ababil-T
AW 1.12	Provide air defense for non-combatant evacuations operations	AS-11	Kilter
AW 1.12	Provide air defense for non-combatant evacuations operations	C-802	Saccade
AW 1.13	Provide air defense for naval/joint/ combined TF operations	C-802	Saccade
AW 1.13	Provide air defense for naval/joint/ combined TF operations	F-14	Tomcat
AW 1.13	Provide air defense for naval/joint/ combined TF operations	AS-11	Kilter
AW 1.13	Provide air defense for naval/joint/ combined TF operations	MiG-19	Fulcrum
AW 1.13	Provide air defense for naval/joint/ combined TF operations	Iranian UAV	Ghods Ababil Ababil-T
AW 1.2	Conduct air self-defense using AW Weapons	C-802	Saccade
AW 1.2	Conduct air self-defense using AW Weapons	AS-11	Kilter

AW 1.2	Conduct air self-defense using AW Weapons	Iranian UAV	Ghods Ababil Ababil-T
AW 1.4	Provide area defense for a convoy or underway replenishment group	C-802	Saccade
AW 1.4	Provide area defense for a convoy or underway replenishment group	F-14	Tomcat
AW 1.4	Provide area defense for a convoy or underway replenishment group	Iranian UAV	Ghods Ababil Ababil-T
AW 1.4	Provide area defense for a convoy or underway replenishment group	AS-11	Kilter
AW 1.4	Provide area defense for a convoy or underway replenishment group	MiG-19	Fulcrum
AW 1.5	Provide area defense for amphibious forces in transit and in the amphibious objective area	C-802	Saccade
AW 1.5	Provide area defense for amphibious forces in transit and in the amphibious objective area	F-14	Tomcat
AW 1.5	Provide area defense for amphibious forces in transit and in the amphibious objective area	Iranian UAV	Ghods Ababil Ababil-T
AW 1.5	Provide area defense for amphibious forces in transit and in the amphibious objective area	AS-11	Kilter
AW 1.5	Provide area defense for amphibious forces in transit and in the amphibious objective area	MiG-19	Fulcrum
AW 1.6	Provide area defense for a surface action group	F-14	Tomcat
AW 1.6	Provide area defense for a surface action group	AS-11	Kilter
AW 1.6	Provide area defense for a surface action group	MiG-19	Fulcrum
AW 1.6	Provide area defense for a surface action group	C-802	Saccade
AW 1.6	Provide area defense for a surface action group	Iranian UAV	Ghods Ababil Ababil-T

AW 9.1	Engage medium/high altitude, high-speed airborne threats with AW weapons	F-14	Tomcat
AW 9.1	Engage medium/high altitude, high-speed airborne threats with AW weapons	MiG-19	Fulcrum
AW 9.3	Engage low altitude threats with AW weapons	C-802	Saccade
AW 9.3	Engage low altitude threats with AW weapons	AS-11	Kilter
AW 9.4	Engage low/medium altitude airborne threats with AW weapons	Iranian UAV	Ghods Ababil Ababil-T
AW 9.4	Engage low/medium altitude airborne threats with AW weapons	Cessna	Cessna 150
NCO 19.6	Conduct seizure of noncombatant vessels	Dhow	Dhow
NCO 19.6	Conduct seizure of noncombatant vessels	FIAC	Fiberglass Boat
NCO 19.9	Conduct drug traffic suppression and interdiction operations	FIAC	Fiberglass Boat
NCO 19.9	Conduct drug traffic suppression and interdiction operations	Dhow	Dhow
SUW 1.10	Conduct close–in surface self-defense using crew operated SUW Weapons	PC	Boghammer
SUW 1.10	Conduct close–in surface self-defense using crew operated SUW Weapons	FIAC	Fiberglass Boat
SUW 1.10	Conduct close–in surface self-defense using crew operated SUW Weapons	FAC	Aluminum Boat
SUW 2.3	Engage surface targets with assigned anti-surface sector	PC	Boghammer
SUW 2.3	Engage surface targets with assigned anti-surface sector	FAC	Aluminum Boat

Mission Weapons

Mission ID	Mission Description	Weapon DESIG	Weapon Name
ATFP 12	Pier Demonstration/Passive Protest Exercise	ADS	Active Denial System
ATFP 15	Nighttime Small Boat Attack at Anchor	ADS	Active Denial System

ATFP 15	Nighttime Small Boat Attack at Anchor	LaWS	LASER Weapon System
ATFP 15	Nighttime Small Boat Attack at Anchor	MK 38 Mod 2	25mm Bushmaster
ATFP 15	Nighttime Small Boat Attack at Anchor	MLD	Maritime LASER Demonstration
ATFP 15	Nighttime Small Boat Attack at Anchor	TLS	Tactical LASER System
ATFP 4	Entry Control Point (ECP)Threat	ADS	Active Denial System
ATFP 8	Pierside Small Boat Attack Exercise	LaWS	LASER Weapon System
ATFP 8	Pierside Small Boat Attack Exercise	ADS	Active Denial System
ATFP 8	Pierside Small Boat Attack Exercise	MK 38 Mod 2	25mm Bushmaster
ATFP 8	Pierside Small Boat Attack Exercise	MLD	Maritime LASER Demonstration
ATFP 8	Pierside Small Boat Attack Exercise	TLS	Tactical LASER System
ATFP 9	Terrorist A/C Attack Exercise	LaWS	LASER Weapon System
ATFP 9	Terrorist A/C Attack Exercise	ADS	Active Denial System
ATFP 9	Terrorist A/C Attack Exercise	MK 38 Mod 2	25mm Bushmaster
ATFP 9	Terrorist A/C Attack Exercise	LaWS+	LASER Weapon System Enhanced
ATFP 9	Terrorist A/C Attack Exercise	MK 15	Close-In Weapon System
ATFP 9	Terrorist A/C Attack Exercise	RIM-116	Rolling Airframe Missile
ATFP 9	Terrorist A/C Attack Exercise	MLD	Maritime LASER Demonstration
ATFP 9	Terrorist A/C Attack Exercise	TLS	Tactical LASER System
AW 1.1	Provide area defense for a strike group	LaWS	LASER Weapon System
AW 1.1	Provide area defense for a strike group	LaWS+	LASER Weapon System Enhanced
AW 1.1	Provide area defense for a strike group	MLD	Maritime LASER Demonstration
AW 1.1	Provide area defense for a strike group	RIM-66 MR	SM-2 Block III Medium Range
AW 1.12	Provide air defense for non-combatant evacuations	LaWS	LASER Weapon System

	operations		
AW 1.12	Provide air defense for non-combatant evacuations operations	LaWS+	LASER Weapon System Enhanced
AW 1.12	Provide air defense for non-combatant evacuations operations	MLD	Maritime LASER Demonstration
AW 1.12	Provide air defense for non-combatant evacuations operations	RIM-66 MR	SM-2 Block III Medium Range
AW 1.13	Provide air defense for naval/joint/ combined TF operations	LaWS	LASER Weapon System
AW 1.13	Provide air defense for naval/joint/ combined TF operations	LaWS+	LASER Weapon System Enhanced
AW 1.13	Provide air defense for naval/joint/ combined TF operations	MLD	Maritime LASER Demonstration
AW 1.13	Provide air defense for naval/joint/ combined TF operations	RIM-66 MR	SM-2 Block III Medium Range
AW 1.2	Conduct air self-defense using AW Weapons	LaWS	LASER Weapon System
AW 1.2	Conduct air self-defense using AW Weapons	RIM-116	Rolling Airframe Missile
AW 1.2	Conduct air self-defense using AW Weapons	LaWS+	LASER Weapon System Enhanced
AW 1.2	Conduct air self-defense using AW Weapons	MK 15	Close-In Weapon System
AW 1.2	Conduct air self-defense using AW Weapons	MLD	Maritime LASER Demonstration
AW 1.2	Conduct air self-defense using AW Weapons	TLS	Tactical LASER System
AW 1.4	Provide area defense for a convoy or underway replenishment group	LaWS	LASER Weapon System
AW 1.4	Provide area defense for a convoy or underway replenishment group	LaWS+	LASER Weapon System Enhanced

AW 1.4	Provide area defense for a convoy or underway replenishment group	MLD	Maritime LASER Demonstration
AW 1.4	Provide area defense for a convoy or underway replenishment group	TLS	Tactical LASER System
AW 1.4	Provide area defense for a convoy or underway replenishment group	RIM-66 MR	SM-2 Block III Medium Range
AW 1.5	Provide area defense for amphibious forces in transit and in the amphibious objective area	LaWS	LASER Weapon System
AW 1.5	Provide area defense for amphibious forces in transit and in the amphibious objective area	LaWS+	LASER Weapon System Enhanced
AW 1.5	Provide area defense for amphibious forces in transit and in the amphibious objective area	MLD	Maritime LASER Demonstration
AW 1.5	Provide area defense for amphibious forces in transit and in the amphibious objective area	RIM-66 MR	SM-2 Block III Medium Range
AW 1.6	Provide area defense for a surface action group	LaWS	LASER Weapon System
AW 1.6	Provide area defense for a surface action group	LaWS+	LASER Weapon System Enhanced
AW 1.6	Provide area defense for a surface action group	MLD	Maritime LASER Demonstration
AW 1.6	Provide area defense for a surface action group	TLS	Tactical LASER System
AW 1.6	Provide area defense for a surface action group	RIM-66 MR	SM-2 Block III Medium Range
AW 1.6	Provide area defense for a surface action group	RIM-116	Rolling Airframe Missile
AW 9.1	Engage medium/high altitude, high-speed airborne threats with AW weapons	LaWS	LASER Weapon System

AW 9.1	Engage medium/high altitude, high-speed airborne threats with AW weapons	LaWS+	LASER Weapon System Enhanced
AW 9.1	Engage medium/high altitude, high-speed airborne threats with AW weapons	MLD	Maritime LASER Demonstration
AW 9.1	Engage medium/high altitude, high-speed airborne threats with AW weapons	TLS	Tactical LASER System
AW 9.1	Engage medium/high altitude, high-speed airborne threats with AW weapons	RIM-66 MR	SM-2 Block III Medium Range
AW 9.3	Engage low altitude threats with AW weapons	ADS	Active Denial System
AW 9.3	Engage low altitude threats with AW weapons	LaWS+	LASER Weapon System Enhanced
AW 9.3	Engage low altitude threats with AW weapons	MK 15	Close-In Weapon System
AW 9.3	Engage low altitude threats with AW weapons	MK 54	5 Inch/54 Cal. Deck Gun
AW 9.3	Engage low altitude threats with AW weapons	MLD	Maritime LASER Demonstration
AW 9.3	Engage low altitude threats with AW weapons	TLS	Tactical LASER System
AW 9.3	Engage low altitude threats with AW weapons	RIM-66 MR	SM-2 Block III Medium Range
AW 9.4	Engage low/medium altitude airborne threats with AW weapons	LaWS	LASER Weapon System
AW 9.4	Engage low/medium altitude airborne threats with AW weapons	RIM-116	Rolling Airframe Missile
AW 9.4	Engage low/medium altitude airborne threats with AW weapons	ADS	Active Denial System
AW 9.4	Engage low/medium altitude airborne threats with AW weapons	LaWS+	LASER Weapon System Enhanced
AW 9.4	Engage low/medium altitude airborne threats with AW weapons	MK 15	Close-In Weapon System

AW 9.4	Engage low/medium altitude airborne threats with AW weapons	MLD	Maritime LASER Demonstration
AW 9.4	Engage low/medium altitude airborne threats with AW weapons	MK 54	5 Inch/54 Cal. Deck Gun
AW 9.4	Engage low/medium altitude airborne threats with AW weapons	TLS	Tactical LASER System
AW 9.4	Engage low/medium altitude airborne threats with AW weapons	RIM-66 MR	SM-2 Block III Medium Range
NCO 19.6	Conduct seizure of noncombatant vessels	ADS	Active Denial System
NCO 19.6	Conduct seizure of noncombatant vessels	MK 38 Mod 2	25mm Bushmaster
NCO 19.9	Conduct drug traffic suppression and interdiction operations	ADS	Active Denial System
NCO 19.9	Conduct drug traffic suppression and interdiction operations	MK 54	5 Inch/54 Cal. Deck Gun
NCO 19.9	Conduct drug traffic suppression and interdiction operations	MK 38 Mod 2	25mm Bushmaster
NCO 19.9	Conduct drug traffic suppression and interdiction operations	LaWS	LASER Weapon System
NCO 19.9	Conduct drug traffic suppression and interdiction operations	LaWS+	LASER Weapon System Enhanced
NCO 19.9	Conduct drug traffic suppression and interdiction operations	MLD	Maritime LASER Demonstration
NCO 19.9	Conduct drug traffic suppression and interdiction operations	TLS	Tactical LASER System
SUW 1.10	Conduct close–in surface self-defense using crew operated SUW Weapons	ADS	Active Denial System
SUW 1.10	Conduct close–in surface self-defense using crew operated	MK 38 Mod 2	25mm Bushmaster

	SUW Weapons		
SUW 1.10	Conduct close–in surface self-defense using crew operated SUW Weapons	MK 15	Close-In Weapon System
SUW 2.3	Engage surface targets with assigned anti-surface sector	LaWS	LASER Weapon System
SUW 2.3	Engage surface targets with assigned anti-surface sector	MK 38 Mod 2	25mm Bushmaster
SUW 2.3	Engage surface targets with assigned anti-surface sector	MK 54	5 Inch/54 Cal. Deck Gun
SUW 2.3	Engage surface targets with assigned anti-surface sector	LaWS+	LASER Weapon System Enhanced
SUW 2.3	Engage surface targets with assigned anti-surface sector	MLD	Maritime LASER Demonstration
SUW 2.3	Engage surface targets with assigned anti-surface sector	TLS	Tactical LASER System
SUW 2.3	Engage surface targets with assigned anti-surface sector	RIM-66 MR	SM-2 Block III Medium Range

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APPENDIX B. GLOBAL INFORMATION NETWORK ARCITECTURE (GINA) CUSTOM CONTENT MANAGER CODE

```
using System.Collections.Generic;
using System.Data;
using Xslent.Base;
using Xslent.Common;
using Xslent.ContentManagers.Elements;
using Xslent.ContentServers;
using Xslent.DssComponents.ContentProxies;
using Xslent.Filters;
using Xslent.Platform;
using System.Diagnostics;
using ModTran5;
using System;

namespace Xslent.ContentManagers
{
    /// <summary>
    /// Provides content manager data services that aggregates data from multiple
types.
    /// </summary>
    class DEWContentManager :
        ContentManagerBase
    {

        private IClient r_client;

        private const string m_modtran_call = “C:\\Program Files\\Spectral
Sciences, Inc\\MODTRAN(R)\\5.2.2\\modtran.bat”;
        private const string m_modtran_input = “C:\\Program Files\\Spectral
Sciences, Inc\\MODTRAN(R)\\5.2.2\\NavyMaritime.tp5”;
        private const string m_modtran_output = “C:\\Program Files\\Spectral
Sciences, Inc\\MODTRAN(R)\\5.2.2\\NavyMaritime.tp6”;

        private object m_lock_object = new object();

        /// <summary>
        /// Initializes a new instance of an AggregateContentManager class.
        /// </summary>
        /// <param name=“p_control_handler”>Provides data and control factory
services.</param>
        /// <param name=“p_xtype_spec”>Specification of XType.</param>
        /// <param name=“p_client”>Provides user access services.</param>
        public DEWContentManager(IContentHandler p_content_handler, IContent
p_xtype_spec, IClient p_client)
            : base(p_content_handler, p_xtype_spec, p_client)
        {
            r_client = p_client;
        }
```

```
        /// <summary>
        /// Cause the content to be pushed all the way to the ContentServer.
        /// </summary>
        /// <param name="p_content">Reference to content.</param>
        public override void updateContent(IContent p_content)
        {
            try
            {
                IContentManagerClient l_content_manager_client =
ProtectedClientFactory.getContentManagerClient(p_content);
                this.protectedMapCollectFilter(l_content_manager_client);
                if (l_content_manager_client.getRowCount() == 0)
                {
                    return;
                }
                foreach (IContent l_resource in p_content)
                {
                    IContentManagerClient l_resource_content_manager_client =
ProtectedClientFactory.getContentManagerClient(l_resource);
                    l_resource_content_manager_client.save();
                    if (l_resource_content_manager_client.isNew())
                    {
                        lock (m_lock_object)
                        {
                            double l_slant_range = this.callModtran(l_resource);
                            this.callAnalyzer(l_resource, l_slant_range);
                        }

                    }
                }

r_content_handler.updateContent(l_content_manager_client.getContentHolder());
       //Update after isNew() checked
            }
            catch (Exception l_exception)
            {
                throw new XslentException(l_exception, "Error processing
engagement");
            }
        }

        private void callAnalyzer(IContent pContent, double p_slant_range)
        {
            try
            {
                /*
                If Engagement.Weapon.WeaponType = HEL Then use the LASER portion
of DEWAnalyzer
                If Enagement.Weapon.WeaponType = HPM Then use the Microwave
portion of DEWAnalyzer
                If Engagement.Weapon.Weapon.Type = CONV Then use
ConventionalWeaponAnalyzer
```

```
                */

                // Get the related threat instance
                Guid threadGuid = UtilityContent.getGuid(pContent, “ThreatGUID”);
                IFilter l_filter = FilterFactory.newFilter(“Threat,” “ThreatGUID,”
threadGuid.ToString());
                IContent                         l_threat                         =
r_content_handler.collectContent(r_client.getDssId(),      “Threat,”      l_filter,
r_client);

                // Get the related weapon instance
                Guid weaponGuid = UtilityContent.getGuid(pContent, “WeaponGUID”);
                l_filter    =    FilterFactory.newFilter(“Weapon,”    “WeaponGUID,”
weaponGuid.ToString());
                IContent                         l_weapon                         =
r_content_handler.collectContent(r_client.getDssId(),      “Weapon,”      l_filter,
r_client);//r_content_handler.collectContent(r_client.getDssId(),        l_filter,
r_client);

                string    l_weapon_type    =    UtilityContent.getString(pContent,
“WeaponType”);

                double     tdAltitude     =     UtilityContent.getDouble(pContent,
“ThreatDetectionAltitude_m”);


                if (“HEL.”Equals(l_weapon_type))
                {
                    // Then use the LASER portion of DEWAnalyzer
                    DEWAnalyzerVS2010.DEWAnalysisSEA19B    dewAnalyzer    =    new
DEWAnalyzerVS2010.DEWAnalysisSEA19B();


                    dewAnalyzer.VitalAreaRadius                                   =
UtilityContent.getDouble(pContent, “VitalAreaRadius_m”);

                    // Set the inputs
                    dewAnalyzer.DetectionAlt  =  UtilityContent.getDouble(pContent,
“ThreatDetectionAltitude_m”);
                    dewAnalyzer.DetectionRange                                    =
UtilityContent.getDouble(pContent, “ThreatDetectionGroundRange_m”);
                    dewAnalyzer.ThreatSpeed   =  UtilityContent.getDouble(l_threat,
“ThreatSpeed_mPERs”);
                    dewAnalyzer.Transmissivity                                    =
UtilityContent.getDouble(pContent, “AtmosphericAttenuation”);

                    // Weapon inputs
                    dewAnalyzer.LSWavelength  =  UtilityContent.getDouble(l_weapon,
“DEWWavelength_m”);
                    dewAnalyzer.LSLensDiameter                                    =
UtilityContent.getDouble(l_weapon, “LaserAppertureDiamater_m”);
                    dewAnalyzer.LSGuassianBeamMFactor                             =
UtilityContent.getDouble(l_weapon, “LaserGaussianBeamMatchingFactor”);
```

```
                    dewAnalyzer.LSPower     =     UtilityContent.getDouble(l_weapon,
“DEWPower”);

                    // Engagement inputs
                    dewAnalyzer.MeltingTemp   =   UtilityContent.getDouble(pContent,
“ArmorMeltingPoint_K”);
                    dewAnalyzer.Density     =     UtilityContent.getDouble(pContent,
“ArmorDensity_gPERcm3”);
                    dewAnalyzer.SpecificHeat   =  UtilityContent.getDouble(pContent,
“ArmorSpecificHeatCapacity_JPERgK”);
                    dewAnalyzer.HeatOfFusion   =  UtilityContent.getDouble(pContent,
“ArmorLatentHeatOfFusion_JPERg”);
                    dewAnalyzer.Thickness    =    UtilityContent.getDouble(pContent,
“ArmorThickness_cm”);
                    dewAnalyzer.Relectance    =   UtilityContent.getDouble(pContent,
“ArmorReflectivity”);

                    // Run that analyzer
                    dewAnalyzer.EvaluateLaserPerformance();

                    // Set the results in the engagement content
                    pContent.setField(“NumberOfHardKillsPossible,”
dewAnalyzer.NumberHKPossible);
                    pContent.setField(“NumberOfSoftKillsPossible,”
dewAnalyzer.NumberSKPossible);
                    pContent.setField(“RangeOfFirstHardKill,”
dewAnalyzer.RangeFirstHK);
                    pContent.setField(“RangeOfFirstSoftKill,”
dewAnalyzer.RangeFirstSK);
                    pContent.setField(“DEWMaximumEffectiveRange,”
dewAnalyzer.MaxEffectiveRange);
                    pContent.setField(“DEWMaximumTacticalRange,”
dewAnalyzer.RayleighRange);


                }
                else if (“HPM.”Equals(l_weapon_type))
                {
                    //Then use the Microwave portion of DEWAnalyzer
                    DEWAnalyzerVS2010.DEWAnalysisSEA19B    dewAnalyzer    =    new
DEWAnalyzerVS2010.DEWAnalysisSEA19B();

                    dewAnalyzer.VitalAreaRadius                                =
UtilityContent.getDouble(pContent, “VitalAreaRadius_m”);

                    if (dewAnalyzer.VitalAreaRadius < p_slant_range)
                    {
                        throw  new  XslentException(“Threat  Detection  Ground  Range
cannot be less than Mission Vital Area Radius”);
                    }

                    // Weapon inputs
```

```
dewAnalyzer.setMicrowaveData(UtilityContent.getDouble(l_weapon,
“DEWWavelength_m”),
                        UtilityContent.getDouble(l_weapon, “DEWPower”),
                        UtilityContent.getDouble(l_weapon,
“MicrowaveAntennaArea_m2”),
                        UtilityContent.getDouble(l_weapon,
“MicrowaveAntennaConstantOfProprtionality”),
                        UtilityContent.getDouble(l_weapon,
“MicrowaveAntennaEfficiency”));

                    // Set the inputs

dewAnalyzer.setMWScenarioData(UtilityContent.getDouble(pContent,
“AtmosphericAttenuation”),
                        UtilityContent.getDouble(pContent,
“ThreatDetectionGroundRange_m”),
                        UtilityContent.getDouble(pContent,
“ThreatDetectionAltitude_m”),
                        UtilityContent.getDouble(l_threat, “ThreatSpeed_mPERs”));

                    // Run the analyzer
                    dewAnalyzer.EvaluateMicrowaveKillEffectiveness();

                    // Set the results in the engagement content
                    pContent.setField(“NumberOfHardKillsPossible,”
dewAnalyzer.MWHKP);
                    pContent.setField(“NumberOfSoftKillsPossible,”
dewAnalyzer.MWSKP);
                    pContent.setField(“RangeOfFirstHardKill,”
dewAnalyzer.MWRangeFirstHardKill);
                    pContent.setField(“RangeOfFirstSoftKill,”
dewAnalyzer.MWRangeFirstSoftKill);

                }
                else if (“CONV.”Equals(l_weapon_type))
                {
                    //Then use ConventionalWeaponAnalyzer
                    DEWAnalyzerVS2010.ConventionalWeaponAnalyzerSEA19B  analyzer  =
new DEWAnalyzerVS2010.ConventionalWeaponAnalyzerSEA19B();

                    // Set the inputs
                    analyzer.ThreatDetectionAltitude                              =
UtilityContent.getDouble(pContent, “ThreatDetectionAltitude_m”);
                    analyzer.ThreatDetectionRange                                 =
UtilityContent.getDouble(pContent, “ThreatDetectionGroundRange_m”);
                    analyzer.ThreatSpeed    =    UtilityContent.getDouble(l_threat,
“ThreatSpeed_mPERs”);

                    analyzer.WeaponActivationTime                                 =
UtilityContent.getDouble(l_weapon, “WeaponActivationTime_sec”);
                    analyzer.WeaponMaxEffectiveRange                              =
UtilityContent.getDouble(l_weapon, “WeaponMaximumEffectiveRange_m”);
```

```
                    analyzer.WeaponMinEffectiveRange                              =
UtilityContent.getDouble(l_weapon, "WeaponMinimumEffectiveRange_m");
                    analyzer.WeaponSpeed    =    UtilityContent.getDouble(l_weapon,
"WeaponSpeed_mPERs");

                    analyzer.VitalAreaRadius  =  UtilityContent.getDouble(pContent,
"VitalAreaRadius_m");

                    // Analyzer does its calcs
                    analyzer.CalculateNumberOfHardKillsPossible();

                    // Set the results in the engagement content
                    pContent.setField("NumberOfHardKillsPossible,"
analyzer.NumberHardKillsPossible);
                    pContent.setField("NumberOfSoftKillsPossible,"
analyzer.NumberSoftKillsPossible);
                    pContent.setField("RangeOfFirstHardKill,"
analyzer.RangeOfFirstHardKill);
                    pContent.setField("RangeOfFirstSoftKill,"
analyzer.RangeOfFirstSoftKill);

                }
                else
                {
                    // Throw error
                }
            }
            catch (Exception ex)
            {
                throw   new   XslentException(ex,   "Error   processing   call   to
analylzer");
            }

        }

        private double callModtran(IContent pContent)
        {
            double l_slantrange = 0.0;
            string      l_weapon_type      =      UtilityContent.getString(pContent,
"WeaponType");
            try
            {
                ModTran5.ModTran5   mt5   =   new   ModTran5.ModTran5(m_modtran_input,
m_modtran_call, m_modtran_output);
                m_diagnostics.debug("Setting up modtran input values");
                double l_wavelength = 0.0;
                if ("HEL."Equals(l_weapon_type))
                {
                    l_wavelength   =   Math.Round(UtilityContent.getDouble(pContent,
"DEWWavelength_m") * 1000000, 4);
                    //LASER wavelength must be specified in micrometers
                    m_diagnostics.debug("Laser   calculated   wave   length:   '{0},'"
l_wavelength);
```

```
        }
        else if (“HPM.”Equals(l_weapon_type))
        {
          l_wavelength = Math.Round((1) /
(UtilityContent.getDouble(pContent, “DEWWavelength_m”) * 100), 4);
          m_diagnostics.debug(“Microwave calculated wave length: ‘{0},’”
l_wavelength);
          //l_wavelength = 1/(UtilityContent.getDouble(pContent,
“DEWWavelength_m”) * 100);
          //Microwave wavelengths must be specified as wavenumbers in
units 1/cm
        }

        string l_rainrate = UtilityContent.getString(pContent,
“EnvironmentRainRate_mmPERhr”);
        m_diagnostics.debug(“Rainrate from engagement: ‘{0},’”
l_rainrate);
        double l_bandwidth = 0.05;// * 0.5;
        m_diagnostics.debug(“Bandwidth (hardcoded): ‘{0},’” l_bandwidth);

        double l_threat_altitude =
Math.Round(UtilityContent.getDouble(pContent, “ThreatDetectionAltitude_m”) / 1000,
4);
        m_diagnostics.debug(“Threat detection altitude from engagement:
‘{0},’” l_threat_altitude);

        double l_threat_range = UtilityContent.getDouble(pContent,
“ThreatDetectionGroundRange_m”) / 1000;
        m_diagnostics.debug(“Threat detection range from engagement:
‘{0},’” l_threat_range);
        //All ranges and altitudes in MODTRAN must be specified as
kilometers

        l_slantrange = Math.Round(Math.Sqrt(Math.Pow(l_threat_range, 2) +
Math.Pow(l_threat_altitude, 2)), 4);
        m_diagnostics.debug(“Calculated slant range: ‘{0},’”
l_slantrange);

        pContent.setField(“InitialSlantRangeToThreat_m,” l_slantrange);

        string V1 = Math.Round((l_wavelength - l_bandwidth),
4).ToString();
        m_diagnostics.debug(“Calculated V1: ‘{0},’” V1);

        string V2 = Math.Round((l_wavelength + l_bandwidth),
4).ToString();
        m_diagnostics.debug(“Calculated V2: ‘{0},’” V2);

        m_diagnostics.debug(“Calling SetParam”);
        mt5.SetParam(l_rainrate, “0,” l_threat_altitude.ToString(),
l_slantrange.ToString(), V1, V2, l_weapon_type);
```

```
                // Don’t run modtran for conventional weapons
                if (“HEL.”Equals(l_weapon_type) || “HPM.”Equals(l_weapon_type))
                {
                    m_diagnostics.debug(“Calling GenerateInput”);
                    mt5.GenerateInput();

                    m_diagnostics.debug(“Calling RunExe”);
                    mt5.RunExe();

                    m_diagnostics.debug(“Calling ReadOutput”);
                    string l_attenuation = mt5.ReadOutput();

                    m_diagnostics.debug(“Returned       attenuation:       ‘{0},’”
l_attenuation);

                    if (null == l_attenuation || l_attenuation.Length == 0)
                    {
                        m_diagnostics.debug(“WARNING!!!  Returned  attenuation  has
no value!  Setting it to 1”);
                        l_attenuation = “1”;
                    }

                    pContent.setField(“AtmosphericAttenuation,” l_attenuation);
                }

            }
            catch (Exception ex)
            {
                throw new XslentException(ex, “Error processing call to modtran”);
            }

            return l_slantrange;
        }
    }

       }
```

APPENDIX C. GLOBAL INFORMATION NETWORK ARCITECTURE (GINA) X-TYPES, VECTORS, AND FORMS

Element	**Source X-Type**
Attenuation	AtmopshericAttenuation
AttenuationGUID	AtmopshericAttenuation
Environment	AtmopshericAttenuation
H1PlatformHeight	AtmopshericAttenuation
H2ThreatDetectAlt	AtmopshericAttenuation
SlantRangeToThreat	AtmopshericAttenuation
Wavelength	AtmopshericAttenuation
AtmosphericAttenuation	AtmosphericAttenuation
Attenuation	AtmosphericAttenuation
AttenuationGUID	AtmosphericAttenuation
H1PlatformHeight	AtmosphericAttenuation
H2ThreatDetectAlt	AtmosphericAttenuation
MetersToKilometers	AtmosphericAttenuation
MetersToMicrons	AtmosphericAttenuation
SlantRangeToThreat	AtmosphericAttenuation
Wavelength	AtmosphericAttenuation
Description	DEWEnumeration
DEWEnumeration	DEWEnumeration
Enumeration	DEWEnumeration
EnumerationGUID	DEWEnumeration
EnumerationType	DEWEnumeration
ArmorDensity_gPERcm3	Engagement
ArmorLatentHeatOfFusion_JPERg	Engagement
ArmorMassPerArea	Engagement
ArmorMeltingPoint_K	Engagement
ArmorReflectivity	Engagement
ArmorSpecificHeatCapacity_JPERgK	Engagement

ArmorThickness_cm	Engagement
AtmosphericAttenuation	Engagement
CelciusToKelvinConstant	Engagement
Constant_1	Engagement
DEWMaximumEffectiveRange	Engagement
DEWMaximumTacticalRange	Engagement
DEWPower	Engagement
DEWWavelength_m	Engagement
EnergyPerMassToMelt	Engagement
Engagement	Engagement
EngagementGUID	Engagement
EnvironmentDescription	Engagement
EnvironmentGUID	Engagement
EnvironmentModel	Engagement
EnvironmentRainRate_mmPERhr	Engagement
InitialSlantRangeToThreat_m	Engagement
LaserAppertureDiamater_m	Engagement
LaserGaussianBeamMatchingFactor	Engagement
MeltingAmbientTDiff	Engagement
MicrowaveAntennaArea_m2	Engagement
MicrowaveAntennaConstantOfProprtionality	Engagement
MicrowaveAntennaEfficiency	Engagement
Mission	Engagement
MissionGUID	Engagement
MissionID	Engagement
NumberOfHardKillsPossible	Engagement
NumberOfSoftKillsPossible	Engagement
Platform	Engagement
PlatformHeight_m	Engagement
RangeOfFirstHardKill	Engagement
RangeOfFirstSoftKill	Engagement
SoftKillPercentageConstant	Engagement

TempuratureAtMSL_Kelvin	Engagement
ThreaSpeed_mPERs	Engagement
Threat	Engagement
ThreatAbsorbtion	Engagement
ThreatDesignator	Engagement
ThreatDetectionAltitude_m	Engagement
ThreatDetectionGroundRange_m	Engagement
ThreatGUID	Engagement
ThreatThresholdFluenceForHardKill_jPERm2	Engagement
ThreatThresholdFluenceForSoftKill_jPERm2	Engagement
ThreatThresholdFluenceNoReflectivity	Engagement
TotalEnergyPerMassForDamage	Engagement
VitalAreaRadius_m	Engagement
WarfareAreaName	Engagement
Weapon	Engagement
WeaponDesignator	Engagement
WeaponGUID	Engagement
WeaponMaximumEffectiveRange_m	Engagement
WeaponMinimumEffectiveRange_m	Engagement
WeaponSpeed_mPERs	Engagement
WeaponType	Engagement
AtmospherName	Environment
CelciusToKelvinConversionFactor	Environment
Environment	Environment
EnvironmentDescription	Environment
EnvironmentGUID	Environment
ModtranModel	Environment
RainRate_mmPERhr	Environment
SurfaceType	Environment
TempuratureAtMSL_celcius	Environment
TempuratureAtMSL_Kelvin	Environment
Engagement	Mission

Mission	Mission
MissionDescription	Mission
MissionGUID	Mission
MissionID	Mission
MissionThreatsMission	Mission
MissionToThreats	Mission
MissionWeapons	Mission
MissionWeaponsMission	Mission
Threat	Mission
VitalAreaRadius_m	Mission
WarfareAreaGUID	Mission
Weapon	Mission
Mission	MissionThreats
MissionGUID	MissionThreats
MissionThreats	MissionThreats
MissionThreatsGUID	MissionThreats
Threat	MissionThreats
ThreatDesignator	MissionThreats
ThreatGUID	MissionThreats
Mission	MissionWeapons
MissionGUID	MissionWeapons
MissionWeapons	MissionWeapons
MissionWeaponsGUID	MissionWeapons
Weapon	MissionWeapons
WeaponDesignator	MissionWeapons
WeaponGUID	MissionWeapons
AmorReflectivity_Percent	Threat
ArmorDensity_gPERcm3	Threat
ArmorEMAbsorbtion_Percent	Threat
ArmorHeatOfVaporization	Threat
ArmorLatentHeatOfFusion_JPERg	Threat
ArmorMass_kg	Threat

ArmorMeltingPoint_K	Threat
ArmorSpecificHeatCapacity_JPERgK	Threat
ArmorThermalConductivity	Threat
ArmorThermalCouplingCoefficient	Threat
ArmorThickness_cm	Threat
ArmorVaporizationTempurature_K	Threat
Constant_1	Threat
HeadOnCrossSectionalArea_m2	Threat
MissionThreats	Threat
MissionToThreats	Threat
SideCrossSectionalArea_m2	Threat
Threat	Threat
ThreatArmorMaterialType	Threat
ThreatCoefficientOfDrag	Threat
ThreatDesignator	Threat
ThreatExplosiveMass_kg	Threat
ThreatExplosiveType	Threat
ThreatGUID	Threat
ThreatInitialTempurature_K	Threat
ThreatMaximumOverpressureSustainable_ATM	Threat
ThreatMissions	Threat
ThreatName	Threat
ThreatSpeed_mPERs	Threat
ThreatThresholdFluenceRequiredForHardKill	Threat
ThreatThresholdFluenceRequiredForSoftKill	Threat
ThreatType	Threat
Mission	WarfareArea
WarfareArea	WarfareArea
WarfareAreaGUID	WarfareArea
WarfareAreaName	WarfareArea
DEWContinuousWaveOnTimeBeforeRecharge_s	Weapon
DEWPower	Weapon

DEWRechargeTime_s	Weapon
DEWWavelength_m	Weapon
LaserAppertureDiamater_m	Weapon
LaserGaussianBeamMatchingFactor	Weapon
LaserJitter_mRadPERsecond	Weapon
MicrowaveAntennaArea_m2	Weapon
MicrowaveAntennaConstantOfProprtionality	Weapon
MicrowaveAntennaEfficiency	Weapon
MicrowaveAntennaGain	Weapon
MicrowaveBeamDivergence_rad	Weapon
MicrowaveBeamWidth_3dB_cm	Weapon
NumberOfMissilesOnboard	Weapon
PenetratorLength_cm	Weapon
PenetratorMass_g	Weapon
PenetratorMaterial	Weapon
PenetratorMaterialDensity_gPERcm3	Weapon
PlatformGUID	Weapon
RateOfFire_PerMin	Weapon
TotalEnergyPerCharge_kw	Weapon
Weapon	Weapon
WeaponActivationTime_sec	Weapon
WeaponCoefficientOfDrag	Weapon
WeaponCrossSectionalArea_m2	Weapon
WeaponDesignator	Weapon
WeaponExplosiveMass_kg	Weapon
WeaponExplosiveType	Weapon
WeaponGUID	Weapon
WeaponMaximumEffectiveRange_m	Weapon
WeaponMinimumEffectiveRange_m	Weapon
WeaponMissions	Weapon
WeaponName	Weapon
WeaponSpeed_mPERs	Weapon

WeaponType	Weapon

SourceXType	**Description**	**Vector**	**Vector1**	**Vector2**	**VectorClass**
AtmosphericAttenuation	Points from AtmosphericAttenation back to itself	AtmosphericAttenuation			Xslent.ContentManagers.Elements.VCollection, Xslent.Dss
Engagement		EngagementWeaponQuery			Xslent.ContentManagers.Elements.VCollection, Xslent.Dss
Engagement		MissionEngagement			Xslent.ContentManagers.Elements.VCollection, Xslent.Dss
Engagement		PlatformToEngagement	Weapon	WeaponEngagement	Xslent.ContentManagers.Elements.VDerivation, Xslent.Dss

Engagement		ThreatEngagement			Xslent.ContentManagers.Elements.VCollection, Xslent.Dss
Engagement		WarfareAreaToEngagement	WarfareAreaMission	MissionEngagement	Xslent.ContentManagers.Elements.VDerivation, Xslent.Dss
Engagement		WeaponEngagement			Xslent.ContentManagers.Elements.VCollection, Xslent.Dss
Engagement	Points back to Engagement.	Engagement			Xslent.ContentManagers.Elements.VCollection, Xslent.Dss
Environment	Points back to Environment	Environment			Xslent.ContentManagers.Elements.VCollection, Xslent.Dss

Mission		ThreatToMission	Mission Threats	Mission	Xslent.ContentManagers.Elements.VDerivation, Xslent.Dss
Mission		WarfareArea Mission			Xslent.ContentManagers.Elements.VCollection, Xslent.Dss
Mission	Points from Mission back to itself.	Mission			Xslent.ContentManagers.Elements.VCollection, Xslent.Dss
MissionThreats		Mission Threats Mission			Xslent.ContentManagers.Elements.VCollection, Xslent.Dss
MissionThreats		Mission Threats Threat			Xslent.ContentManagers.Elements.VCollection, Xslent.Dss

MissionThreats	Points back to MissionThreats	Mission Threats			Xslent.ContentManagers.Elements.VCollection, Xslent.Dss
MissionWeapons		Mission WeaponsMission			Xslent.ContentManagers.Elements.VCollection, Xslent.Dss
MissionWeapons		Mission WeaponsWeapon			Xslent.ContentManagers.Elements.VCollection, Xslent.Dss
MissionWeapons	Points back to MissionWeapons	Mission Weapons			Xslent.ContentManagers.Elements.VCollection, Xslent.Dss
Threat		Mission ToThreats	Mission Threats Mission	Threat	Xslent.ContentManagers.Elements.VDerivation, Xslent.Dss

Threat		ThreatForEngagement			Xslent.ContentManagers.Elements.VCollection, Xslent.Dss
Threat	Points back to Threat from itself.	Threat			Xslent.ContentManagers.Elements.VCollection, Xslent.Dss
WarfareArea		EngagementToWarfareArea	Mission	Warfare Area	Xslent.ContentManagers.Elements.VDerivation, Xslent.Dss
WarfareArea	Points from WarfareArea back to itself.	WarfareArea			Xslent.ContentManagers.Elements.VCollection, Xslent.Dss
Weapon		MissionToWeapon	MissionWeapons	Weapon	Xslent.ContentManagers.Elements.VDerivation, Xslent.Dss

Weapon		WeaponQuery			Xslent.ContentManagers.Elements.VCollection, Xslent.Dss
Weapon	Points from Weapon back to itself.	Weapon			Xslent.ContentManagers.Elements.VCollection, Xslent.Dss

APPENDIX D. VISIUAL BASIC (VB) .NET CODE

Note: originally, a Type I Engagement was called “Hard Kill” and a Type II Engagement was called “Soft Kill.” The original terminology was changed due to confusion, but remains in the code.

```
Imports System.Math

Public Class DEWAnalysisSEA19B
    ‘Thesis Advisor: Prof. Gary O. Langford, Naval Postgraduate School, Systems
Engineering Department
    ‘Contact: golangfo@nps.edu

    ‘Software Author: LT Daniel P. Ciullo (USN)
    ‘Contact: dan.ciullo@gmail.com

    ‘LASER Analysis Code

    ‘Laser Weapon Variables
    Public LSWavelength As Double
    Public LSLensDiameter As Double
    Public LSGuassianBeamMFactor As Double
    Public LSPower As Double

    ‘Laser Calculated Variables
    Public Waist As Double
    Public Divergence As Double
    Public HalfAngle As Double
    Public RayleighRange As Double
    Public MaxEffectiveRange As Double
    Private PeakIntensityAtRange As Double
    Private AvgIntensityAtRange As Double
    Public TotalIntensityOnThreat As Double


    ‘Threat Target Variables
    Public MeltingTemp As Double
    Public Density As Double
    Public SpecificHeat As Double
    Public HeatOfFusion As Double
    Public Thickness As Double
    Public Relectance As Double
    Public DetectionRange As Double
    Public DetectionAlt As Double
    Public ThreatSpeed As Double


    ‘Threat Calculated Variables
    Public FluenceForHardKill As Double
```

```
    Public FluenceForSoftKill As Double
    Public LSHardKillsPossible As Double
    Public LSSoftKillsPossible As Double
    Public ThreatSlantRange As Double

    ‘Scenario Variables
    Public Transmissivity As Double
    Public AmbientTemp As Double
    Public Attenuation As Double

    ‘Scenarior Calculated Variables
    Public NumberHKPossible As Double
    Public NumberSKPossible As Double
    Public VitalAreaRadius As Double
    Public RangeFirstHK As Double
    Public RangeFirstSK As Double

    ‘For GINA to run the MODTRAN 5 software
    Public Function CalculateSlantRange(GroundRange As Double, Altitude As Double)
        Return Sqrt(Pow(GroundRange, 2) + Pow(Altitude, 2))
    End Function

    ‘Equation 3.37 from Combat Systems Vol. 2, Dr. Robert C. Harney
    Private Function CalculateRayleighRange() As Double
        Return (PI * Pow(LSLensDiameter, 2.0)) / (LSGuassianBeamMFactor *
LSWavelength)
    End Function

    ‘Combat Systems Volume 2, equation 3.37, Dr. Robert C. Harney
    Private Function CalculateBeamWaist() As Double
        Return LSLensDiameter / Sqrt(LSGuassianBeamMFactor)
    End Function

    ‘Equation G.69 from Combat Systems Appendix G, Dr. Robert C. Harney.
    ‘In this version, the full angle diverence is calculated differently using the
M-squared beam quality factor.
    Private Function CalculateHalfAngle() As Double
        Return LSWavelength / (PI * Waist)
    End Function

    ‘Combat Systems Volume 6, equation M.6, Dr. Robert C. Harney
    Private Function CalculateDivergence() As Double
        Return Sqrt(2) * HalfAngle
    End Function

    ‘Converts the total transmittance over the detection range and allows it to be
considered at each point of integration as the threat moves inbound
    Private Function CalculateThreatSlantRange() As Double
        Return Pow(Pow(DetectionAlt, 2.0) + Pow(DetectionRange, 2.0), 0.5)
    End Function

    Private Sub ConvertTransmittanceToAttenuation()
        Attenuation = -1 * (Math.Log(Transmissivity) / (ThreatSlantRange / 1000))
```

```
    End Sub

    ‘Equation M.5 from Combat Systems Appendix M, Dr. Robert C. Harney
    Private Function CalculatePeakIntensityAtRange(ByVal Range As Double) As
Double
        Return (4.0 * LSPower * Pow(Math.E, -1 * Attenuation * (Range / 1000))) /
(PI * (Pow(Waist, 2.0) + Pow(Range, 2.0) * Pow(Divergence, 2.0)))
    End Function

    ‘Equation 17.8 from Combat Systems Vol. 3, Dr. Robert C. Harney
    Public Function CalculateFluenceForHardKill() As Double
        Return Density * Thickness * (SpecificHeat * (MeltingTemp - AmbientTemp) +
HeatOfFusion) / (1 - Relectance)
    End Function

    ‘Prof. Gary O. Langford, NPS SE Department, LASER Weapon SME, based on
empirical data. For CO2 LASERs ONLY use 20% reduction.
    ‘Contact: golangfo@nps.edu
    Public Function CalculateFluenceForSoftKill() As Double
        Return FluenceForHardKill / 6
    End Function

    Public Sub EvaluateLaserPerformance()
        ThreatSlantRange = CalculateThreatSlantRange()
        ConvertTransmittanceToAttenuation()  ‘This allows a more accurate
integration of Intensity by considering attenuation at each point of integration
        RayleighRange = CalculateRayleighRange()
        Waist = CalculateBeamWaist()
        HalfAngle = CalculateHalfAngle()
        Divergence = CalculateDivergence()
        FluenceForHardKill = CalculateFluenceForHardKill()
        FluenceForSoftKill = CalculateFluenceForSoftKill()

        RangeFirstHK = 0
        RangeFirstSK = 0
        MaxEffectiveRange = 0


        Dim CRange As Double
        CRange = ThreatSlantRange

        Dim Time As Double = 0

        Do While CRange > VitalAreaRadius

            PeakIntensityAtRange = 0.0

            PeakIntensityAtRange = CalculatePeakIntensityAtRange(CRange)

            ‘Total Average Intensity on Threat: Average computed using a conical
intensity profile
            ‘Conical intensity profile is a simplified model of the Guassian
intensity profile
```

```
            ‘This accounts for any jitter that may be inherent in the system
            ‘From Prof. Gary O. Langford, LASER Weapon SME, NPS, SE Dept. Contact:
golangfo@nps.edu
            ‘For description of Guassian intensity profile see fig. M-8, Combat
Systems Appendix M, Dr. Robert C. Harney
            ‘Division by 10000 converts W/m^2 to W/cm^2 (to compare against
fluence for damage units)
            TotalIntensityOnThreat = TotalIntensityOnThreat + (((1 / 3) *
(PeakIntensityAtRange)) / 10000)

            ‘Check to see if Hard Kill threshold has been reached for the first
time
            If RangeFirstHK = 0 And TotalIntensityOnThreat > FluenceForHardKill
Then
                RangeFirstHK = CRange
            End If

            ‘Check to see if Soft Kill threshold has been reached for the first
time
            If RangeFirstSK = 0 And TotalIntensityOnThreat > FluenceForSoftKill
Then
                RangeFirstSK = CRange
            End If

            ‘MER as 10% of fluence for hard kill from Prof. Gary O. Langford,
LASER Weapon SME, NPS, SE Dept.
            ‘Contact: golangfo@nps.edu
            If MaxEffectiveRange = 0 And TotalIntensityOnThreat > 0.1 *
FluenceForHardKill Then
                MaxEffectiveRange = CRange
            End If


            CRange = CRange - ThreatSpeed
        Loop

        NumberHKPossible = TotalIntensityOnThreat / FluenceForHardKill
        NumberSKPossible = TotalIntensityOnThreat / FluenceForSoftKill


    End Sub

    ‘Microwave Analysis Code

    ‘Microwave Weapon Variables
    Public MWWavelength As Double
    Public MWPower As Double
    Public MWAntennaArea As Double
    Public MWAntennaK As Double
    Public MWAntennaGain As Double
    Public MWAntennaEfficiency As Double

    ‘Microwave Scenario Variables
```

```
    Public MWTrans As Double
    Public MWThreatRange As Double
    Public MWThreatSpeed As Double

    'Resultant Variables
    Public MWHKP As Double
    Public MWSKP As Double
    Public HKRadDose As Double
    Public SKRadDose As Double
    Public MWKillWindow As Double
    Public MWIntialIntensity As Double
    Public TimeToMWSK As Double
    Public TimeToMWHK As Double
    Private KWIntensity As Double
    Public MWRangeFirstHardKill As Double
    Public MWRangeFirstSoftKill As Double



    Public Sub setMicrowaveData(W As Double, P As Double, AA As Double, AK As
Double, AE As Double)
        MWAntennaArea = AA
        MWAntennaEfficiency = AE
        MWWavelength = W
        MWPower = P
        MWAntennaK = AK

        MWAntennaGain = CalculateAntennaGain()

    End Sub

    Public Sub setMWScenarioData(atn As Double, TrRng As Double, TrAlt As Double,
TrSpd As Double)
        MWTrans = atn
        MWThreatSpeed = TrSpd
        MWThreatRange = Sqrt(Pow(TrRng, 2) + Pow(TrAlt, 2))

    End Sub


    'Payne, Craig. Principles of Naval Weapon Systems 2ed. Naval Institute Press:
Anapolis, MD, 2010
    'Eq. 3-13
    Private Function CalculateAntennaGain()
        Return ((4 * PI * MWAntennaArea * MWAntennaEfficiency) / (Pow(MWAntennaK,
2) * Pow(MWWavelength, 2)))
    End Function

    'Eq. 3-20 with atmospheric attenuation from Harney ch 17 pg. 1037.
    'Payne, Craig. Principles of Naval Weapon Systems 2ed. Naval Institute Press:
Anapolis, MD, 2010.
```

```
    ‘Transmittance is used instead of attenuation because in this case we are not integrating over the entire range since we are predominately dealing with short ranges of engagement
    ‘By using transmittance which is calculated in MODTRAN5, we save calculation time by not coverting back to attenuation as in the LASER use case
    Private Function CalculateIntensityOnTarget()
        Return ((MWPower * MWAntennaGain * MWTrans)) / ((4 * PI * Pow(MWThreatRange, 2)))
    End Function

    ‘Derived by LT Daniel Ciullo from data from Hymes, Boydell and Prescott. “Thermal Radiation: Physiological and Pathological Effects.” Tables 4.3 & 4.4
    ‘Derived using power regression in MS Excel.
    Private Function CalculateTimeToPain()
        Return 99.896 * Pow(KWIntensity, -1.336)
    End Function

    ‘Derived by LT Daniel Ciullo from data from Hymes, Boydell and Prescott. “Thermal Radiation: Physiological and Pathological Effects.” Tables 4.3 & 4.4
    ‘Derived using power regression in MS Excel.
    Private Function CalculateTimeToLeathality()
        Return 99.896 * Pow(KWIntensity / 10, -1.336)
    End Function

    ‘Developed by LT Daniel Ciullo
    Public Sub EvaluateMicrowaveKillEffectiveness()

        MWIntialIntensity = CalculateIntensityOnTarget()

        KWIntensity = MWIntialIntensity / 1000

        MWKillWindow = MWThreatRange / MWThreatSpeed

        TimeToMWHK = CalculateTimeToLeathality()
        TimeToMWSK = CalculateTimeToPain()

        MWRangeFirstHardKill = TimeToMWHK * MWThreatSpeed
        MWRangeFirstSoftKill = TimeToMWSK * MWThreatSpeed

        MWSKP = MWKillWindow / TimeToMWSK
        MWHKP = MWKillWindow / TimeToMWHK

    End Sub

End Class
```

APPENDIX E. THREAT AND CONVENTIONAL WEAPON DATA

A. CONVENTIONAL WEAPON DATA

Designator	Name	Speed (m/s)[12]	Time Between Shots (s)	Maximum Number of Shots[13]	Maximum Effective Range (m)	Minimum Effective Range (m)[14]
M45 Mod 4	5"/54 Cal Gun	838 (Navweaps.com 2011)	Assuming 18 rpm (Navweaps.com 2011), 3.33	20 (in drum) (Navweaps.com 2011)	15000 (Navweaps.com 2011)	200 (assumed)
MK15	Phalanx CIWS	1490 (Navweaps.com 2010)	Assuming a burst of 225 rounds, 3	6.89 (based on bursts of 225 and 1550 rounds total) (Navweaps.com 2010)	1490 (Navweaps.com 2010)	50 (assumed)
RIM-66 MR	Standard Missile 2, Medium Range	1191.015 (Encyclopedia Astronautica n.d.)	1 (Alternatewars.com 2012)	96 (DDG-51 FLT II)	166680 (United States Navy 2012)	2000 (assumed)
RIM-116	Rolling Airframe Missile	680.58 (Naval-technology.com 2012)	2 (CVN 76 RAM Rolling Airframe Missile Shoot 2012)	21 (LSD-41)	9000 (Naval-technology.com 2012)	500 (assumed)
MK38 Mod 2	25mm Bushmaster	1100 (Navweaps.com 2006)	Assuming 5 round bursts, 1.7 (Navweaps.com 2006)	Assuming 5 round bursts and 175 rounds total, 35 (Navweaps.com	2457 (Navweaps.com 2006)	100 (assumed)

---

[12] Muzzle velocity for guns, average speed for missiles

[13] Number of bursts for guns, single missile launch for missiles

[14] Based on gun elevation, approximate threat speeds, and project team experience

				2006)		

B. THREAT DATA

Designator	Name	Type	Speed (m/s)	Material	Thickness (cm)
AS-11	Kilter	Missile	1167 (IHS Jane's 2012)	Stainless Steel (IHS Jane's 2012)	0.1 (assumed)
C-802	Saccade	Missile	266 (IHS Jane's 2012)	Stainless Steel (IHS Jane's 2012)	0.1 (assumed)
Cessna	Cessna 150	Low Slow Flyer	49 (Federal Aviation Administration 2007, 1)	Aluminum (WAG-AERO 2013)	0.051 (WAG-AERO 2013)[15]
Dhow	Dhow	Small Boat	4 (assumed)	Oak (assumed)	2.5 (assumed)
F-14	Tomcat	Fighter	555 (IHS Jane's 2011)	Titanium (IHS Jane's 2011)	1.27 (assumed)
FAC	Aluminum Boat	Small Boat	23 (assumed)	Aluminum	1 (assumed)
FIAC	Fiberglass Boat	Small Boat	23 (assumed)	Fiberglass (assumed)	2.5 (assumed)
Iranian UAV	Ghods Ababil Ababil-T	UAV	103 (IHS Jane's 2011)	Aluminum (IHS Jane's 2011)	0.4 (IHS Jane's 2011)
MiG-29	Fulcrum	Fighter	666 (Airforce-technology.com 2012)	Aluminum (Airforce-technology.com 2012)	1.27 (assumed)
PC	Boghammer	Patrol Craft	9 (IHS Jane's 2010)	Stainless Steel (IHS Jane's 2010)	1.27 (assumed)
Person	Running 5 mph	Personnel	2 (assumed)	N/A	N/A

---

[15] Assuming original dimension is given in inches

APPENDIX F. TAPE 5 BASELINE INPUT FILE

```
M   1    1    0    0    0    0    0    0    0    0    0    0    0    .000    .00
f   8    0  380.000   1.00000   1.00000 3f 4 f
01_2009
 1.00 1.00 1.05 1.00 1.00 1.00 1.00 1.00 1.00 1.00                              !CARD 1A5
 1.85 2.25 1.00 1.00 2.75 4.00 1.00 1.00 1.00 1.00 0.73 1.00 1.00               !CARD 1A6
    3    0    0    0    0    0      .000      .000      .000      .000      .000
      .000      .000      .000    10.000      .000      .000    0        0.00000
       900      1145         1        2rn         w1aa
    0
```

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APPENDIX G. CONVENTIONAL WEAPON ANALYSIS CLASS WRAPPER CODE

```
Imports System.Math

Public Class ConventionalWeaponAnalyzerSEA19B
    ‘Thesis Advisor: Prof. Gary O. Langford, Naval Postgraduate School, Systems
Engineering Department
    ‘Contact: golangfo@nps.edu

    ‘Software Author: LT Daniel P. Ciullo (USN)
    ‘Contact: dan.ciullo@gmail.com


    ‘Allows an array of missiles to be evaluated in order to determine how many
kills are possible
    Class Missile
        ‘Allow main class variables to be visible
        Inherits ConventionalWeaponAnalyzerSEA19B

        Public CurrentDistanceFromPlatform As Double
        Public LaunchInterval As Double = WeaponActivationTime
        Public InFlight As Boolean = False

    End Class

    ‘Threat Input Variables
    Public ThreatSpeed As Double ‘meters per second
    Public ThreatDetectionRange As Double ‘meters
    Public ThreatDetectionAltitude As Double ‘meters


    ‘Platform Input Variable
    Public VitalAreaRadius As Double ‘meters

    ‘Weapon Input Variables
    Public WeaponSpeed As Double ‘meters per second
    Public WeaponMaxEffectiveRange As Double ‘meters
    Public WeaponMinEffectiveRange As Double ‘meters
    Public WeaponActivationTime As Double ‘Seconds between rounds/missiles fired
from platform

    ‘Intermediate Variables
    Public ThreatSlantRange As Double

    ‘Analysis Output Variables
    Public NumberHardKillsPossible As Double
    Public NumberSoftKillsPossible As Double = 0.0 ‘Always Zero for Conventional
Weapons
    Public RangeOfFirstHardKill As Double
```

```
    Public    RangeOfFirstSoftKill    As    Double    =    0.0    ‘Always    Zero    for
ConvetionalWeapons

    Private Function CalculateThreatSlantRange()

        Return  Sqrt(Pow(ThreatDetectionAltitude,  2.0)  +  Pow(ThreatDetectionRange,
2.0))

    End Function


    ‘Calculate total kills possible and record range of first kill
    Public Sub CalculateNumberOfHardKillsPossible()

        Dim tIntercept As Double = 0
        Dim RangeIntercept As Double = 0

        NumberHardKillsPossible = 0
        RangeOfFirstHardKill = 0

        ThreatSlantRange = CalculateThreatSlantRange()

        NumberHardKillsPossible   =   Truncate(ThreatSlantRange   /   ThreatSpeed   /
WeaponActivationTime - Max(VitalAreaRadius, WeaponMinEffectiveRange) / ThreatSpeed
/ WeaponActivationTime)

        tIntercept  =  (ThreatSlantRange  +  WeaponActivationTime)  /  (WeaponSpeed  +
ThreatSpeed)

        RangeOfFirstHardKill    =    tIntercept    *    (-1.0    *    ThreatSpeed)    +
ThreatSlantRange

    End Sub


       End Class
```

APPENDIX H. MODTRAN 5 CLASS WRAPPER

A. DEVELOPMENT PROCESS

MODTRAN5 runs by receiving inputs via an input file in order to perform atmospheric calculations. This is called a Tape 5 file, which harkens back to the original FORTRAN implementation of the application of the early 1980s. MODTRAN5 then writes the results into an output file. Several output files are generated, but we were concerned with the Tape 6 file in particular because it provides a point estimate of average transmittance over a user-defined frequency band. In order for GINA to leverage MODTRAN5 for atmospheric calculations, the team developed a MODTRAN5 C# Wrapper as a gateway.

The MODTRAN5 C# Wrapper would write to the input file using values from the GINA model, run MODTRAN5 and then read the output file, returning the resultant value back to the GINA model.

The software development effort for MODTRAN5 C# Wrapper was broken down into three tasks: (1) Input File Format Analysis and Creation, (2) Output File Analysis and Extraction, and (3) Software Coding.

1. Input File Format Analysis and Creation

The input file to be read by MODTRAN5 and generated by MODTRAN5 C# Wrapper was a “NavyMaritime.tp5” file. According to the MODTRAN®5.2.1 User’s Manual, each input file must be formatted to include six cards minimally: Card 1, Card 1A, Card 2, Card 3, Card 4 and Card 5. For our model, three additional cards were required: Card 1A Option, Card 3A1 and Card 3A2. The additional cards allowed us to evaluate the effect of rain as well as to take slant path propagation into account.

In order for the wrapper to generate a valid and correct input file, the team had to analyze the complicated input file structure. Each card contained the values of the following variables[16]:

- **CARD 1:** MODTRN, SPEED, BINARY, LYMOLC, MODEL, T_BEST, ITYPE, IEMSCT, IMULT, M1, M2, M3, M4, M5, M6, MDEF, I_RD2C, NOPRNT, TPTEMP, SURREF

  FORMAT (4A1, I1, A1, I4, 10I5, 1X, I4, F8.0, A7)
- **CARD 1A:** DIS, DISAZM, DISALB, NSTR, SFWHM, CO2MX, H2OSTR, O3STR, C_PROF, LSUNFL, LBMNAM, LFLTNM, H2OAER, CDTDIR, SOLCON, CDASTM, ASTMC, ASTMX, ASTMO, AERRH, NSSALB

  FORMAT (3A1, I3, F4.0, F10.0, 2A10, 2A1, 4(1X, A1), F10.0, A1, F9.0, 3F10.0, I10)
- **CARD 2:** APLUS, IHAZE, CNOVAM, ISEASN, *ARUSS*, IVULCN, ICSTL, ICLD, IVSA, VIS, WSS, WHH, RAINRT, GNDALT

  FORMAT (A2, I3, A1, I4, A3, I2, 3I5, 5F10.0)
- **CARD 3:** H1, H2, ANGLE, RANGE, BETA, RO, LENN, PHI

  FORMAT (6F10.0, I5, 5X, 2F10.0)
- **CARD 3A1:** IPARM, IPH, IDAY, ISOURC

  FORMAT (4I5) (If IEMSCT = 2 or 4)
- **CARD 3A2:** PARM1, PARM2, PARM3, PARM4, TIME, PSIPO, ANGLEM, G

  FORMAT (8F10.0)
- **CARD 4:** V1, V2, DV, FWHM, YFLAG, XFLAG, DLIMIT, FLAGS, *MLFLX*, *VRFRAC*

  FORMAT (4F10.0, 2A1, A8, A7, I3, F10.0)
- **CARD 5:** IRPT

  FORMAT (I5)

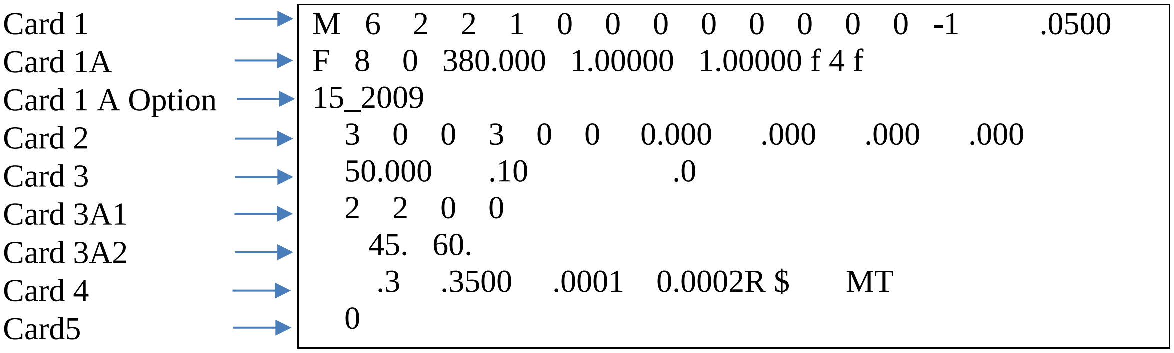
---

[16] The cards did not lend themself to human-interpretation as they record only the values of the listed variables without indication of what they represented. The above formats extracted from the user manual were more helpful but still contained archaic abbreviations.

The value formats were specified using the codes listed below with their representation listed on the right:

- A – Alphabet
- I – Integer
- F – Floating Point
- 2A1 – 2 Alphabet with up to 1 Character
- 10I5 – 10 Integer with up to 5 Characters
- F10.0 – Floating Point with up to 10 Characters

If no value was available for a variable, it would be represented by a blank space. Figure 99 shows the input file “NavyMaritime.tp5,” the file format and the lines representing the cards.

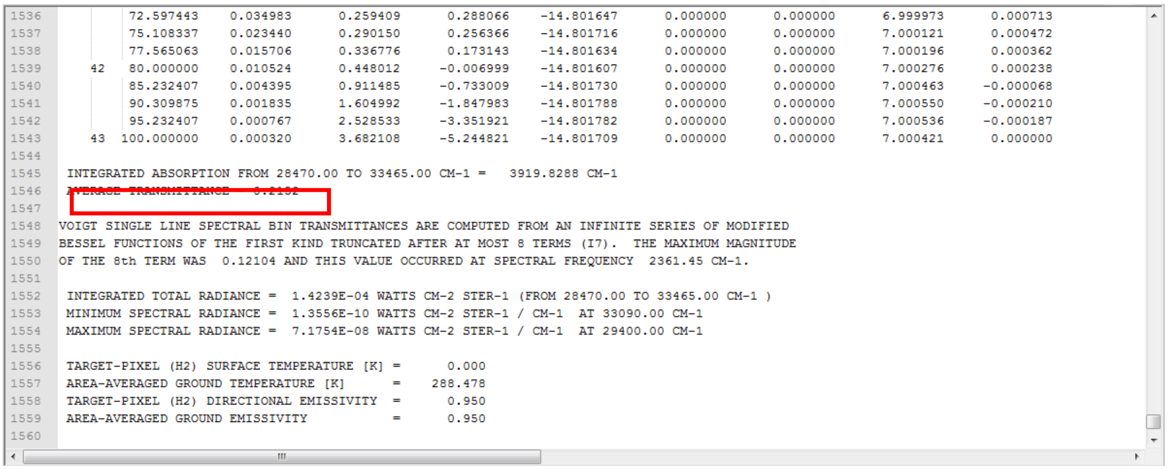


```
M   6    2    2    1    0    0    0    0    0    0    0    0  -1          .0500
F   8    0   380.000   1.00000   1.00000 f 4 f
15_2009
    3    0    0    3    0    0     0.000      .000      .000      .000
    50.000      .10                .0
    2    2    0    0
       45.   60.
        .3     .3500     .0001    0.0002R $      MT
    0
```

Figure 99. NavyMaritime.tp5 File Format

2. Output File Format Analysis and Extraction

The output file generated by MODTRAN5 was named “NavyMaritime.tp6.” The MODTRAN5 C# Wrapper would be able to read the contents and extract the Average Transmittance Result if the file contained no error. Figure 100 shows a correctly generated “NavyMaritime.tp6” with the Average Transmittance result calculated.



```
         72.597443    0.034983    0.259409    0.288066   -14.801647    0.000000    0.000000    6.999973    0.000713
         75.108337    0.023440    0.290150    0.256366   -14.801716    0.000000    0.000000    7.000121    0.000472
         77.565063    0.015706    0.336776    0.173143   -14.801634    0.000000    0.000000    7.000196    0.000362
    42   80.000000    0.010524    0.448012   -0.006999   -14.801607    0.000000    0.000000    7.000276    0.000238
         85.232407    0.004395    0.911485   -0.733009   -14.801730    0.000000    0.000000    7.000463   -0.000068
         90.309875    0.001835    1.604992   -1.847983   -14.801788    0.000000    0.000000    7.000550   -0.000210
         95.232407    0.000767    2.528533   -3.351921   -14.801782    0.000000    0.000000    7.000536   -0.000187
    43  100.000000    0.000320    3.682108   -5.244821   -14.801709    0.000000    0.000000    7.000421    0.000000

 INTEGRATED ABSORPTION FROM 28470.00 TO 33465.00 CM-1 =   3919.8288 CM-1
 AVERAGE TRANSMITTANCE =   0.2152

VOIGT SINGLE LINE SPECTRAL BIN TRANSMITTANCES ARE COMPUTED FROM AN INFINITE SERIES OF MODIFIED
BESSEL FUNCTIONS OF THE FIRST KIND TRUNCATED AFTER AT MOST 8 TERMS (I7).  THE MAXIMUM MAGNITUDE
OF THE 8th TERM WAS  0.12104 AND THIS VALUE OCCURRED AT SPECTRAL FREQUENCY  2361.45 CM-1.

 INTEGRATED TOTAL RADIANCE =  1.4239E-04 WATTS CM-2 STER-1 (FROM 28470.00 TO 33465.00 CM-1 )
 MINIMUM SPECTRAL RADIANCE =  1.3556E-10 WATTS CM-2 STER-1 / CM-1  AT 33090.00 CM-1
 MAXIMUM SPECTRAL RADIANCE =  7.1754E-08 WATTS CM-2 STER-1 / CM-1  AT 29400.00 CM-1

 TARGET-PIXEL (H2) SURFACE TEMPERATURE [K] =      0.000
 AREA-AVERAGED GROUND TEMPERATURE [K]      =    288.478
 TARGET-PIXEL (H2) DIRECTIONAL EMISSIVITY  =      0.950
 AREA-AVERAGED GROUND EMISSIVITY           =      0.950
```

Figure 100. MODTRAN Tape 6 File Format

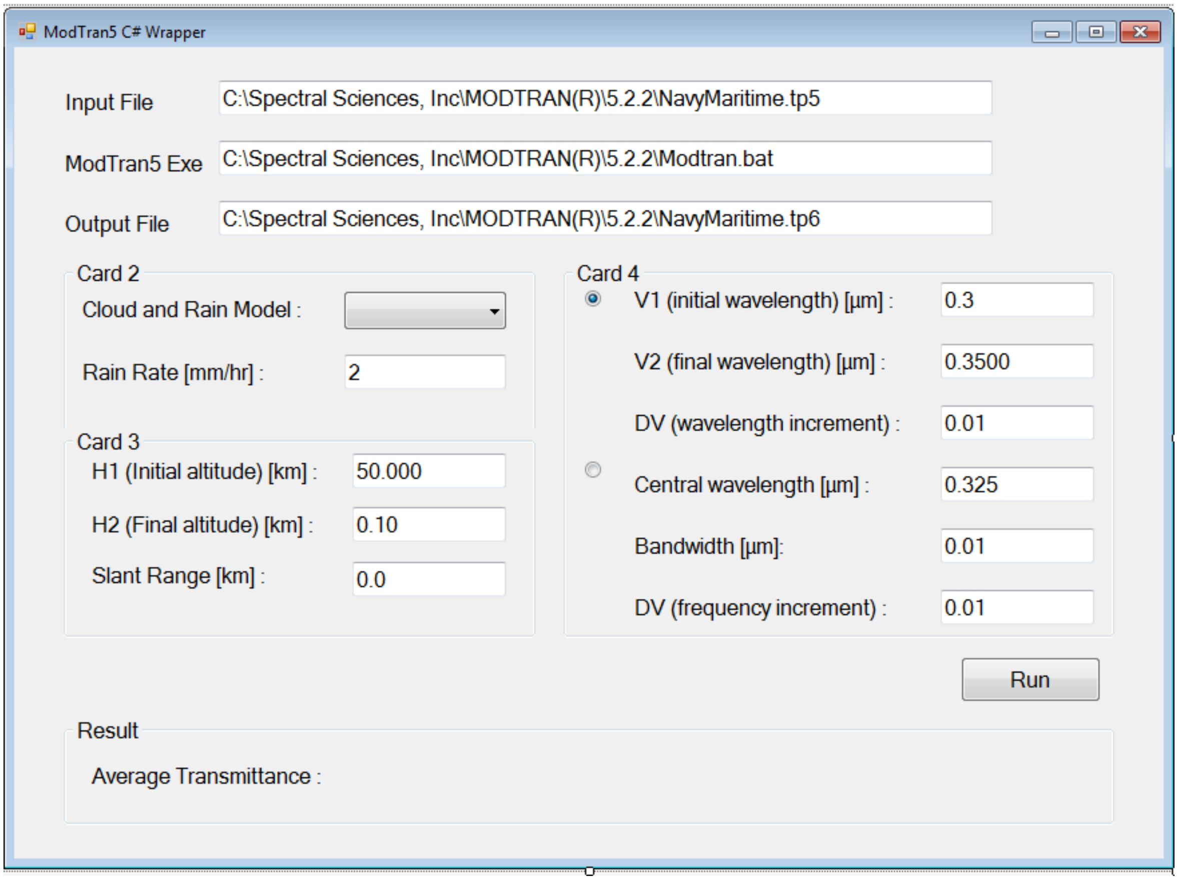
3. Coding of Software

The MODTRAN5 Wrapper was written in .NET Framework 4.5 using C# Programming Language. The software package contained three C# source files: (1) Program.cs, (2) Form1.cs, and (3) MODTRAN5.cs.

The Program.cs file starts the program in standalone mode. The Form1.cs file encodes the Graphical Interface through which a human user can enter inputs to be read by the MODTRAN5 executable for atmospheric calculations. This was used for software debugging and verification. Figure 101 shows the Graphical Interface of the MODTRAN5 C# Wrapper. The file MODTRAN5.cs is the main library class file for creating the input file, running the MODTRAN5 executable and extracting of result from the output file.

The software package could be compiled into a library file (.dll file) so that MODTRAN5 class can be called or imported into other software (such as GINA). To do so, one could refer to Form1.cs which is an example of how the MODTRAN5 class could be invoked and passed parameters.

The input file for MODTRAN5 was created by MODTRAN5.cs based on the format as understood from the "Input File Format Analysis and Creation" task. Each card was coded as a C# struct for ease of reference and development. The MODTRAN5.cs file then executes the MODTRAN5 executable file by calling a batch file that wraps the executable file. The MODTRAN5 executable file then reads the input file and performs its calculations before generating the output file. The output file is read by the MODTRAN5.cs where it looks for a specific line containing the result required as shown from the "Output File Format Analysis and Extraction."



Input File: C:\Spectral Sciences, Inc\MODTRAN(R)\5.2.2\NavyMaritime.tp5

ModTran5 Exe: C:\Spectral Sciences, Inc\MODTRAN(R)\5.2.2\Modtran.bat

Output File: C:\Spectral Sciences, Inc\MODTRAN(R)\5.2.2\NavyMaritime.tp6

Card 2

Cloud and Rain Model :

Rain Rate [mm/hr] : 2

Card 3

H1 (Initial altitude) [km] : 50.000

H2 (Final altitude) [km] : 0.10

Slant Range [km] : 0.0

Card 4

● V1 (initial wavelength) [µm] : 0.3

V2 (final wavelength) [µm] : 0.3500

DV (wavelength increment) : 0.01

○ Central wavelength [µm] : 0.325

Bandwidth [µm]: 0.01

DV (frequency increment) : 0.01

Result

Average Transmittance :

Figure 101. MODTRAN5 C# Wrapper Form1 User Interface

Once tested, the wrapper class was then interfaced into GINA using a custom content manager. Content managers are objects used by GINA to process, move, and store data within GINA. The software team at Big Kahuna Technologies modified the

“Save and Update” content manager so that when an Engagement X-type is saved, this code as well as the appropriate analysis code is called so that the engagement results can be calculated and saved in the GINA model.

B. CODE

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;
using System.Threading.Tasks;
using System.IO;
using System.Diagnostics;

namespace ModTran5
{
    class ModTran5
    {
        Card1 c1 = new Card1();
        Card1A c1A = new Card1A();
        Card1AOption c1AOption = new Card1AOption();
        Card2 c2 = new Card2();
        Card3 c3 = new Card3();
        Card3A1 c3A1 = new Card3A1();
        Card3A2 c3A2 = new Card3A2();
        Card4 c4 = new Card4();
        Card5 c5 = new Card5();
        string inputfile = ““;
        string outputfile = ““;
        string exefile = ““;

        public  ModTran5(string input, string exe, string output)
        {
            inputfile = input;
            outputfile = output;
            exefile  =  exe;  //MODTRAN  cannot  be  run  directly  from  the  exe  file.
Therefore, this points to a batch file that runs MODTRAN
        }

        public struct Card1
        {
            // Set up Card 1 (mandatory - main radiative transport)
            public string MODTRN;     // MODTRAN band model
            public string SPEED ;      // Slow algorithm
            public string BINARY ;     // Output will be ASCII
            public string LYMOLC ;     // Exclude 16 auxiliary trace gases
            public  string  MODEL  ;             //  Mid-latitude  wstringer  canned
atmosphere
            public  string  T_BEST;              //  Mid-latitude  wstringer  canned
atmosphere
```

```
            public string ITYPE;        // Slant path to ground
            public string IEMSCT;        // Compute path radiance, including solar
scatter
            public string IMULT;       // Include multiple scatter, computed at H2
(target/pixel)
            public string M1;             // Temperature/pressure default to MODEL
(Mid-latitude wstringer profile)
            public string M2;           // Water vapor defaults to MODEL profile
            public string M3;           // Ozone defaults to MODEL profile1.
            public string M4;           // Methane defaults to MODEL profile
            public string M5;           // Nitrous oxide defaults to MODEL profile
            public string M6;                // Carbon monoxide defaults to MODEL
profile
            public string MDEF;          // Default O2, NO, SO2, NO2, NH3, and HNO3
species profiles.
            public string I_RD2C;          // Normal program operation - no user
input for profiles
            public string NOPRNT;         // Minimize prstringing to Tape6 output
file
            public string TPTEMP;       // Temperature at H2 - not important, only
VIS/NIR
            public string SURREF;     // Earth reflectance (albedo) 50// right
across spectrum

        }

        public struct Card1A
        {
            // Set up Card 1A (mandatory - main radiative transport continued)
            public string DIS;           // Not using DISORT multiple scattering
algorithm
            public string DISAZM ;        // Therefore, also not using azimuth
dependence in DISORT
            public string DISALB ;      // Don”t calculate atmospheric correction
data
            public string NSTR ;           // Isaacs 2-stream multiple scattering
model
            public string SFWHM ;        // Default solar irradiance data
            public string CO2MX ;      // CO2 mixing ratio, 370 ppm by volume
            public string H2OSTR ;     // No scaling of canned water vapor profile
(MODEL/M2)ing
            public string O3STR ;        // No scaling of canned ozone profile
(MODEL/M3)
            public string C_PROF ;      // No scaling of default molecular species
profiles
            public string LSUNFL ;      // Don”t read alternative solar irradiance
data
            public string LBMNAM ;     // Don”t read alternative band model file
            public string LFLTNM ;     // Must read filter file specified
            public string H2OAER ;          // Don”t bother to modify aerosol
properties on the basis of H2OSTR
            public string CDTDIR ;     // Data files are in the default location
```

```
            public string SOLCON ;       // Unity scaling of TOA solar irradiance,
but apply seasonal correction
            public string CDASTM ;      // No Angstrom law manipulations
            public string NSSALB ;          // Use reference aerosol single-
scattering albedo

        }

        public struct Card1AOption
        {
            public string Card1AOptionFName;
        }

        public struct Card2
        {
            // Set up Card 2 (mandatory - main aerosol and cloud options)
            public string APLUS ;     // Don’t use flexible aerosol manipulations
            public string IHAZE;        // Rural aerosol model, visibility = 23 km
(modified below)
            public string CNOVAM;     // Don’t invoke NOVAM
            public string ISEASN;       // Use default seasonal aerosol tweaking
            public string ARUSS;      // Don’t use extended user-defined aerosol
facility
            public string IVULCN;           // Background stratospheric aerosol
profile
            public string ICSTL;            // Continental influence of maritime
aerosols - not applicable to this case
            public string ICLD;         // ** No clouds or rain
            public string IVSA;             // Don’t use Army Vertical Structure
Algorithm for boundary layer aerosols
            public string VIS;          // km. Reduce visibility, scales up aerosol
amount in boundary layer
            public string WSS;          // Use default wind speed for named MODEL
            public string WHH;             // Use default 24 hr average wind speed
for named MODEL
            public string RAINRT;        // ** Rain rate is zero (mm/hour), anyway
no cloud/rain (ICLD)
            public string GNDALT;       // Target surface (H2) is at sea level
        }

        public struct Card3
        {
            // Set up Card 3 (mandatory - Line of sight geometry)
            // To define path (LOS) geometry in this case use PHI, H1 and H2
(combination 3c in manual)
            public string H1;            // **Not used in this case - we are using
a slant path to space
            public string H2;           // **km. Target pixel is at sea level
            public string ANGLE;        // Not used in this case. (Zenith angle at
H1)
            public string RANGE;        // **Not used in this case. Path length.
            public string BETA;            // Not used in this case. Earth centre
angle.
```

```
            public string RO ;            // Not used in this case. Radius of the Earuth, will default to a reasonable value.
            public string LENN;          // Not used in this case. Short path/long path switch.
            public string PHI;                 // degrees. Zenith angle at H2 (pixel/target) to H1 (satellite camera)
        }

        public struct Card3A1
        {
            // Set up Card 3A1 (Solar scattering geometry, required for IEMSCT = 2)
            public string IPARM;          // Will specify relative solar azimuth angle and solar zenith angle below (PARM1 and PARM2)
            public string IPH;           // Use Mie-generated internal database for aerosol phase functions
            public string IDAY;// Compute day number corresponding to 2 Nov 2009 (works out as IDAY = 306).
            public string ISOURC;        // The Sun is the extraterrestrial source of scattered radiation
        }

        public struct Card3A2
        {
            // Set up Card 3A2 (Solar scattering geometry, also required for IEMSCT = 2)
            public string PARM1;        // deg. The Sun azimuth is 50 deg East of LOS azimuth (H2 to H1)
            public string PARM2;             // deg. Sun zenith angle at H2 (target/pixel).
            public string PARM3;        // Not used in this case.
            public string PARM4;        // Not used in this case.
            public string TIME;         // Not used in this case.
            public string PSIPO;        // Not used in this case.
            public string ANGLEM;       // Not used in this case.
            public string G;                 // Not used in this case. (Henyey-Greenstein asymmetry parameter)
        }

        public struct Card4
        {
            // Set up Card 4 (mandatory - spectral range and resolution)
            public string V1;         // Start of spectral computation range in nm (see FLAGS(1))
            public string V2;         // End of spectral computation range in nm
            public string DV;         // Spectral increment in nm
            public string FWHM;         // Convolution filter width in nm
            public string YFLAG;      // Not going to generate .plt or .psc files
            public string XFLAG;      // Not going to generate .plt or .psc files
            public string DLIMIT;
            public string FLAGS1;      // Use nanometres for spectral units (FLAGS(1)).
```

```
            public string FLAGS2;      // Use nanometres for spectral units
(FLAGS(1)).
            public string FLAGS3;      // Use nanometres for spectral units
(FLAGS(1)).
            public string FLAGS4;    // Put ALL radiance components in convolved
data (tp7)
            public string FLAGS5;      // Use nanometres for spectral units
(FLAGS(1)).
            public string FLAGS6;      // Use nanometres for spectral units
(FLAGS(1)).
            public string FLAGS7;    // Put ALL radiance components in convolved
data (tp7)
        }

        public struct Card5
        {
            // Set up Card 5 (mandatory - Repeat option)
            public string IRPT;          // Stop program, only one sub-case in this
run
        }

        public void SetupCard1(){
        // Set up Card 1 (mandatory - main radiative transport)
            c1.MODTRN = “M”;     // MODTRAN band model
            c1.SPEED = “ “;      // Slow algorithm
            c1.BINARY = “ “;     // Output will be ASCII
            c1.LYMOLC = “ “;     // Exclude 16 auxiliary trace gases
            c1.MODEL = “6”;        // Mid-latitude wstringer canned atmosphere
            c1.T_BEST = “ “;        // Mid-latitude wstringer canned atmosphere
            c1.ITYPE = “2.”PadLeft(4);        // Slant path to ground
            c1.IEMSCT = “2.”PadLeft(5);        // Compute path radiance, including
solar scatter
            c1.IMULT = “1.”PadLeft(5);       // Include multiple scatter, computed
at H2 (target/pixel)
            c1.M1 = “0.”PadLeft(5);             // Temperature/pressure default to
MODEL (Mid-latitude wstringer profile)
            c1.M2 = “0.”PadLeft(5);             // Water vapor defaults to MODEL
profile
            c1.M3 = “0.”PadLeft(5);           // Ozone defaults to MODEL profile1.
            c1.M4 = “0.”PadLeft(5);           // Methane defaults to MODEL profile
            c1.M5 = “0.”PadLeft(5);             // Nitrous oxide defaults to MODEL
profile
            c1.M6 = “0.”PadLeft(5);           // Carbon monoxide defaults to MODEL
profile
            c1.MDEF = “0.”PadLeft(5);           // Default O2, NO, SO2, NO2, NH3,
and HNO3 species profiles.
            c1.I_RD2C = “0.”PadLeft(5);         // Normal program operation - no
user input for profiles
            c1.NOPRNT = “-1.”PadLeft(5);         // Minimize prstringing to Tape6
output file
            c1.TPTEMP = “  .”PadLeft(8);            // Temperature at H2 - not
important, only VIS/NIR
```

```
            c1.SURREF = .”0500.”PadLeft(7);    // Earth reflectance (albedo) 50//
right across spectrum

        }

        public void SetupCard1A()
        {
            // Set up Card 1A (mandatory - main radiative transport continued)
            c1A.DIS  =  “F”;             //  Not  using  DISORT  multiple  scattering
algorithm
            c1A.DISAZM = “ “;      // Therefore, also not using azimuth dependence
in DISORT
            c1A.DISALB = “ “;     // Don”t calculate atmospheric correction data
            c1A.NSTR = “ 8 “;         // Isaacs 2-stream multiple scattering model
            c1A.SFWHM = “0.”PadLeft(4);        // Default solar irradiance data
            c1A.CO2MX = “380.000.”PadLeft(10);       // CO2 mixing ratio, 370 ppm
by volume
            c1A.H2OSTR = “1.00000.”PadLeft(10);     // No scaling of canned water
vapor profile (MODEL/M2)ing
            c1A.O3STR = “1.00000.”PadLeft(10);      // No scaling of canned ozone
profile (MODEL/M3)
            c1A.C_PROF  =  “  “;       //  No  scaling  of  default  molecular  species
profiles
            c1A.LSUNFL = “f”;     // Don”t read alternative solar irradiance data
            c1A.LBMNAM = “ “;     // Don”t read alternative band model file
            c1A.LFLTNM = “4”;     // Must read filter file specified
            c1A.H2OAER = “ “;      // Don”t bother to modify aerosol properties on
the basis of H2OSTR
            c1A.CDTDIR = “f”;     // Data files are in the default location
            c1A.SOLCON = “ “;       // Unity scaling of TOA solar irradiance, but
apply seasonal correction
            c1A.CDASTM = “ “;     // No Angstrom law manipulations
            c1A.NSSALB  =  “  “;         // Use reference aerosol single-scattering
albedo


        }

        public void SetupCard1AOption()
        {
            c1AOption.Card1AOptionFName = “15_2009”;

        }

        public void SetupCard2()
        {
            // Set up Card 2 (mandatory - main aerosol and cloud options)
            c2.APLUS = “  “;     // Don’t use flexible aerosol manipulations
            c2.IHAZE = “4.”PadLeft(3);         // MARITIME extinction, default VIS
= 23 km (LOWTRAN model).
            c2.CNOVAM = “ “;     // Don’t invoke NOVAM
            c2.ISEASN  =  “0.”PadLeft(4);         //  Use  default  seasonal  aerosol
tweaking
```

```
            c2.ARUSS = “    “;      // Don’t use extended user-defined aerosol
facility
            c2.IVULCN = “0.”PadLeft(2);        // Background stratospheric aerosol
profile
            c2.ICSTL = “3.”PadLeft(5);         // Continental influence of maritime
aerosols - not applicable to this case
            c2.ICLD = “0.”PadLeft(5);          // ** No clouds or rain
            c2.IVSA = “0.”PadLeft(5);          // Don’t use Army Vertical Structure
Algorithm for boundary layer aerosols
            c2.VIS = “0.000.”PadLeft(10);          // km. Reduce visibility, scales
up aerosol amount in boundary layer
            c2.WSS = .”000.”PadLeft(10);             // Use default wind speed for
named MODEL
            c2.WHH = .”000.”PadLeft(10);              // Use default 24 hr average
wind speed for named MODEL
            c2.RAINRT = .”000.”PadLeft(10);            // ** Rain rate is zero
(mm/hour), anyway no cloud/rain (ICLD)
            c2.GNDALT = “0.”PadLeft(10);         // Target surface (H2) is at sea
level

        }

        public void SetupCard3()
        {
            // Set up Card 3 (mandatory - Line of sight geometry)
            // To define path (LOS) geometry in this case use PHI, H1 and H2
(combination 3c in manual)
            c3.H1 = “0.0000.”PadLeft(10);           // Weapon Height
            c3.H2 = “  0.0.”PadRight(10);           // Threat Height
            c3.ANGLE = “ .”PadLeft(10);          // Not used in this case. (Zenith
angle at H1)
            c3.RANGE = “1.”PadLeft(10);         // Slant Range
            c3.BETA = “ .”PadLeft(10);             // Not used in this case. Earth
centre angle.
            c3.RO = “ .”PadLeft(10);            // Not used in this case. Radius of
the Earuth, will default to a reasonable value.
            c3.LENN = “0.”PadLeft(10);            // Not used in this case. Short
path/long path switch.
            c3.PHI = “ .”PadLeft(10);              // degrees. Zenith angle at H2
(pixel/target) to H1 (satellite camera)

        }

        public void SetupCard3A1()
        {

            // Set up Card 3A1 (Solar scattering geometry, required for IEMSCT =
2)
            c3A1.IPARM = “2.”PadLeft(5);          // Will specify relative solar
azimuth angle and solar zenith angle below (PARM1 and PARM2)
            c3A1.IPH = “2.”PadLeft(5);              // Use Mie-generated internal
database for aerosol phase functions
```

```
            c3A1.IDAY = “0.”PadLeft(5);// Compute day number corresponding to 2
Nov 2009 (works out as IDAY = 306).
            c3A1.ISOURC = “0.”PadLeft(5);       // The Sun is the extraterrestrial
source of scattered radiation

        }

        public void SetupCard3A2()
        {
            // Set up Card 3A2 (Solar scattering geometry, also required for
IEMSCT = 2)
            c3A2.PARM1 = “45..”PadLeft(10);         // deg. The Sun azimuth is 50
deg East of LOS azimuth (H2 to H1)
            c3A2.PARM2 = “60.     .”PadLeft(10);        // deg. Sun zenith angle at
H2 (target/pixel).
            c3A2.PARM3 = “.”PadLeft(10);        // Not used in this case.
            c3A2.PARM4 = “.”PadLeft(10);        // Not used in this case.
            c3A2.TIME = “.”PadLeft(10);         // Not used in this case.
            c3A2.PSIPO = “.”PadLeft(10);        // Not used in this case.
            c3A2.ANGLEM = “.”PadLeft(10);       // Not used in this case.
            c3A2.G = “.”PadLeft(10);             // Not used in this case. (Henyey-
Greenstein asymmetry parameter)

        }

        public void SetupCard4()
        {

            // Set up Card 4 (mandatory - spectral range and resolution)
            c4.V1 = .”3.”PadLeft(10);            // Start of spectral computation
range in nm (see FLAGS(1))
            c4.V2 = .”3500.”PadLeft(10);           // End of spectral computation
range in nm
            c4.DV = .”005.”PadLeft(10);          // Spectral increment in nm
            c4.FWHM = .”010.”PadLeft(10);          // Full Width Half Maximum
            c4.YFLAG = “T”;      // Not going to generate .plt or .psc files
            c4.XFLAG = “ “;      // Not going to generate .plt or .psc files
            c4.DLIMIT = “$.”PadRight(8);
            c4.FLAGS1 = “M”;    // Use µm for spectral units (FLAGS(1)).
            c4.FLAGS2 = “R”;    // Use nanometres for spectral units (FLAGS(1)).
            c4.FLAGS3 = “ “;    // Use nanometres for spectral units (FLAGS(1)).
            c4.FLAGS4 = “ “;    // Put ALL radiance components in convolved data
(tp7)
            c4.FLAGS5 = “ “;    // Use nanometres for spectral units (FLAGS(1)).
            c4.FLAGS6 = “ “;    // Use nanometres for spectral units (FLAGS(1)).
            c4.FLAGS7 = “ “;    // Put ALL radiance components in convolved data
(tp7)
        }

        public void SetupCard5()
        {
            // Set up Card 5 (mandatory - Repeat option)
```

```
            c5.IRPT = “0.”PadLeft(5);          // Stop program, only one sub-case
in this run

        }

        public void SetParam(string RAINRT, string H1, string H2, string RANGE,
string V1, string V2)
        {
            SetupCard1();
            SetupCard1A();
            SetupCard1AOption();
            SetupCard2();
            SetupCard3();
            SetupCard3A1();
            SetupCard3A2();
            SetupCard4();
            SetupCard5();


            c2.RAINRT = RAINRT.PadLeft(10);
            c3.H1 = H1.PadLeft(10);
            c3.H2 = H2.PadLeft(10);
            c3.RANGE = RANGE.PadLeft(10);
            c4.V1 = V1.PadLeft(10);
            c4.V2 = V2.PadLeft(10);

        }

        public void GenerateInput()
        {
            FileInfo fi = new FileInfo(inputfile);
            StreamWriter sw = fi.CreateText();

            //SetParam();

            string Card1 = c1.MODTRN + c1.SPEED + c1.BINARY + c1.LYMOLC + c1.MODEL
+ c1.T_BEST + c1.ITYPE + c1.IEMSCT + c1.IMULT + c1.M1 + c1.M2 + c1.M3 + c1.M4
                + c1.M5 + c1.M6 + c1.MDEF + c1.I_RD2C + c1.NOPRNT + c1.TPTEMP +
c1.SURREF;

            string Card1A = c1A.DIS + c1A.DISAZM + c1A.DISALB + c1A.NSTR +
c1A.SFWHM + c1A.CO2MX + c1A.H2OSTR + c1A.O3STR + c1A.C_PROF + c1A.LSUNFL +
c1A.LBMNAM
                + c1A.LFLTNM + c1A.H2OAER + c1A.CDTDIR + c1A.SOLCON + c1A.CDASTM +
c1A.NSSALB;

            string Card1AOption = c1AOption.Card1AOptionFName;
            string Card2 = c2.APLUS + c2.IHAZE + c2.CNOVAM + c2.ISEASN + c2.ARUSS
+ c2.IVULCN + c2.ICSTL + c2.ICLD + c2.IVSA + c2.VIS + c2.WSS + c2.WHH + c2.RAINRT
+ c2.GNDALT;

            string Card3 = c3.H1 + c3.H2 + c3.ANGLE + c3.RANGE + c3.BETA + c3.RO +
c3.LENN + c3.PHI;
```

```
            string Card3A1 = c3A1.IPARM + c3A1.IPH + c3A1.IDAY + c3A1.ISOURC;

            string Card3A2 = c3A2.PARM1 + c3A2.PARM2 + c3A2.PARM3 + c3A2.PARM4 +
c3A2.TIME + c3A2.PSIPO + c3A2.ANGLEM + c3A2.G;

            string Card4 = c4.V1 + c4.V2 + c4.DV + c4.FWHM + c4.YFLAG + c4.XFLAG +
c4.DLIMIT + c4.FLAGS1 + c4.FLAGS2 + c4.FLAGS3 + c4.FLAGS4 + c4.FLAGS5 + c4.FLAGS6
+ c4.FLAGS7;

            string Card5 = c5.IRPT;

            sw.WriteLine(Card1);
            sw.WriteLine(Card1A);
            sw.WriteLine(Card1AOption);
            sw.WriteLine(Card2);
            sw.WriteLine(Card3);
            sw.WriteLine(Card3A1);
            sw.WriteLine(Card3A2);
            sw.WriteLine(Card4);
            sw.WriteLine(Card5);
            sw.Close();

        }

        public void RunExe()
        {
            // Prepare the process to run
            ProcessStartInfo start = new ProcessStartInfo();
            // Enter the executable to run, including the complete path
            start.FileName = exefile;
            // Do you want to show a console window?
            start.WindowStyle = ProcessWindowStyle.Hidden;
            start.CreateNoWindow = true;

            // Run the external process & wait for it to finish
            using (Process proc = Process.Start(start))
            {
                proc.WaitForExit(20000);
            }

        }

        public string ReadOutput()
        {
            string output = ““;

            try
            {
                using (FileStream fs = new FileStream(outputfile, FileMode.Open))
                {
                    using (StreamReader reader = new StreamReader(fs,
Encoding.UTF8))
```

```
                    {
                        string line = null;
                        while ((line = reader.ReadLine()) != null)
                        {
                            //Console.WriteLine(line);
                            if (line.Contains(“AVERAGE TRANSMITTANCE”))
                            {
                                output = line.Split(new char[] { ‘=‘ },
StringSplitOptions.RemoveEmptyEntries)[1].Trim() ;
                            }
                        }
                    }
                }
            }
            catch (Exception ex)
            {
                Console.WriteLine(ex.ToString());
            }
            return output;

        }

    }
       }
```

APPENDIX I. MICROWAVE FULL SENSITIVITY ANALYSIS VALUES

Antenna Area (m^2)	Antenna Efficiency (%)	Antenna Constant K	Power (W)	Seconds to Pain	Seconds to Lethal
4	0.8	1.27324	100000	1.8015	39.053
1	0.8	1.27324	100000	11.4818	248.891
2	0.8	1.27324	100000	4.5481	98.59
6	0.8	1.27324	100000	1.0481	22.719
8	0.8	1.27324	100000	0.7136	15.47
10	0.8	1.27324	100000	0.5297	11.482
4	0.8	0.5	100000	0.1482	3.214
4	0.8	0.7	100000	0.3643	7.897
4	0.8	0.8	100000	0.5205	11.282
4	0.8	0.88	100000	0.6714	14.554
4	0.8	1	100000	0.9448	20.48
4	0.8	1.1	100000	1.2188	26.42
4	0.8	1.2	100000	1.5378	33.336
4	0.8	1.3	100000	1.9046	41.285
4	0.8	1.5	100000	2.7916	60.513
4	0.8	2	100000	6.0213	130.523
4	0.1	1.27324	100000	28.9857	628.325
4	0.2	1.27324	100000	11.4818	248.89
4	0.3	1.27324	100000	6.6796	144.794
4	0.4	1.27324	100000	4.5481	98.59
4	0.5	1.27324	100000	3.3757	73.175
4	0.6	1.27324	100000	2.6459	57.355
4	0.7	1.27324	100000	2.1534	46.68

4	0.8	1.27324	100000	1.8016	39.053
4	0.9	1.27324	100000	1.5393	33.367
4	0.95	1.27324	100000	1.432	31.042
4	0.8	1.27324	10000	39.0532	846.557
4	0.8	1.27324	20000	15.4696	335.336
4	0.8	1.27324	30000	8.9996	195.084
4	0.8	1.27324	40000	6.1278	132.832
4	0.8	1.27324	50000	4.5481	98.59
4	0.8	1.27324	60000	3.5649	77.276
4	0.8	1.27324	70000	2.9014	62.893
4	0.8	1.27324	80000	2.4273	52.617
4	0.8	1.27324	90000	2.0739	44.956
4	0.8	1.27324	150000	1.0481	22.719
4	0.8	1.27324	200000	0.7136	15.47
4	0.8	1.27324	300000	0.4152	9
4	0.8	1.27324	400000	0.2827	6.128
4	0.8	1.27324	500000	0.2098	4.548
4	0.8	1.27324	600000	0.1645	3.565
4	0.8	1.27324	700000	0.1338	2.901
4	0.8	1.27324	800000	0.112	2.427
4	0.8	1.27324	900000	0.0957	2.074
4	0.8	1.27324	1000000	0.0831	1.802

APPENDIX J. LASER SENSITIVITY FULL RANGE OF FACTORS

Wavelength (um)	Lens Diameter (m)	Gaussian Factor M	Power (kW)	Target Reflectance (%)	Maximum Effective Range (m)	Number T1E	Range 1st T1E	Number T2E	Range 1st T2E
1.064	0.66	6.5	33	0.89	7500	0.40802	0	2.4481	5800
1.6	0.66	6.5	33	0.89	7400	0.40717	0	2.443	5800
1.064	0.66	5	33	0.89	6700	0.31369	0	1.8821	4500
1.064	0.66	5.5	33	0.89	7000	0.34489	0	2.0694	5000
1.064	0.66	6	33	0.89	7200	0.37606	0	2.2563	5400
1.064	0.66	7	33	0.89	7600	0.43823	0	2.6294	6000
1.064	0.66	7.5	33	0.89	7800	0.46923	0	2.8154	6300
1.064	0.66	8	33	0.89	7900	0.50018	0	3.0011	6500
1.064	0.1	6.5	33	0.89	8800	5.28482	4100	31.7089	8200
1.064	0.2	6.5	33	0.89	9500	3.30804	5700	19.8482	9100
1.064	0.3	6.5	33	0.89	9400	1.82745	4100	10.9647	8900
1.064	0.4	6.5	33	0.89	9000	1.08315	700	6.4989	8300
1.064	0.5	6.5	33	0.89	8500	0.70415	0	4.2249	7500
1.064	0.6	6.5	33	0.89	7900	0.49183	0	2.951	6500
1.064	0.7	6.5	33	0.89	7100	0.36225	0	2.1735	5200
1.064	0.8	6.5	33	0.89	6300	0.27769	0	1.6661	3900

1.064	0.9	6.5	33	0.89	5300	0.21955	0	1.3173	2300
1.064	1	6.5	33	0.89	4200	0.1779	0	1.0674	600
1.064	0.66	6.5	10	0.89	1800	0.12339	0	0.7403	*
1.064	0.66	6.5	20	0.89	5800	0.24677	0	1.4806	3100
1.064	0.66	6.5	40	0.89	7900	0.49354	0	2.9612	6500
1.064	0.66	6.5	50	0.89	8300	0.61693	0	3.7016	7200
1.064	0.66	6.5	60	0.89	8600	0.74031	0	4.4419	7700
1.064	0.66	6.5	70	0.89	8800	0.8637	0	5.1822	8000
1.064	0.66	6.5	80	0.89	9000	0.98708	0	5.9225	8200
1.064	0.66	6.5	90	0.89	9100	1.11047	1000	6.6628	8400
1.064	0.66	6.5	100	0.89	9200	1.23385	1800	7.4031	8600
1.064	0.66	6.5	110	0.89	9300	1.35724	2500	8.1434	8700
1.064	0.66	6.5	120	0.89	9300	1.48062	3100	8.8837	8800
1.064	0.66	6.5	130	0.89	9400	1.60401	3600	9.624	8900
1.064	0.66	6.5	140	0.89	9400	1.72739	4100	10.3643	9000
1.064	0.66	6.5	150	0.89	9500	1.85078	4400	11.1047	9100
1.064	0.66	6.5	200	0.89	9600	2.4677	5800	14.8062	9300
1.064	0.66	6.5	300	0.89	9800	3.70155	7200	22.2093	9600
1.064	0.66	6.5	400	0.89	9800	4.9354	7900	29.6124	9700
1.064	0.66	6.5	500	0.89	9900	6.16925	8300	37.0155	9800
1.064	0.66	6.5	33	0.8	8600	0.74031	0	4.4419	7700
1.064	0.66	6.5	33	0.85	8100	0.55523	0	3.3314	6900

1.064	0.66	6.5	33	0.9	7200	0.37016	0	2.2209	5300
1.064	0.66	6.5	33	0.95	4400	0.18508	0	1.1105	1000
1.064	0.66	6.5	33	0.99	0	0.03702	0	0.2221	0

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APPENDIX K. LASER SENSITIVITY FULL 2^K VALUES

Diameter (m)	Gaussian Factor M	Power (kW)	Reflectance (%)	Wavelength (um)	Maximum Effective Range (m)	Range First T1E (m)	Range First T2E (m)
0.3	5	10	0.8	1.6	8600	0	7700
0.66	8	150	0.8	1.064	9800	7600	9600
0.3	5	150	0.8	1.6	10000	9100	9900
0.66	5	150	0.99	1.6	2400	0	0
0.66	5	10	0.99	1.064	0	0	0
0.66	5	10	0.8	1.6	4200	0	500
0.66	5	150	0.8	1.064	9600	6100	9400
0.3	5	150	0.8	1.064	10000	9200	9900
0.66	5	10	0.99	1.6	0	0	0
0.66	5	150	0.99	1.064	2400	0	0
0.66	8	10	0.8	1.6	6300	0	3900
0.3	8	150	0.99	1.6	8700	0	7800
0.3	8	10	0.8	1.064	9100	2100	8600
0.66	5	10	0.8	1.064	4200	0	600
0.66	8	150	0.8	1.6	9800	7500	9600
0.3	5	10	0.99	1.064	0	0	0
0.66	8	10	0.99	1.064	0	0	0
0.3	5	150	0.99	1.6	8200	0	7000
0.3	8	10	0.8	1.6	9000	1600	8300
0.3	8	150	0.99	1.064	8900	0	8100
0.3	8	10	0.99	1.6	0	0	0
0.3	8	150	0.8	1.6	10000	9300	9900

0.3	8	10	0.99	1.064	0	0	0
0.66	8	150	0.8	1.064	9800	7600	9600
0.66	8	10	0.99	1.6	0	0	0
0.66	8	150	0.99	1.6	5100	0	2000
0.3	5	150	0.99	1.064	8300	0	7200
0.66	8	150	0.99	1.064	5200	0	2000
0.3	5	10	0.8	1.6	8600	0	7700
0.66	5	150	0.8	1.6	9600	6100	9400
0.3	5	10	0.8	1.064	8700	0	7900
0.3	8	150	0.8	1.064	10000	9400	9900

APPENDIX L. GLOBAL INFORMATION NETWORK ARCHITECTURE (GINA) ENGAGEMENTS FROM ENGAGEMENT QUERY

Mission ID	ThreatDesignator	ThreatDetectionAltitude_m	ThreatDetectionGroundRange_m	WeaponDesignator
ATFP 8	FIAC	1	1000	ADS
ATFP 9	Cessna	500	1500	ADS
ATFP 9	Cessna	500	1500	ADS
AW 9.3	AS-11	5	8000	ADS
SUW 1.10	FAC	1	1000	ADS
SUW 1.10	FAC	1	1000	ADS
SUW 1.10	FAC	1	1000	ADS
SUW 1.10	PC	1	1500	ADS
SUW 1.10	PC	1	1500	ADS
SUW 1.10	PC	1	1500	ADS
ATFP 15	FIAC	1	700	ADS
SUW 1.10	FIAC	1	700	ADS
SUW 1.10	FIAC	1	700	ADS
ATFP 15	FIAC	1	700	ADS
SUW 1.10	FIAC	1	700	ADS
SUW 1.10	PC	1	1500	ADS
ATFP 9	Cessna	500	1500	ADS
NCO 19.6	FIAC	1	500	ADS
NCO 19.6	FIAC	1	500	ADS
NCO	FIAC	1	500	ADS

19.9				
NCO 19.6	FIAC	1	500	ADS
SUW 1.10	FAC	1	1000	ADS
ATFP 4	Person	1	300	ADS
SUW 1.10	FIAC	1	700	ADS
ATFP 4	Person	1	300	ADS
ATFP 4	Person	1	300	ADS
NCO 19.6	Dhow	1	250	ADS
NCO 19.6	Dhow	1	250	ADS
NCO 19.6	Dhow	1	250	ADS
NCO 19.6	FIAC	1	500	ADS
NCO 19.9	FIAC	1	500	ADS
NCO 19.6	Dhow	1	250	ADS
ATFP 9	Cessna	500	1500	ADS
AW 1.4	MiG-29	30000	20000	LaWS
AW 1.5	F-14	1000	30000	LaWS
AW 1.5	MiG-29	10000	20000	LaWS
AW 1.6	Iranian UAV	500	10000	LaWS
AW 1.6	MiG-29	10000	20000	LaWS
AW 1.4	AS-11	5	7000	LaWS
AW 1.2	Iranian UAV	500	3000	LaWS
AW 9.1	F-14	40000	20000	LaWS
AW 1.2	AS-11	200	2500	LaWS
AW 1.2	Iranian UAV	500	3000	LaWS
AW 1.2	C-802	5	2000	LaWS
AW 1.2	AS-11	200	2500	LaWS
ATFP 9	Cessna	500	1500	LaWS
AW 1.2	C-802	5	2000	LaWS
AW 1.2	Iranian	500	3000	LaWS

	UAV			
ATFP 9	Iranian UAV	500	1000	LaWS
ATFP 9	Cessna	500	1500	LaWS
AW 1.2	C-802	5	2000	LaWS
ATFP 9	Iranian UAV	500	1000	LaWS
ATFP 15	FIAC	1	700	LaWS
ATFP 8	FIAC	1	1000	LaWS
AW 1.6	Iranian UAV	500	10000	LaWS
ATFP 9	Cessna	500	1500	LaWS
AW 1.13	C-802	5	7000	LaWS
AW 1.4	AS-11	5	7000	LaWS
NCO 19.9	Dhow	1	500	LaWS
ATFP 15	FIAC	1	700	LaWS
ATFP 9	Iranian UAV	500	1000	LaWS
AW 1.5	AS-11	5	1000	LaWS
AW 1.1	C-802	5	5000	LaWS
NCO 19.9	Dhow	1	500	LaWS
AW 1.5	MiG-29	10000	20000	LaWS
ATFP 15	FIAC	1	700	LaWS
AW 1.2	Iranian UAV	500	3000	LaWS
AW 1.2	AS-11	200	2500	LaWS
AW 1.2	C-802	5	2000	LaWS
ATFP 9	Cessna	500	1500	LaWS
ATFP 9	Iranian UAV	500	1000	LaWS
ATFP 15	FIAC	1	700	LaWS
AW 1.12	AS-11	5	10000	LaWS
AW	AS-11	5	10000	LaWS

1.12				
AW 1.2	AS-11	200	2500	LaWS
AW 1.5	AS-11	5	10000	LaWS
AW 1.6	AS-11	5	10000	LaWS
AW 1.6	AS-11	5	10000	LaWS
AW 1.6	AS-11	5	10000	LaWS
AW 1.13	AS-11	5	9000	LaWS
AW 1.13	AS-11	5	9000	LaWS
ATFP 8	FIAC	1	1000	LaWS
AW 1.6	C-802	5	15000	LaWS
AW 1.13	F-14	2000	20000	LaWS+
AW 1.13	MiG-29	10000	30000	LaWS+
AW 1.5	Iranian UAV	500	10000	LaWS+
AW 9.1	MiG-29	60000	30000	LaWS+
AW 9.4	Cessna	500	15000	LaWS+
AW 1.13	Iranian UAV	1000	15000	LaWS+
AW 1.4	MiG-29	30000	20000	LaWS+
AW 1.6	F-14	1000	30000	LaWS+
AW 1.6	Iranian UAV	500	10000	LaWS+
AW 9.4	Cessna	500	15000	LaWS+
AW 1.4	F-14	10000	10000	LaWS+
AW 9.3	AS-11	5	8000	LaWS+
AW 1.2	Iranian UAV	500	3000	LaWS+
AW 1.4	MiG-29	30000	20000	LaWS+
AW 1.2	AS-11	200	2500	LaWS+
AW 1.2	C-802	5	2500	LaWS+
AW 1.1	AS-11	5	5000	LaWS+
AW 1.2	Iranian UAV	500	3000	LaWS+
AW 1.2	AS-11	200	2500	LaWS+
AW 1.2	C-802	5	2000	LaWS+
AW 1.2	Iranian UAV	500	3000	LaWS+

ATFP 9	Iranian UAV	500	1000	LaWS+
AW 1.1	Iranian UAV	500	1000	LaWS+
AW 1.2	AS-11	200	2500	LaWS+
ATFP 9	Cessna	500	1500	LaWS+
AW 1.4	Iranian UAV	1000	2000	LaWS+
AW 1.2	C-802	5	2000	LaWS+
ATFP 9	Iranian UAV	500	1000	LaWS+
ATFP 9	Cessna	500	1500	LaWS+
AW 1.1	F-14	1000	10000	LaWS+
AW 9.3	AS-11	5	8000	LaWS+
AW 1.12	C-802	5	8000	LaWS+
AW 1.13	C-802	5	7000	LaWS+
AW 1.1	Iranian UAV	100	7000	LaWS+
NCO 19.9	Dhow	1	500	LaWS+
ATFP 9	Iranian UAV	500	1000	LaWS+
ATFP 9	Cessna	500	1000	LaWS+
AW 1.1	C-802	5	5000	LaWS+
NCO 19.9	FIAC	1	500	LaWS+
AW 1.2	Iranian UAV	500	3000	LaWS+
AW 1.4	MiG-29	30000	20000	LaWS+
AW 1.2	C-802	5	2000	LaWS+
ATFP 9	Cessna	500	1500	LaWS+
ATFP 9	Iranian UAV	500	1000	LaWS+
AW 1.13	AS-11	5	9000	LaWS+
AW 1.2	AS-11	200	2500	LaWS+
ATFP 9	Cessna	500	1500	LaWS+
SUW 2.3	FAC	1	4000	LaWS+

SUW 2.3	FAC	1	4000	LaWS+
SUW 2.3	PC	1	7000	LaWS+
SUW 2.3	PC	1	7000	LaWS+
AW 1.5	C-802	5	15000	LaWS+
ATFP 9	Iranian UAV	500	1000	MK 15
ATFP 9	Iranian UAV	500	1000	MK 15
ATFP 9	Iranian UAV	500	1500	MK 15
ATFP 9	Cessna	500	1500	MK 15
ATFP 9	Cessna	500	1500	MK 15
ATFP 9	Cessna	500	1500	MK 15
ATFP 9	Cessna	500	1500	MK 15
ATFP 9	Cessna	500	1500	MK 15
AW 1.2	AS-11	200	2500	MK 15
AW 1.2	AS-11	200	2500	MK 15
AW 1.2	AS-11	200	2500	MK 15
AW 1.2	AS-11	200	2500	MK 15
AW 1.2	C-802	5	2000	MK 15
AW 1.2	C-802	5	2000	MK 15
AW 1.2	C-802	5	2000	MK 15
AW 1.2	C-802	5	2000	MK 15
AW 1.2	Iranian UAV	500	3000	MK 15
AW 1.2	Iranian UAV	500	3000	MK 15
AW 1.2	Iranian UAV	500	3000	MK 15
AW 9.3	AS-11	5	8000	MK 15
AW 9.3	C-802	5	7000	MK 15
AW 9.4	Cessna	500	15000	MK 15
SUW 1.10	FIAC	1	700	MK 15
SUW 1.10	FIAC	1	700	MK 15
SUW 1.10	FIAC	1	700	MK 15

SUW 1.10	FIAC	1	700	MK 15
SUW 1.10	FAC	1	1000	MK 15
SUW 1.10	FAC	1	1000	MK 15
SUW 1.10	FAC	1	1000	MK 15
SUW 1.10	FAC	1	1000	MK 15
SUW 1.10	PC	1	1500	MK 15
SUW 1.10	PC	1	1500	MK 15
SUW 1.10	PC	1	1500	MK 15
SUW 1.10	PC	1	1500	MK 15
ATFP 9	Iranian UAV	500	1000	MK 15
AW 1.2	Iranian UAV	500	3000	MK 15
ATFP 15	FIAC	1	700	MK 38 Mod 2
ATFP 15	FIAC	1	700	MK 38 Mod 2
ATFP 15	FIAC	1	700	MK 38 Mod 2
ATFP 15	FIAC	1	700	MK 38 Mod 2
ATFP 9	Iranian UAV	500	1000	MK 38 Mod 2
ATFP 9	Iranian UAV	500	1000	MK 38 Mod 2
ATFP 9	Iranian UAV	500	1000	MK 38 Mod 2
ATFP 9	Iranian UAV	500	1000	MK 38 Mod 2
ATFP 9	Cessna	500	1500	MK 38 Mod 2
ATFP 9	Cessna	500	1500	MK 38 Mod 2

ATFP 9	Cessna	500	1500	MK 38 Mod 2
ATFP 9	Cessna	500	1500	MK 38 Mod 2
NCO 19.6	Dhow	1	250	MK 38 Mod 2
NCO 19.6	Dhow	1	250	MK 38 Mod 2
NCO 19.6	Dhow	1	250	MK 38 Mod 2
NCO 19.6	Dhow	1	250	MK 38 Mod 2
NCO 19.6	FIAC	1	500	MK 38 Mod 2
NCO 19.6	FIAC	1	500	MK 38 Mod 2
NCO 19.6	FIAC	1	500	MK 38 Mod 2
NCO 19.6	FIAC	1	500	MK 38 Mod 2
NCO 19.9	Dhow	1	500	MK 38 Mod 2
NCO 19.9	Dhow	1	500	MK 38 Mod 2
SUW 1.10	FIAC	1	700	MK 38 Mod 2
SUW 1.10	FIAC	1	700	MK 38 Mod 2
SUW 1.10	FIAC	1	700	MK 38 Mod 2
SUW 1.10	FIAC	1	700	MK 38 Mod 2
SUW 1.10	FAC	1	1000	MK 38 Mod 2
SUW 1.10	FAC	1	1000	MK 38 Mod 2
SUW 1.10	FAC	1	1000	MK 38 Mod 2
SUW 1.10	FAC	1	1000	MK 38 Mod 2
SUW 1.10	PC	1	1500	MK 38 Mod 2

SUW 1.10	PC	1	1500	MK 38 Mod 2
SUW 1.10	PC	1	1500	MK 38 Mod 2
SUW 1.10	PC	1	1500	MK 38 Mod 2
SUW 2.3	PC	1	7000	MK 38 Mod 2
AW 9.3	AS-11	5	8000	MK 54
AW 9.3	C-802	5	7000	MK 54
NCO 19.9	FIAC	1	500	MK 54
SUW 2.3	FAC	1	4000	MK 54
SUW 2.3	FAC	1	4000	MK 54
SUW 2.3	PC	1	7000	MK 54
AW 1.1	F-14	1000	10000	MLD
AW 1.13	MiG-29	10000	30000	MLD
AW 1.4	MiG-29	30000	20000	MLD
AW 1.6	Iranian UAV	500	10000	MLD
AW 1.1	MiG-29	700	10000	MLD
AW 1.5	F-14	1000	30000	MLD
AW 1.5	MiG-29	10000	20000	MLD
AW 1.6	F-14	1000	30000	MLD
AW 9.1	F-14	40000	20000	MLD
AW 9.4	Iranian UAV	250	10000	MLD
AW 1.5	MiG-29	10000	20000	MLD
AW 1.6	MiG-29	10000	20000	MLD
AW 9.4	Iranian UAV	250	10000	MLD
AW 1.1	F-14	1000	10000	MLD
AW 1.2	Iranian UAV	500	3000	MLD
AW 1.4	C-802	5	3000	MLD
AW 9.3	C-802	5	7000	MLD
AW 9.1	F-14	40000	20000	MLD

AW 1.2	AS-11	200	2500	MLD
AW 1.2	C-802	5	2000	MLD
AW 1.5	F-14	1000	30000	MLD
AW 1.2	AS-11	200	2500	MLD
ATFP 9	Cessna	500	1500	MLD
AW 1.2	C-802	5	2000	MLD
AW 1.2	Iranian UAV	500	3000	MLD
ATFP 9	Iranian UAV	500	1000	MLD
AW 1.2	AS-11	200	2500	MLD
ATFP 9	Cessna	500	1500	MLD
AW 9.4	Cessna	500	15000	MLD
AW 1.13	F-14	2000	20000	MLD
AW 1.4	Iranian UAV	1000	2000	MLD
AW 1.13	Iranian UAV	1000	15000	MLD
AW 1.2	C-802	5	2000	MLD
ATFP 9	Iranian UAV	500	1000	MLD
AW 9.4	Iranian UAV	250	10000	MLD
ATFP 15	FIAC	1	700	MLD
ATFP 8	FIAC	1	1000	MLD
ATFP 9	Cessna	500	1500	MLD
ATFP 15	FIAC	1	700	MLD
ATFP 9	Iranian UAV	500	1000	MLD
ATFP 9	Iranian UAV	500	1000	MLD
ATFP 8	FIAC	1	1000	MLD
ATFP 9	Cessna	500	1500	MLD
AW 1.5	MiG-29	10000	20000	MLD
ATFP 15	FIAC	1	700	MLD
AW 1.4	C-802	5	3000	MLD
NCO	FIAC	1	500	MLD

19.9				
AW 1.2	Iranian UAV	500	3000	MLD
AW 1.4	F-14	10000	10000	MLD
AW 1.2	AS-11	200	2500	MLD
AW 1.2	C-802	5	2000	MLD
ATFP 15	FIAC	1	700	MLD
AW 1.13	AS-11	5	9000	MLD
AW 1.5	AS-11	5	10000	MLD
AW 1.6	AS-11	5	10000	MLD
AW 1.6	AS-11	5	10000	MLD
AW 1.13	F-14	2000	20000	MLD
AW 1.12	AS-11	5	10000	MLD
AW 1.2	Iranian UAV	500	3000	MLD
AW 1.6	Iranian UAV	5	10000	MLD
AW 1.5	C-802	5	15000	MLD
AW 1.2	C-802	5	2000	RIM-116
AW 1.1	C-802	5	5000	RIM-66 MR
AW 1.1	F-14	1000	10000	RIM-66 MR
AW 1.1	Iranian UAV	100	7000	RIM-66 MR
AW 1.12	AS-11	5	10000	RIM-66 MR
AW 1.13	AS-11	5	9000	RIM-66 MR
AW 1.13	AS-11	5	9000	RIM-66 MR
AW 1.13	AS-11	5	9000	RIM-66 MR
AW 1.13	C-802	5	7000	RIM-66 MR
AW 1.13	MiG-29	10000	30000	RIM-66 MR
AW 1.4	Iranian UAV	1000	2000	RIM-66 MR

AW 1.5	AS-11	5	10000	RIM-66 MR
AW 1.5	MiG-29	10000	20000	RIM-66 MR
AW 1.5	C-802	5	16000	RIM-66 MR
AW 1.5	F-14	1000	30000	RIM-66 MR
AW 1.5	Iranian UAV	500	10000	RIM-66 MR
AW 1.6	AS-11	5	10000	RIM-66 MR
AW 1.6	MiG-29	10000	20000	RIM-66 MR
AW 1.6	Iranian UAV	500	10000	RIM-66 MR
AW 9.1	F-14	40000	20000	RIM-66 MR
AW 9.1	MiG-29	60000	30000	RIM-66 MR
AW 9.3	AS-11	5	8000	RIM-66 MR
SUW 2.3	FAC	1	4000	RIM-66 MR
SUW 2.3	PC	1	7000	RIM-66 MR
AW 1.6	F-14	1000	30000	TLS
AW 1.6	F-14	1000	30000	TLS
AW 9.3	AS-11	5	8000	TLS
AW 9.3	AS-11	5	8000	TLS
AW 9.4	Cessna	500	15000	TLS
AW 1.6	MiG-29	10000	20000	TLS
AW 9.1	F-14	40000	20000	TLS
AW 9.3	AS-11	5	8000	TLS
AW 1.2	Iranian UAV	500	3000	TLS
AW 1.4	AS-11	5	7000	TLS
AW 1.2	AS-11	200	2500	TLS
AW 1.2	Iranian UAV	500	3000	TLS
AW 1.2	C-802	5	2000	TLS
AW 1.2	AS-11	200	2500	TLS
ATFP 9	Cessna	500	1500	TLS
AW 1.6	F-14	1000	30000	TLS
AW 1.2	C-802	5	2000	TLS
AW 1.2	Iranian UAV	500	3000	TLS
ATFP 9	Iranian UAV	500	1000	TLS
ATFP 9	Cessna	500	1500	TLS

AW 1.2	AS-11	200	2500	TLS
AW 1.2	C-802	5	2000	TLS
ATFP 9	Iranian UAV	500	1000	TLS
ATFP 15	FIAC	1	700	TLS
ATFP 9	Cessna	500	1500	TLS
ATFP 15	FIAC	1	700	TLS
ATFP 9	Iranian UAV	500	1000	TLS
AW 9.3	AS-11	5	8000	TLS
AW 1.4	AS-11	5	7000	TLS
AW 9.3	C-802	5	7000	TLS
ATFP 15	FIAC	1	700	TLS
AW 1.4	C-802	5	3000	TLS
AW 1.2	Iranian UAV	500	3000	TLS
AW 1.4	F-14	10000	10000	TLS
AW 1.2	AS-11	200	2500	TLS
AW 1.2	C-802	5	2000	TLS
ATFP 9	Cessna	500	1500	TLS
ATFP 9	Iranian UAV	500	1000	TLS
ATFP 15	FIAC	1	700	TLS
SUW 2.3	FAC	1	4000	TLS
AW 9.4	Cessna	500	15000	TLS

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APPENDIX M. MAP AWARE NON-UNIFORM AUTOMATA (MANA) SIMULATION RESULTS

MANA Result for UAV Scenario				
	LaWS	LaWS+	TLS	MLD
1	3	7	1	5
2	4	7	0	5
3	3	7	0	5
4	3	7	1	5
5	4	7	1	5
6	3	7	0	5
7	4	7	0	5
8	4	7	0	5
9	4	7	1	5
10	4	7	1	5
11	3	7	1	5
12	4	7	0	4
13	4	7	0	5
14	3	7	0	5
15	4	7	1	4
16	3	7	1	5
17	4	7	1	5
18	3	7	0	5
19	3	7	0	4
20	4	7	0	5
21	4	7	0	5
22	3	7	1	5
23	3	7	0	5
24	3	7	1	5
25	4	7	1	5
26	4	7	1	5
27	4	7	0	5
28	4	7	0	5
29	4	7	0	5
30	3	7	0	5

Average	3.57	7.00	0.43	4.90

MANA Result for Small Boat Scenario				
	LaWS	LaWS+	TLS	MLD
1	3	7	0	3
2	2	7	0	3
3	3	7	0	3
4	3	7	0	3
5	3	7	0	3
6	2	7	0	3
7	2	7	0	3
8	2	7	0	4
9	3	7	0	3
10	3	7	0	3
11	2	7	0	3
12	3	7	0	3
13	3	7	0	3
14	2	7	0	3
15	3	7	0	3
16	3	7	0	3
17	2	7	0	3
18	2	7	0	3
19	3	7	0	3
20	3	7	0	3
21	3	7	0	3
22	3	7	0	3
23	2	7	0	3
24	3	7	0	3
25	2	7	0	3
26	3	7	0	3
27	3	7	0	3
28	2	7	0	3
29	2	7	0	3
30	2	7	0	3
Average	2.57	7.00	0.00	3.03

MANA Result for Supersonic ASCM Scenario				
	LaWS	LaWS+	TLS	MLD
1	0	2	0	0
2	0	2	0	0
3	0	2	0	0
4	0	2	0	0
5	0	1	0	0
6	0	2	0	0
7	0	2	0	0
8	0	1	0	0
9	0	2	0	0
10	0	2	0	0
11	0	2	0	0
12	0	2	0	0
13	0	2	0	0
14	0	2	0	0
15	0	2	0	0
16	0	2	0	0
17	0	2	0	0
18	0	2	0	0
19	0	2	0	0
20	0	2	0	0
21	0	2	0	0
22	0	2	0	0
23	0	2	0	0
24	0	1	0	0
25	0	2	0	0
26	0	2	0	0
27	0	2	0	0
28	0	2	0	0
29	0	2	0	0
30	0	2	0	0
Average	0.00	1.90	0.00	0.00

MANA Result for Subsonic ASCM Scenario				
	LaWS	LaWS+	TLS	MLD
1	1	5	0	2
2	1	5	0	2
3	1	5	0	2
4	2	5	0	2
5	1	5	0	2
6	2	5	0	2
7	1	5	0	2
8	1	5	0	2
9	1	5	0	2
10	1	5	0	2
11	2	5	0	2
12	1	5	0	2
13	2	5	0	2
14	1	5	0	2
15	1	5	0	2
16	1	5	0	2
17	2	5	0	2
18	1	5	0	2
19	1	5	0	2
20	1	5	0	2
21	1	5	0	2
22	1	5	0	2
23	2	5	0	2
24	1	5	0	2
25	2	5	0	2
26	1	5	0	2
27	1	5	0	2
28	1	5	0	2
29	1	5	0	2
30	1	5	0	2
Average	1.23	5.00	0.00	2.00

Multiple targets For LaWS			
	Subsonic ASCM	UAV	Small Boat
1	1	3	1
2	1	3	1
3	1	3	1
4	1	3	0
5	1	3	1
6	1	3	1
7	1	3	1
8	1	3	2
9	1	3	1
10	1	3	1
11	1	3	1
12	1	3	1
13	1	3	1
14	1	3	1
15	1	3	1
16	1	3	1
17	1	3	1
18	1	3	2
19	1	3	1
20	1	3	1
21	1	3	1
22	1	3	1
23	1	3	1
24	1	3	2
25	1	3	1
26	1	3	2
27	1	3	1
28	1	3	1
29	1	3	1
30	1	3	1
Average	1.00	3.00	1.10

Multiple targets For LaWS+			
	Subsonic ASCM	UAV	Small Boat
1	1	3	5
2	1	3	5
3	1	3	5
4	1	3	5
5	1	3	5
6	1	3	5
7	1	3	5
8	1	3	5
9	1	3	5
10	1	3	5
11	1	3	5
12	1	3	5
13	1	3	5
14	1	3	5
15	1	3	5
16	1	3	5
17	1	3	5
18	1	3	5
19	1	3	5
20	1	3	5
21	1	3	5
22	1	3	5
23	1	3	5
24	1	3	5
25	1	3	5
26	1	3	5
27	1	3	5
28	1	3	5
29	1	3	5
30	1	3	5
Average	1.00	3.00	5.00

Multiple targets MLD			
	Subsonic ASCM	UAV	Small Boat
1	1	3	3
2	1	3	3
3	1	3	2
4	1	3	3
5	1	3	2
6	1	3	2
7	1	3	3
8	1	3	3
9	1	3	3
10	1	3	1
11	1	3	1
12	1	3	3
13	1	3	2
14	1	3	1
15	1	3	2
16	1	3	3
17	1	3	2
18	1	3	2
19	1	3	2
20	1	3	3
21	1	3	2
22	1	3	3
23	1	3	3
24	1	3	3
25	1	3	3
26	1	3	3
27	1	3	2
28	1	3	2
29	1	3	3
30	1	3	3
Average	1.00	3.00	2.43

Multiple targets TLS			
	Subsonic ASCM	UAV	Small Boat
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	0
13	0	0	0
14	0	0	0
15	0	0	0
16	0	0	0
17	0	0	0
18	0	0	0
19	0	0	0
20	0	0	0
21	0	0	0
22	0	0	0
23	0	0	0
24	0	0	0
25	0	0	0
26	0	0	0
27	0	0	0
28	0	0	0
29	0	0	0
30	0	0	0
Average	0.00	0.00	0.00

APPENDIX N. FINAL PROGRESS REVIEW (FPR) SLIDES


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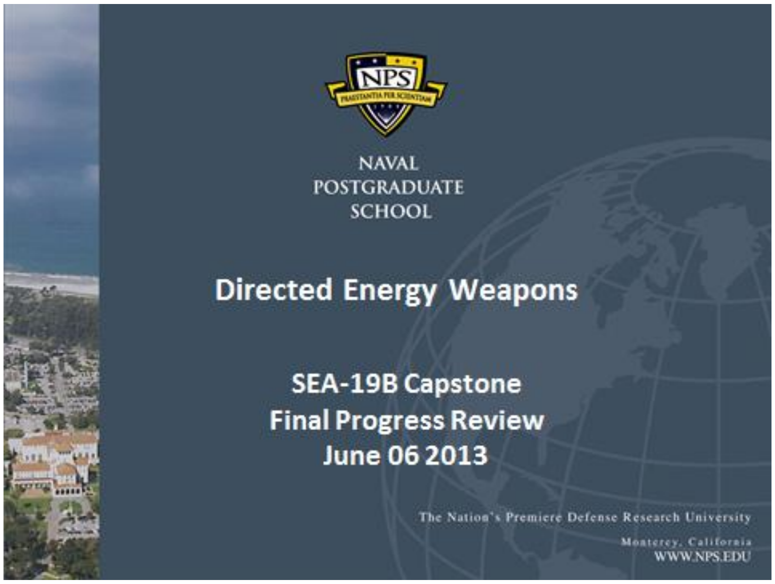
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Directed Energy Weapons

SEA-19B Capstone
Final Progress Review
June 06 2013

The Nation's Premiere Defense Research University
Monterey, California
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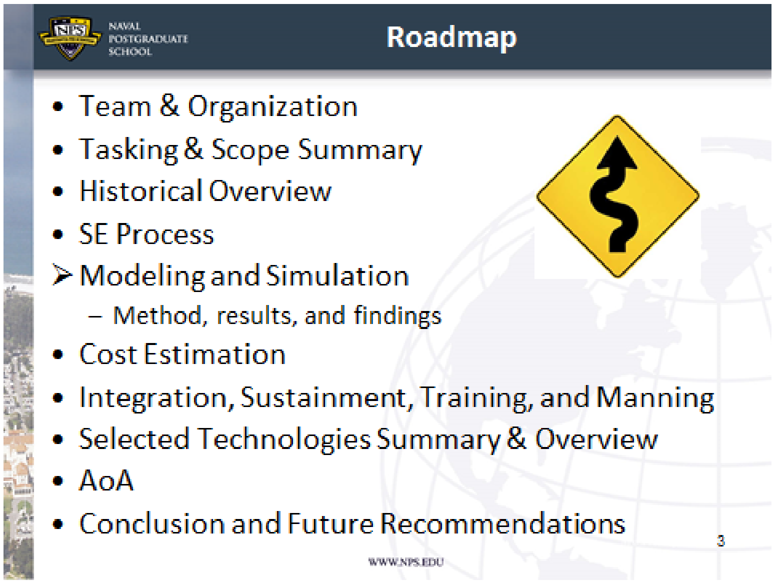

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Roadmap

- Team & Organization
- Tasking & Scope Summary
- Historical Overview
- SE Process
- ➢ Modeling and Simulation
  - – Method, results, and findings
- Cost Estimation
- Integration, Sustainment, Training, and Manning
- Selected Technologies Summary & Overview
- AoA
- Conclusion and Future Recommendations

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Bottom Line Up Front

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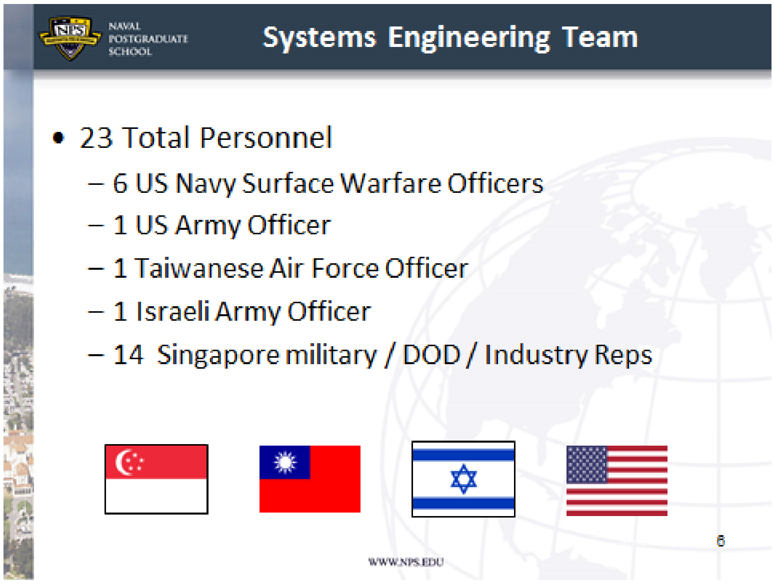
Bottom Line Up Front

- DEW can and will be "game changing," just not in the next 4 years
- Current DEW tech levels inadequate for "one for one" weapon replacement
- Aggregate estimate for shipboard fuel cost associated with a DEW shot is less than $1
  - Compare to $800K to $3.6M AD interceptors
- Tactical Laser System (TLS) currently offers the best "bang for the buck"
- Active Denial System (ADS) has potential to fill unique capability gap for Anti-Terrorism and Force Protection
- Both TLS and ADS are significantly cheaper than other alternatives of comparable performance



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Systems Engineering Team

- 23 Total Personnel
  - 6 US Navy Surface Warfare Officers
  - 1 US Army Officer
  - 1 Taiwanese Air Force Officer
  - 1 Israeli Army Officer
  - 14 Singapore military / DOD / Industry Reps

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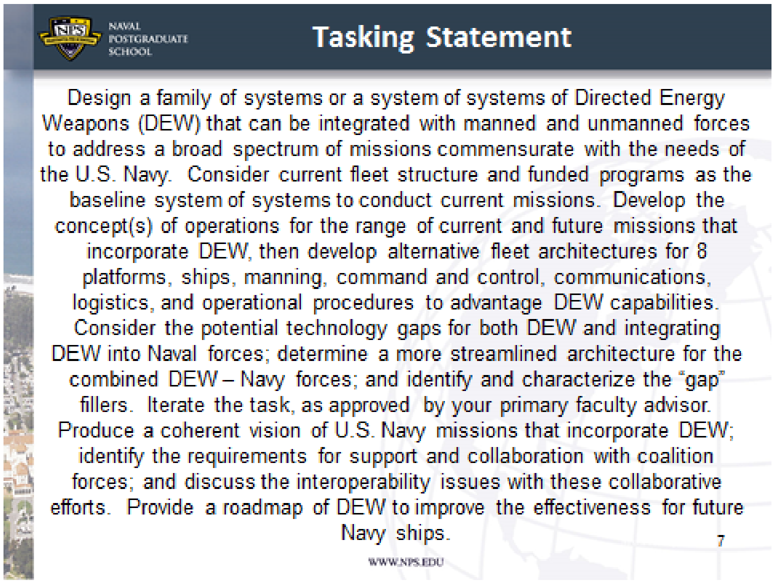
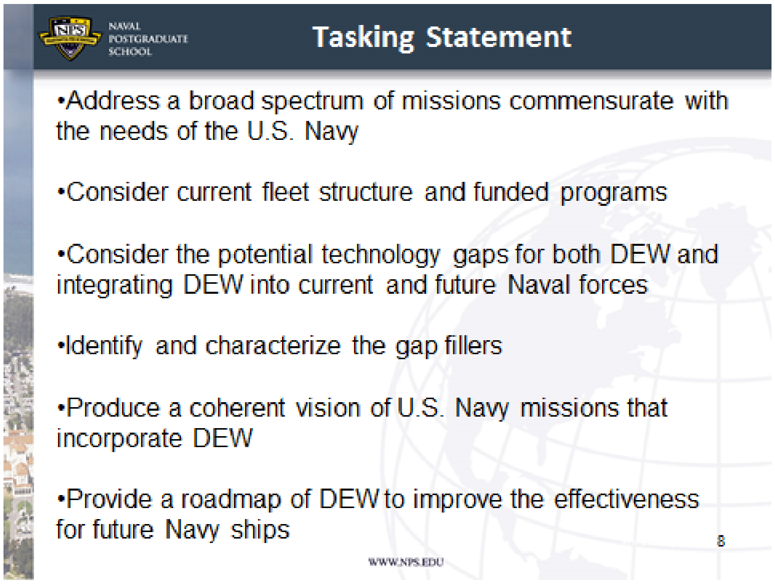


Tasking Statement

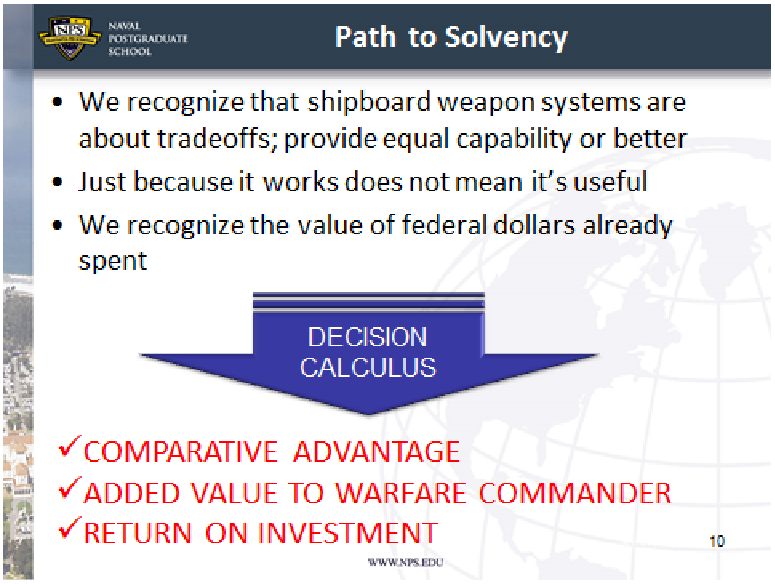
Design a family of systems or a system of systems of Directed Energy Weapons (DEW) that can be integrated with manned and unmanned forces to address a broad spectrum of missions commensurate with the needs of the U.S. Navy. Consider current fleet structure and funded programs as the baseline system of systems to conduct current missions. Develop the concept(s) of operations for the range of current and future missions that incorporate DEW, then develop alternative fleet architectures for 8 platforms, ships, manning, command and control, communications, logistics, and operational procedures to advantage DEW capabilities. Consider the potential technology gaps for both DEW and integrating DEW into Naval forces; determine a more streamlined architecture for the combined DEW – Navy forces; and identify and characterize the "gap" fillers. Iterate the task, as approved by your primary faculty advisor. Produce a coherent vision of U.S. Navy missions that incorporate DEW; identify the requirements for support and collaboration with coalition forces; and discuss the interoperability issues with these collaborative efforts. Provide a roadmap of DEW to improve the effectiveness for future Navy ships.



Tasking Statement

- Address a broad spectrum of missions commensurate with the needs of the U.S. Navy
- Consider current fleet structure and funded programs
- Consider the potential technology gaps for both DEW and integrating DEW into current and future Naval forces
- Identify and characterize the gap fillers
- Produce a coherent vision of U.S. Navy missions that incorporate DEW
- Provide a roadmap of DEW to improve the effectiveness for future Navy ships

What is the problem?

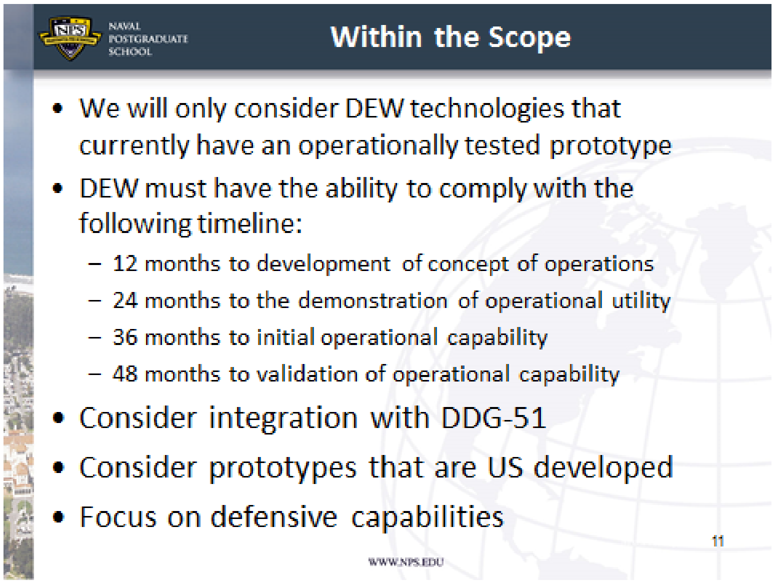


Path to Solvency

- We recognize that shipboard weapon systems are about tradeoffs; provide equal capability or better
- Just because it works does not mean it's useful
- We recognize the value of federal dollars already spent

DECISION CALCULUS

✓COMPARATIVE ADVANTAGE
✓ADDED VALUE TO WARFARE COMMANDER
✓RETURN ON INVESTMENT



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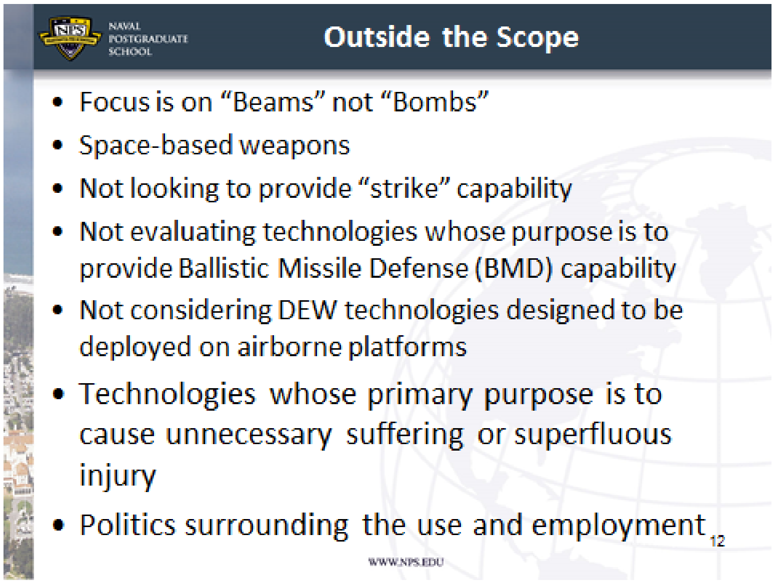
Within the Scope

- We will only consider DEW technologies that currently have an operationally tested prototype
- DEW must have the ability to comply with the following timeline:
  - 12 months to development of concept of operations
  - 24 months to the demonstration of operational utility
  - 36 months to initial operational capability
  - 48 months to validation of operational capability
- Consider integration with DDG-51
- Consider prototypes that are US developed
- Focus on defensive capabilities



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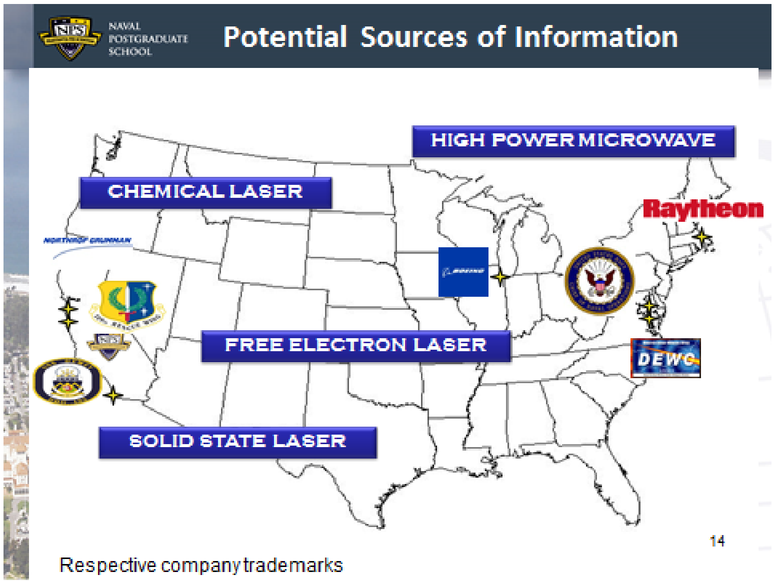
Outside the Scope

- Focus is on “Beams” not “Bombs”
- Space-based weapons
- Not looking to provide “strike” capability
- Not evaluating technologies whose purpose is to provide Ballistic Missile Defense (BMD) capability
- Not considering DEW technologies designed to be deployed on airborne platforms
- Technologies whose primary purpose is to cause unnecessary suffering or superfluous injury
- Politics surrounding the use and employment

Stakeholders

NPS and N9I are the two project stakeholders.

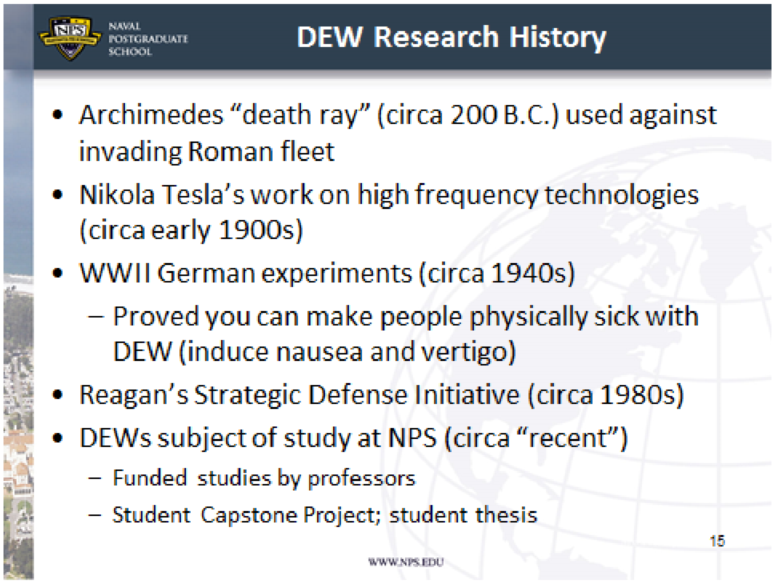
13



Potential Sources of Information

14

Respective company trademarks



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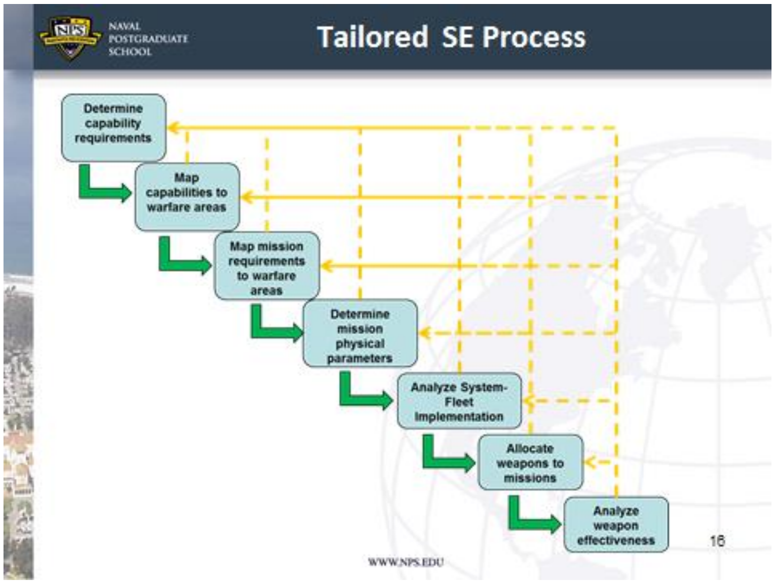
DEW Research History

- Archimedes "death ray" (circa 200 B.C.) used against invading Roman fleet
- Nikola Tesla's work on high frequency technologies (circa early 1900s)
- WWII German experiments (circa 1940s)
  - Proved you can make people physically sick with DEW (induce nausea and vertigo)
- Reagan's Strategic Defense Initiative (circa 1980s)
- DEWs subject of study at NPS (circa "recent")
  - Funded studies by professors
  - Student Capstone Project; student thesis



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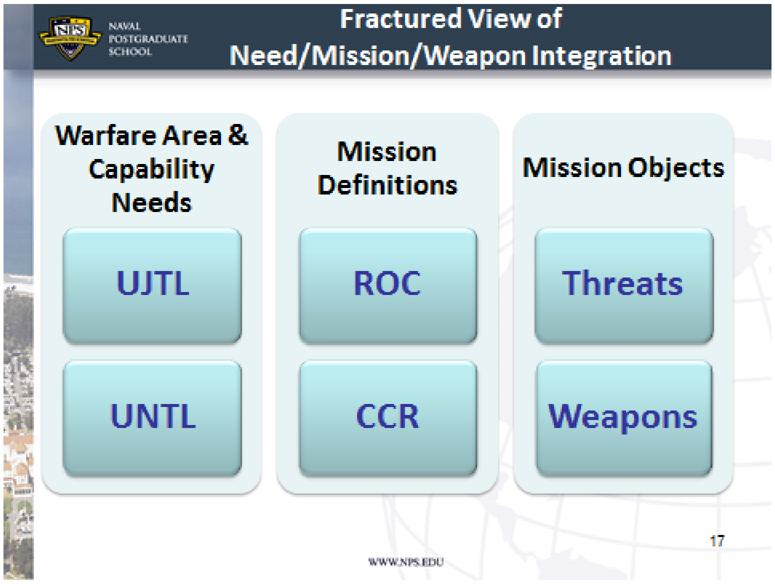
Tailored SE Process

Determine capability requirements
Map capabilities to warfare areas
Map mission requirements to warfare areas
Determine mission physical parameters
Analyze System-Fleet Implementation
Allocate weapons to missions
Analyze weapon effectiveness



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Fractured View of Need/Mission/Weapon Integration

Warfare Area & Capability Needs
- UJTL
- UNTL

Mission Definitions
- ROC
- CCR

Mission Objects
- Threats
- Weapons

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17

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Needs/Mission/Weapon Mapping Method

Universal Naval Task List

- Identify Navy weapon needs

Required Operational Capabilities/Critical Capabilities Requirements

- Identify specific weapon missions/use cases

Weapon Systems + Threats

- Identify context appropriate weapons and threats for evaluation

18

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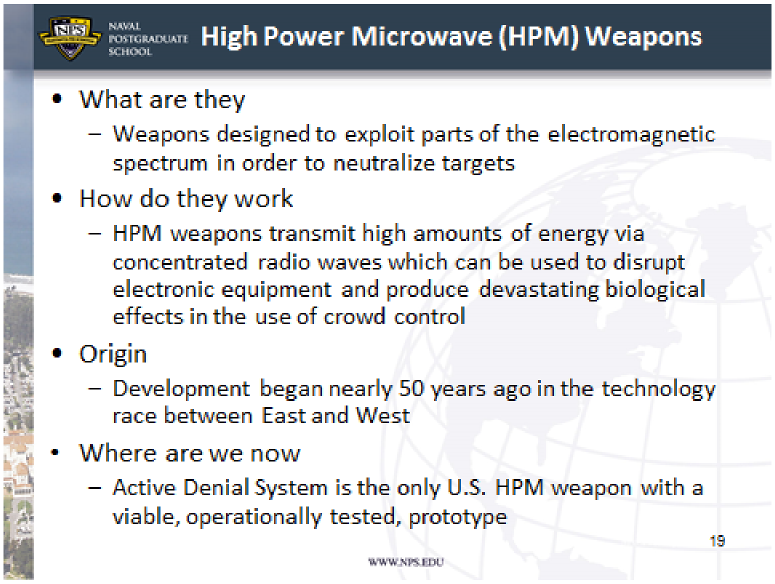
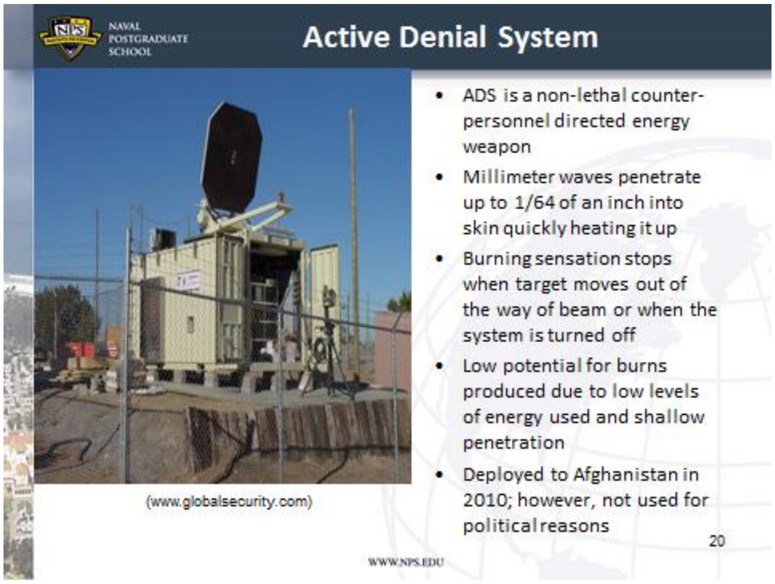


High Power Microwave (HPM) Weapons

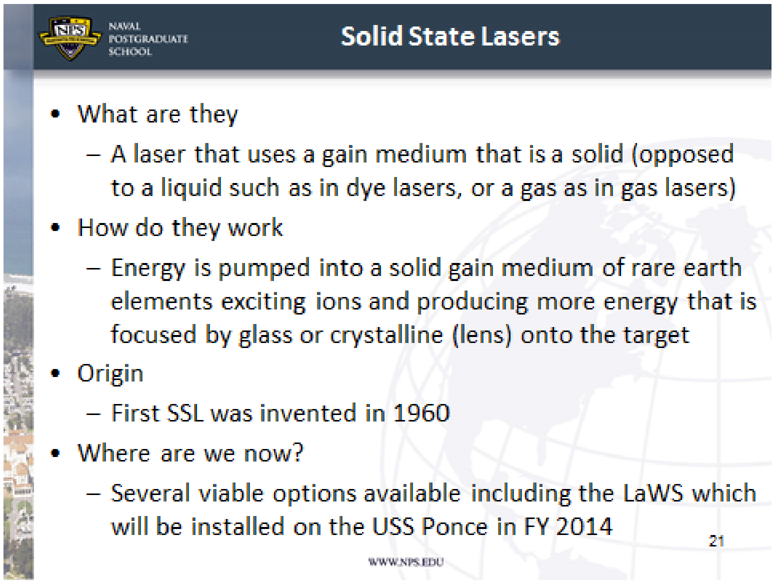
- What are they
  - Weapons designed to exploit parts of the electromagnetic spectrum in order to neutralize targets
- How do they work
  - HPM weapons transmit high amounts of energy via concentrated radio waves which can be used to disrupt electronic equipment and produce devastating biological effects in the use of crowd control
- Origin
  - Development began nearly 50 years ago in the technology race between East and West
- Where are we now
  - Active Denial System is the only U.S. HPM weapon with a viable, operationally tested, prototype



Active Denial System

(www.globalsecurity.com)

- ADS is a non-lethal counter-personnel directed energy weapon
- Millimeter waves penetrate up to 1/64 of an inch into skin quickly heating it up
- Burning sensation stops when target moves out of the way of beam or when the system is turned off
- Low potential for burns produced due to low levels of energy used and shallow penetration
- Deployed to Afghanistan in 2010; however, not used for political reasons



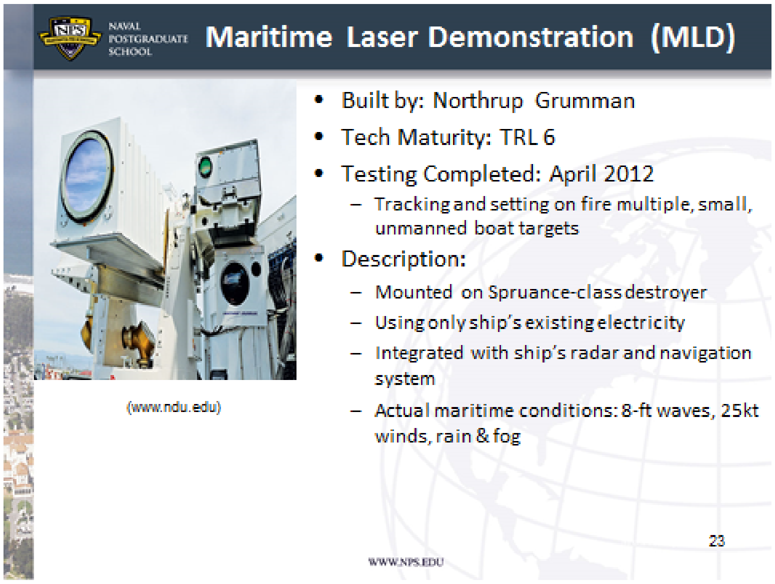
Solid State Lasers

- What are they
  - A laser that uses a gain medium that is a solid (opposed to a liquid such as in dye lasers, or a gas as in gas lasers)
- How do they work
  - Energy is pumped into a solid gain medium of rare earth elements exciting ions and producing more energy that is focused by glass or crystalline (lens) onto the target
- Origin
  - First SSL was invented in 1960
- Where are we now?
  - Several viable options available including the LaWS which will be installed on the USS Ponce in FY 2014

Laser Weapon System (LaWS)

(www.popsci.com)

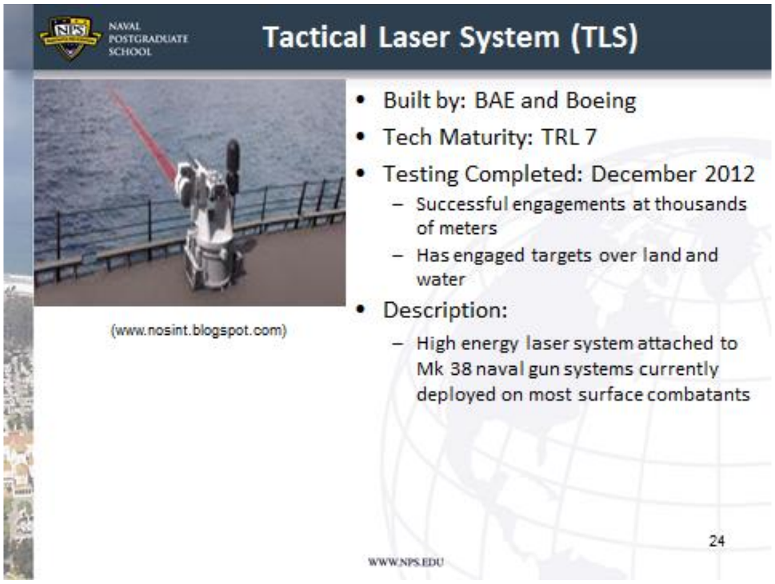
- Technical Maturity: TRL 6
- Working on ASCM capability
  -Not demonstrated yet
- NAVSEA 05 Tentative Green Light
- 33 - 150 KW technically acceptable to be fitted onto DDG-51
  -All blueprints and technical drawings exist



Maritime Laser Demonstration (MLD)

(www.ndu.edu)

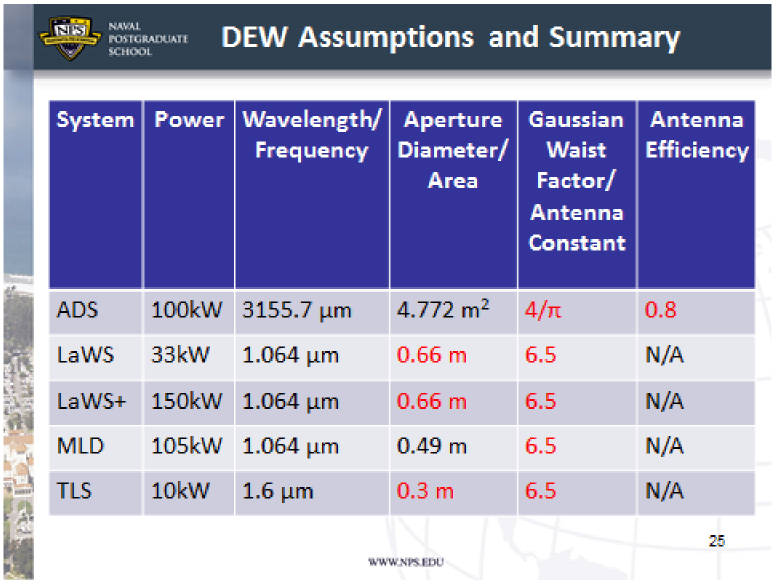
- Built by: Northrup Grumman
- Tech Maturity: TRL 6
- Testing Completed: April 2012
  - Tracking and setting on fire multiple, small, unmanned boat targets
- Description:
  - Mounted on Spruance-class destroyer
  - Using only ship's existing electricity
  - Integrated with ship's radar and navigation system
  - Actual maritime conditions: 8-ft waves, 25kt winds, rain & fog



Tactical Laser System (TLS)

(www.nosint.blogspot.com)

- Built by: BAE and Boeing
- Tech Maturity: TRL 7
- Testing Completed: December 2012
  - Successful engagements at thousands of meters
  - Has engaged targets over land and water
- Description:
  - High energy laser system attached to Mk 38 naval gun systems currently deployed on most surface combatants



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DEW Assumptions and Summary

System	Power	Wavelength/ Frequency	Aperture Diameter/ Area	Gaussian Waist Factor/ Antenna Constant	Antenna Efficiency
ADS	100kW	3155.7 μm	4.772 m^2	4/π	0.8
LaWS	33kW	1.064 μm	0.66 m	6.5	N/A
LaWS+	150kW	1.064 μm	0.66 m	6.5	N/A
MLD	105kW	1.064 μm	0.49 m	6.5	N/A
TLS	10kW	1.6 μm	0.3 m	6.5	N/A

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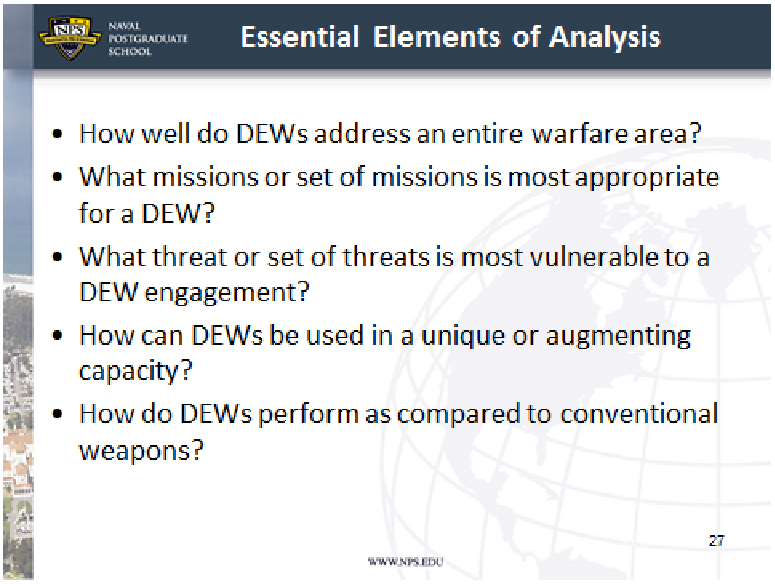
Modeling and Simulation



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Essential Elements of Analysis

- How well do DEWs address an entire warfare area?
- What missions or set of missions is most appropriate for a DEW?
- What threat or set of threats is most vulnerable to a DEW engagement?
- How can DEWs be used in a unique or augmenting capacity?
- How do DEWs perform as compared to conventional weapons?

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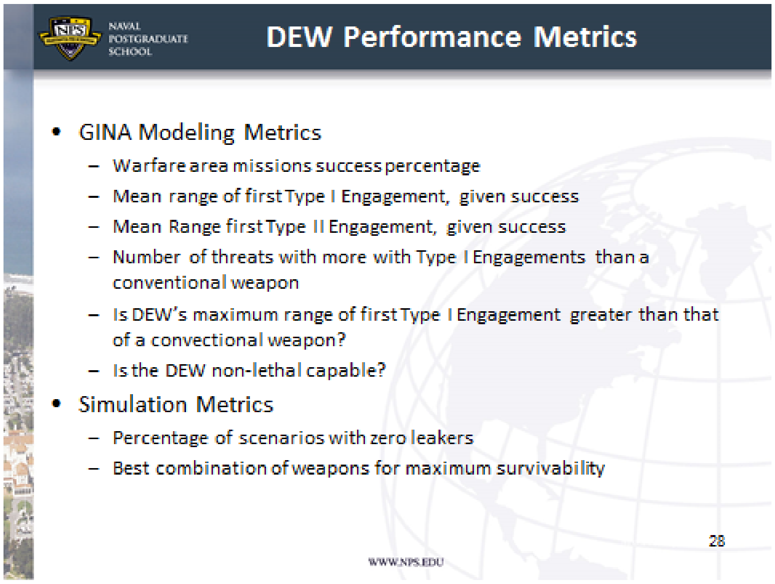

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DEW Performance Metrics

- GINA Modeling Metrics
  - Warfare area missions success percentage
  - Mean range of first Type I Engagement, given success
  - Mean Range first Type II Engagement, given success
  - Number of threats with more with Type I Engagements than a conventional weapon
  - Is DEW's maximum range of first Type I Engagement greater than that of a convectional weapon?
  - Is the DEW non-lethal capable?
- Simulation Metrics
  - Percentage of scenarios with zero leakers
  - Best combination of weapons for maximum survivability

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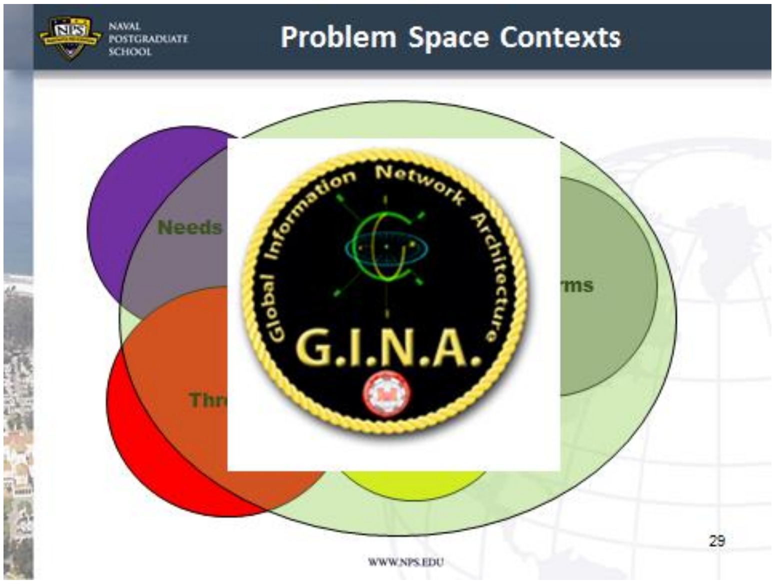

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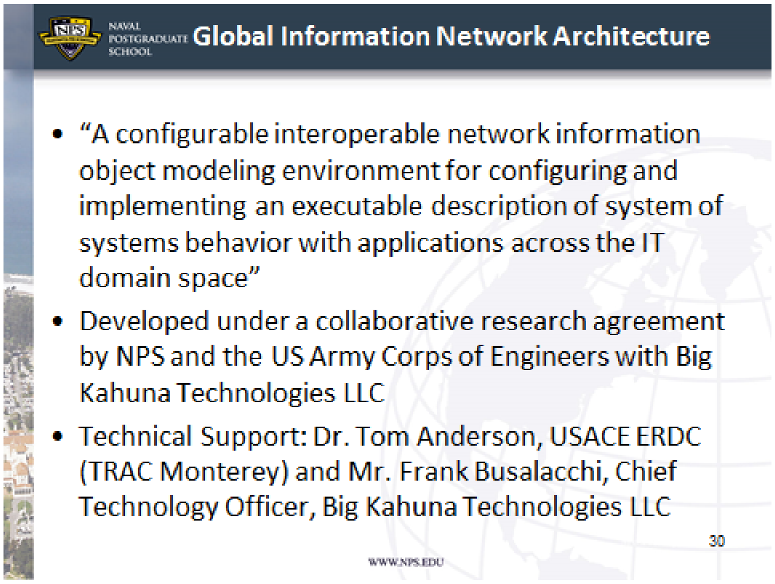
Problem Space Contexts



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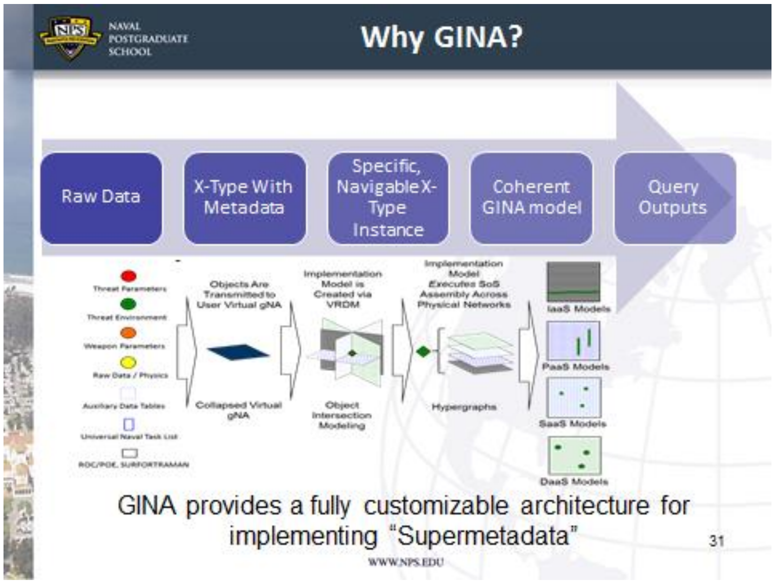
Global Information Network Architecture

- "A configurable interoperable network information object modeling environment for configuring and implementing an executable description of system of systems behavior with applications across the IT domain space"
- Developed under a collaborative research agreement by NPS and the US Army Corps of Engineers with Big Kahuna Technologies LLC
- Technical Support: Dr. Tom Anderson, USACE ERDC (TRAC Monterey) and Mr. Frank Busalacchi, Chief Technology Officer, Big Kahuna Technologies LLC

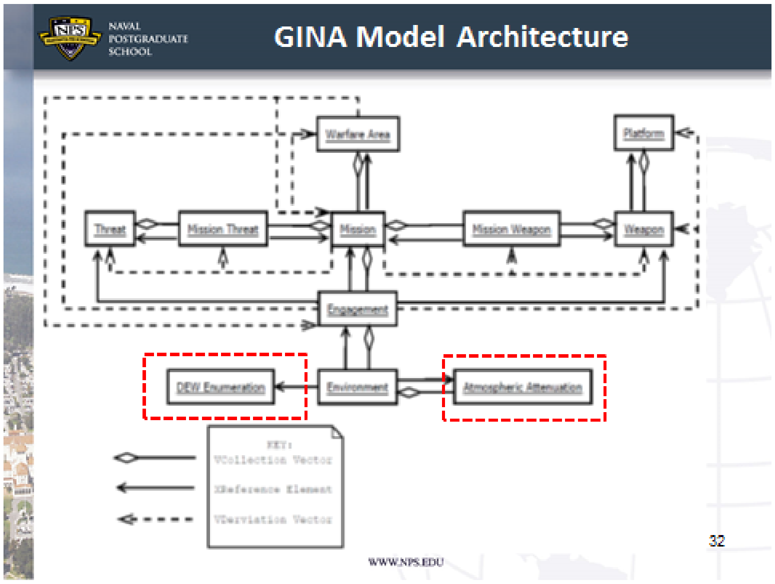


NAVAL POSTGRADUATE SCHOOL

Why GINA?

Raw Data → X-Type With Metadata → Specific, Navigable X-Type Instance → Coherent GINA model → Query Outputs

GINA provides a fully customizable architecture for implementing "Supermetadata"



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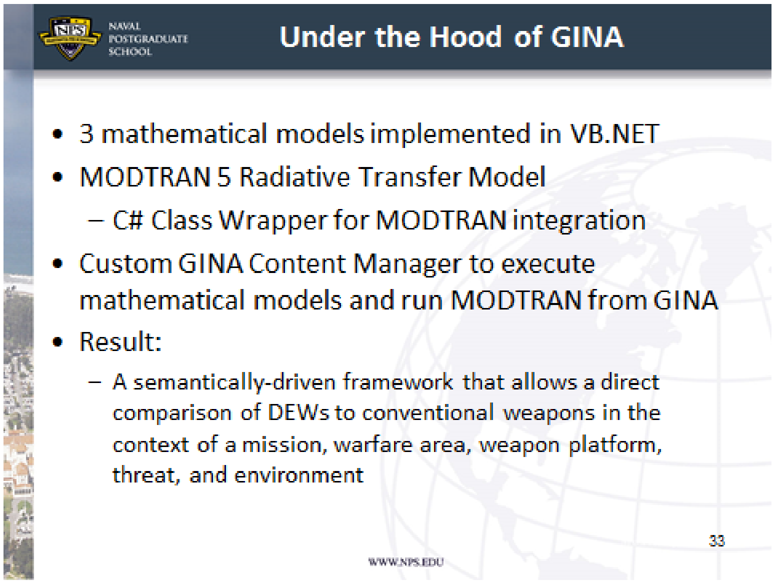
GINA Model Architecture

KEY:
VCollection Vector
XReference Element
VDerviation Vector



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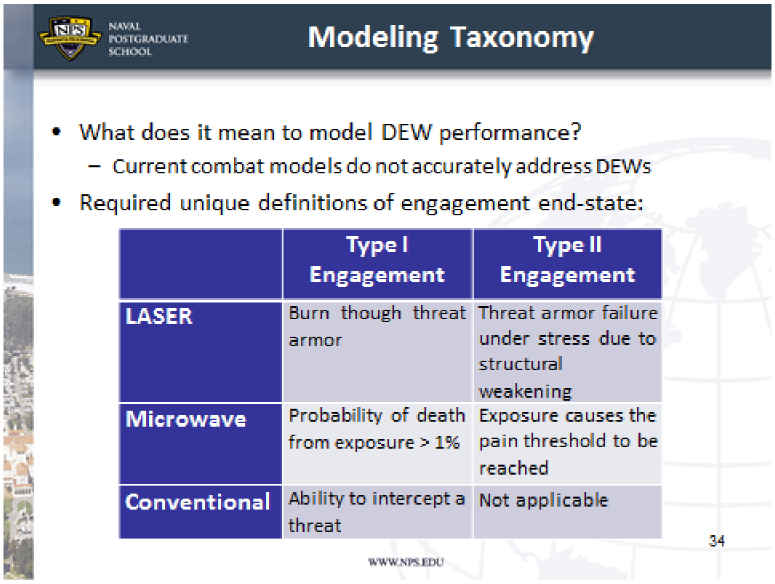
Under the Hood of GINA

- 3 mathematical models implemented in VB.NET
- MODTRAN 5 Radiative Transfer Model
  - C# Class Wrapper for MODTRAN integration
- Custom GINA Content Manager to execute mathematical models and run MODTRAN from GINA
- Result:
  - A semantically-driven framework that allows a direct comparison of DEWs to conventional weapons in the context of a mission, warfare area, weapon platform, threat, and environment



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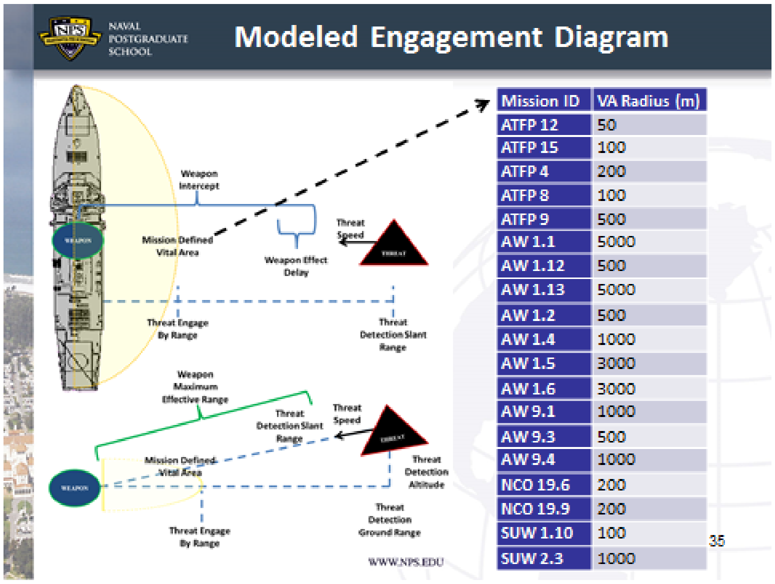
Modeling Taxonomy

- What does it mean to model DEW performance?
  - Current combat models do not accurately address DEWs
- Required unique definitions of engagement end-state:

	Type I Engagement	Type II Engagement
LASER	Burn though threat armor	Threat armor failure under stress due to structural weakening
Microwave	Probability of death from exposure > 1%	Exposure causes the pain threshold to be reached
Conventional	Ability to intercept a threat	Not applicable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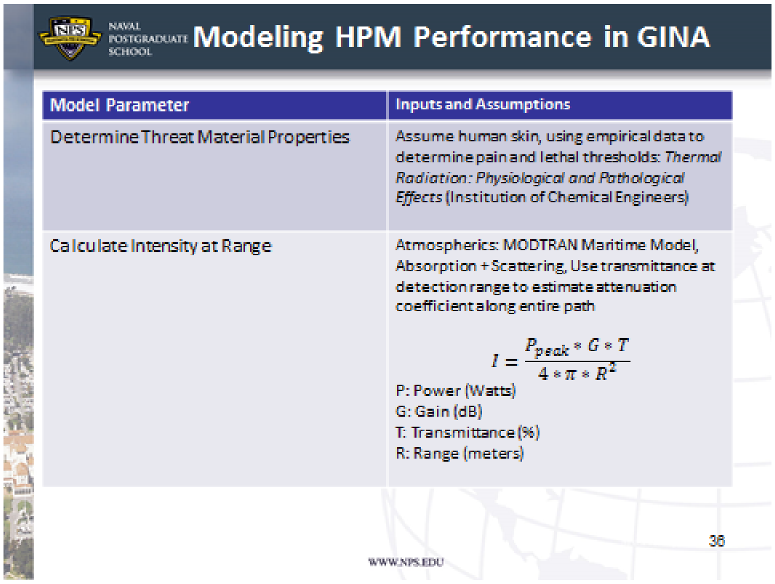
Modeled Engagement Diagram

Mission ID	VA Radius (m)
ATFP 12	50
ATFP 15	100
ATFP 4	200
ATFP 8	100
ATFP 9	500
AW 1.1	5000
AW 1.12	500
AW 1.13	5000
AW 1.2	500
AW 1.4	1000
AW 1.5	3000
AW 1.6	3000
AW 9.1	1000
AW 9.3	500
AW 9.4	1000
NCO 19.6	200
NCO 19.9	200
SUW 1.10	100
SUW 2.3	1000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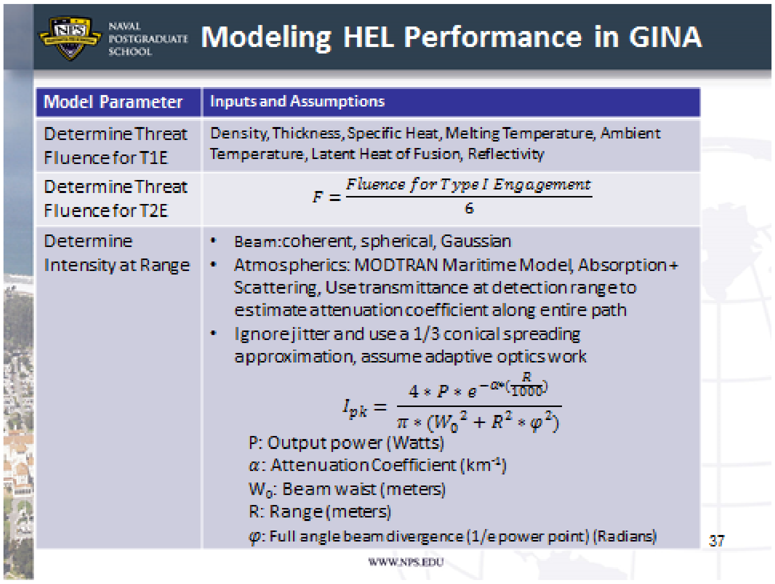
Modeling HPM Performance in GINA

Model Parameter	Inputs and Assumptions
Determine Threat Material Properties	Assume human skin, using empirical data to determine pain and lethal thresholds: *Thermal Radiation: Physiological and Pathological Effects* (Institution of Chemical Engineers)
Calculate Intensity at Range	Atmospherics: MODTRAN Maritime Model, Absorption + Scattering, Use transmittance at detection range to estimate attenuation coefficient along entire path $I = \dfrac{P_{peak} * G * T}{4 * \pi * R^2}$ P: Power (Watts) G: Gain (dB) T: Transmittance (%) R: Range (meters)



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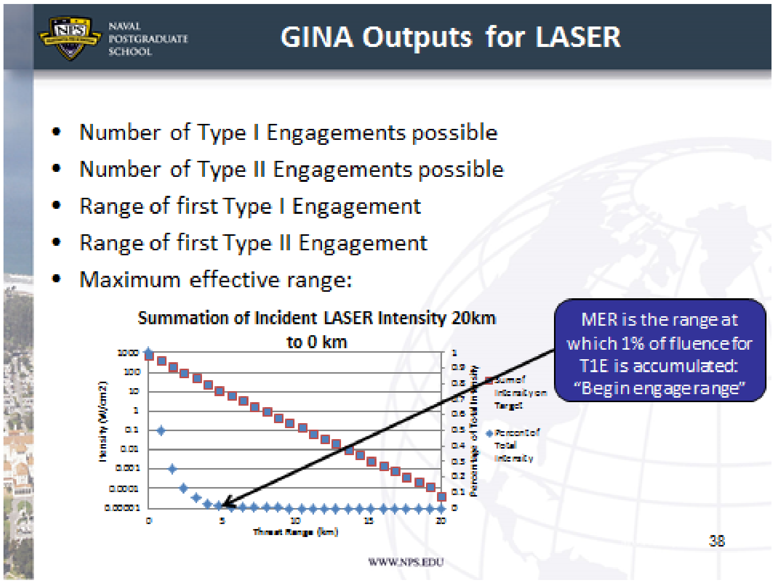
Modeling HEL Performance in GINA

Model Parameter	Inputs and Assumptions
Determine Threat Fluence for T1E	Density, Thickness, Specific Heat, Melting Temperature, Ambient Temperature, Latent Heat of Fusion, Reflectivity
Determine Threat Fluence for T2E	$F = \frac{Fluence\ for\ Type\ I\ Engagement}{6}$
Determine Intensity at Range	• Beam: coherent, spherical, Gaussian • Atmospherics: MODTRAN Maritime Model, Absorption + Scattering, Use transmittance at detection range to estimate attenuation coefficient along entire path • Ignore jitter and use a 1/3 conical spreading approximation, assume adaptive optics work $I_{pk} = \frac{4 * P * e^{-\alpha * (\frac{R}{1000})}}{\pi * ({W_0}^2 + R^2 * \varphi^2)}$ P: Output power (Watts) α: Attenuation Coefficient (km^{-1}) W_0: Beam waist (meters) R: Range (meters) φ: Full angle beam divergence (1/e power point) (Radians)



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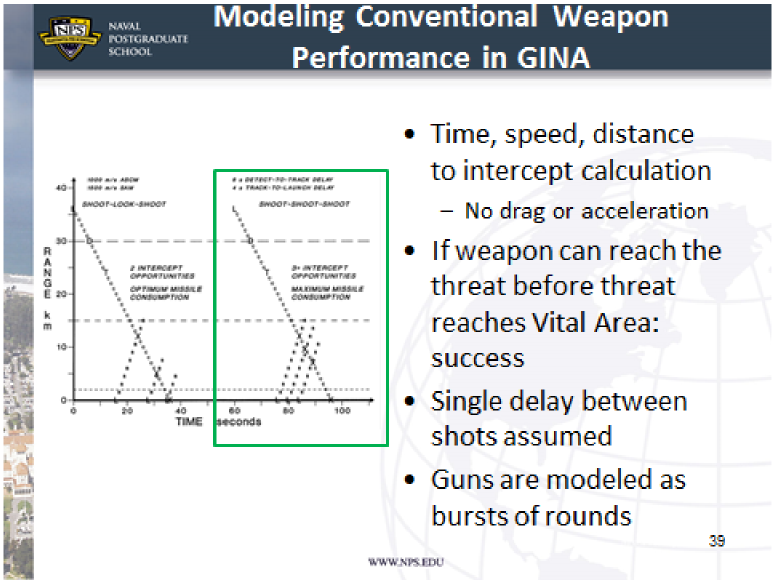
GINA Outputs for LASER

- Number of Type I Engagements possible
- Number of Type II Engagements possible
- Range of first Type I Engagement
- Range of first Type II Engagement
- Maximum effective range:

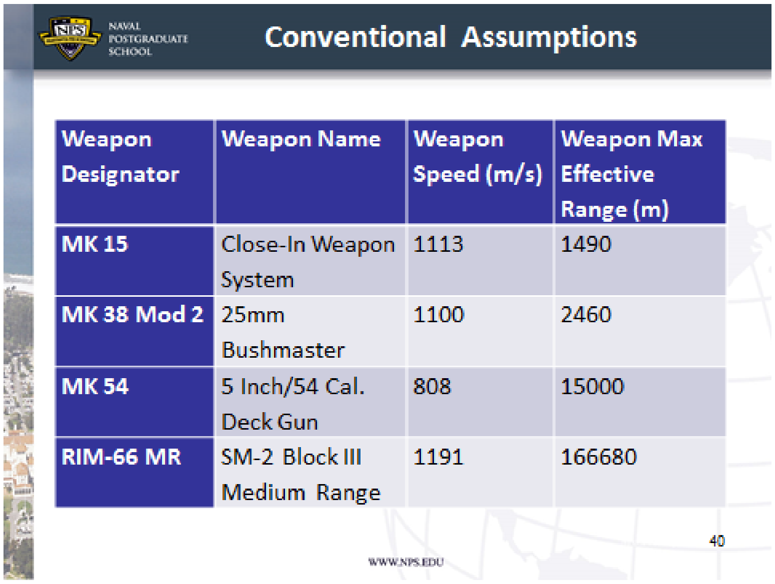
Summation of Incident LASER Intensity 20km to 0 km

MER is the range at which 1% of fluence for T1E is accumulated: “Begin engage range”



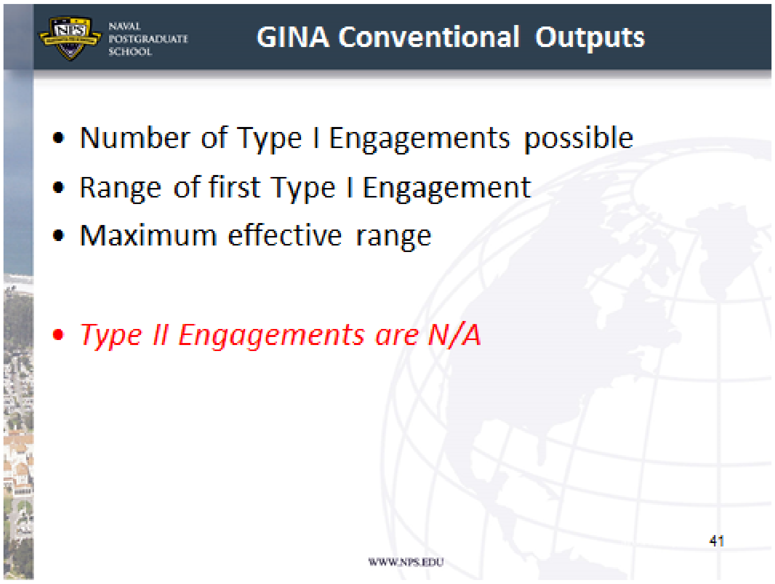
Modeling Conventional Weapon Performance in GINA

- Time, speed, distance to intercept calculation
  - No drag or acceleration
- If weapon can reach the threat before threat reaches Vital Area: success
- Single delay between shots assumed
- Guns are modeled as bursts of rounds



Conventional Assumptions

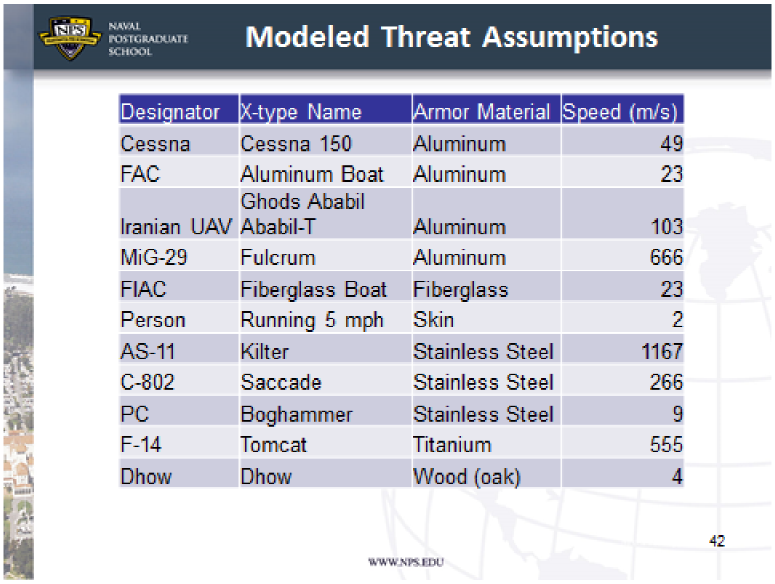
Weapon Designator	Weapon Name	Weapon Speed (m/s)	Weapon Max Effective Range (m)
MK 15	Close-In Weapon System	1113	1490
MK 38 Mod 2	25mm Bushmaster	1100	2460
MK 54	5 Inch/54 Cal. Deck Gun	808	15000
RIM-66 MR	SM-2 Block III Medium Range	1191	166680



GINA Conventional Outputs

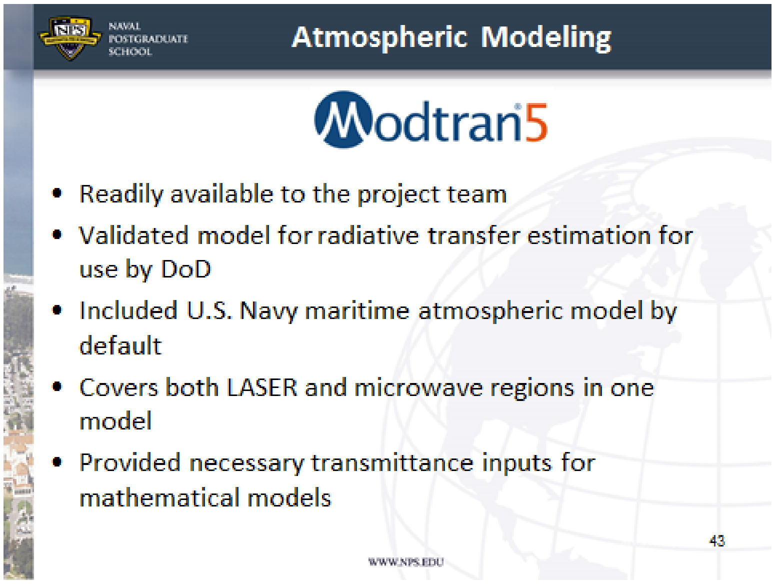
- Number of Type I Engagements possible
- Range of first Type I Engagement
- Maximum effective range

- *Type II Engagements are N/A*



Modeled Threat Assumptions

Designator	X-type Name	Armor Material	Speed (m/s)
Cessna	Cessna 150	Aluminum	49
FAC	Aluminum Boat	Aluminum	23
Iranian UAV	Ghods Ababil Ababil-T	Aluminum	103
MiG-29	Fulcrum	Aluminum	666
FIAC	Fiberglass Boat	Fiberglass	23
Person	Running 5 mph	Skin	2
AS-11	Kilter	Stainless Steel	1167
C-802	Saccade	Stainless Steel	266
PC	Boghammer	Stainless Steel	9
F-14	Tomcat	Titanium	555
Dhow	Dhow	Wood (oak)	4



NAVAL POSTGRADUATE SCHOOL

Atmospheric Modeling

Modtran5

- Readily available to the project team
- Validated model for radiative transfer estimation for use by DoD
- Included U.S. Navy maritime atmospheric model by default
- Covers both LASER and microwave regions in one model
- Provided necessary transmittance inputs for mathematical models

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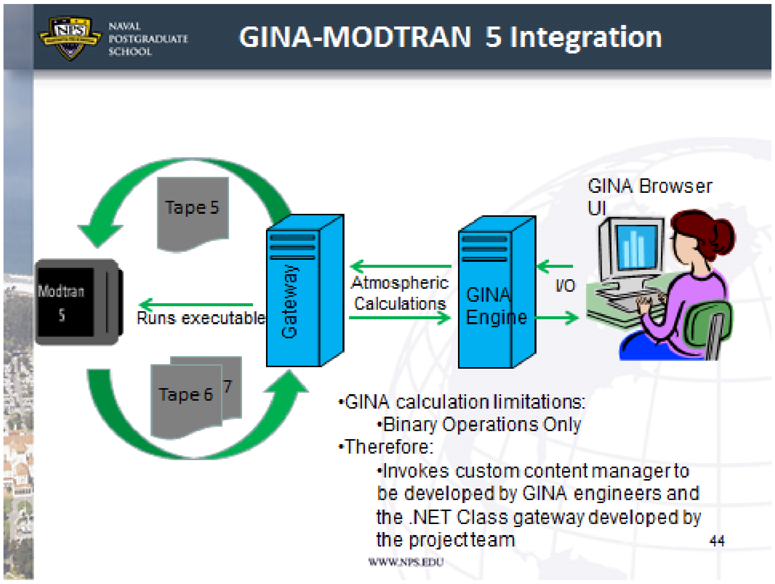
43



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GINA-MODTRAN 5 Integration

- GINA calculation limitations:
    - Binary Operations Only
- Therefore:
    - Invokes custom content manager to be developed by GINA engineers and the .NET Class gateway developed by the project team

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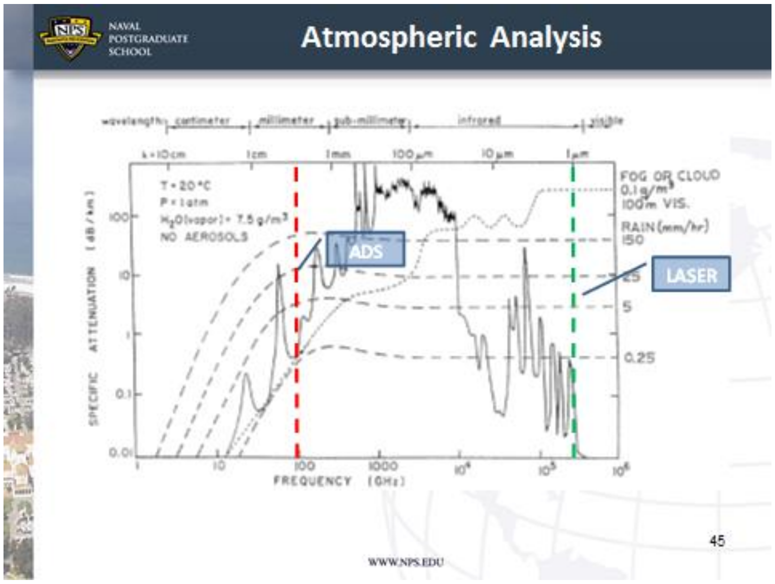
44



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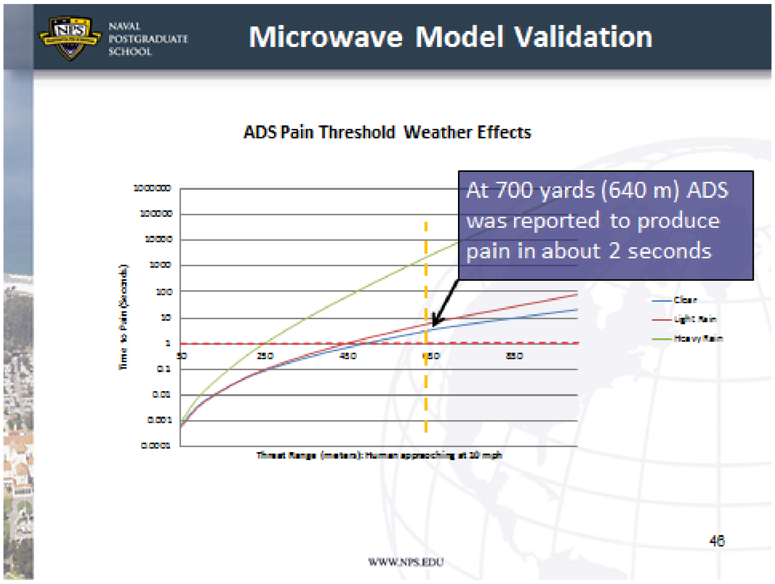
Atmospheric Analysis



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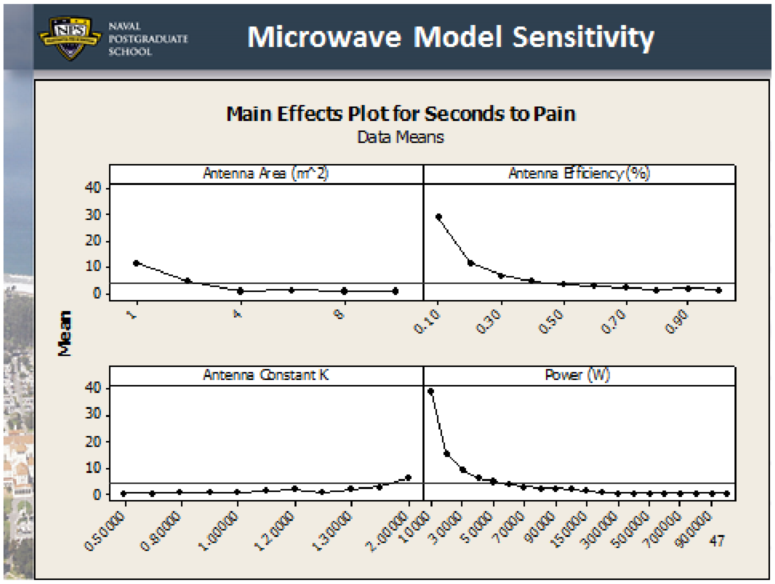
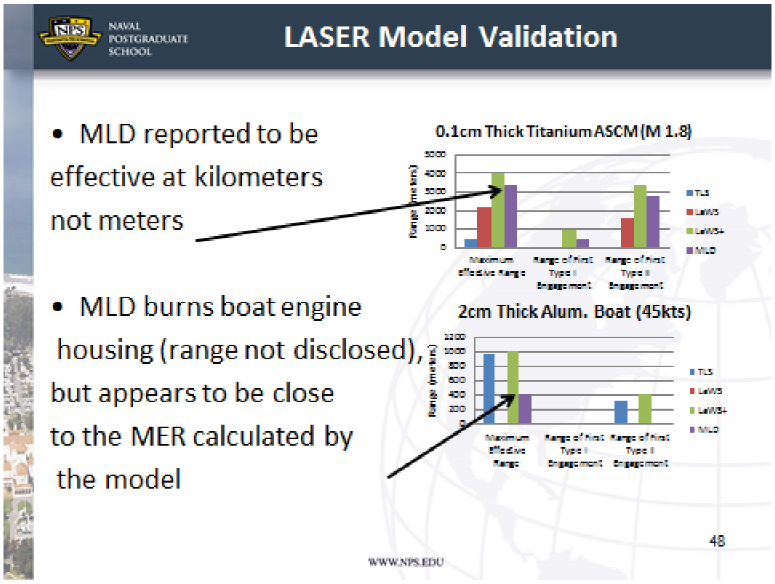
Microwave Model Validation

ADS Pain Threshold Weather Effects

At 700 yards (640 m) ADS was reported to produce pain in about 2 seconds



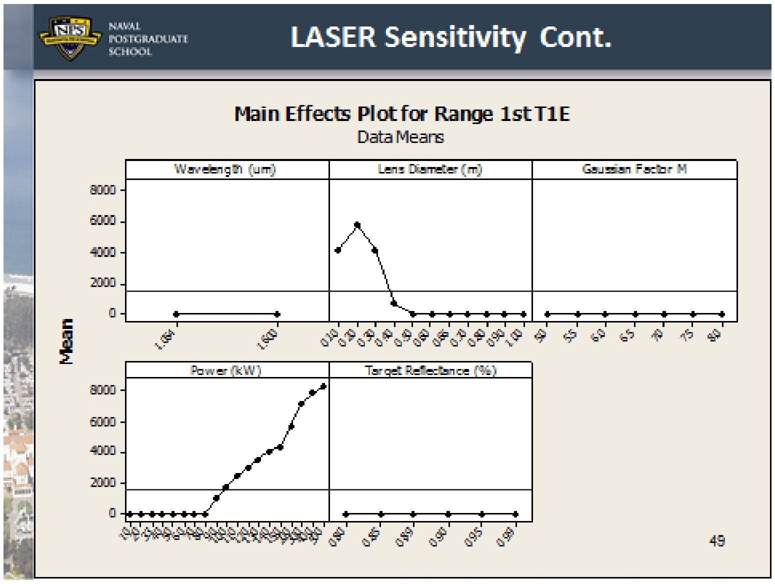
Microwave Model Sensitivity



LASER Model Validation

- MLD reported to be effective at kilometers not meters

- MLD burns boat engine housing (range not disclosed), but appears to be close to the MER calculated by the model



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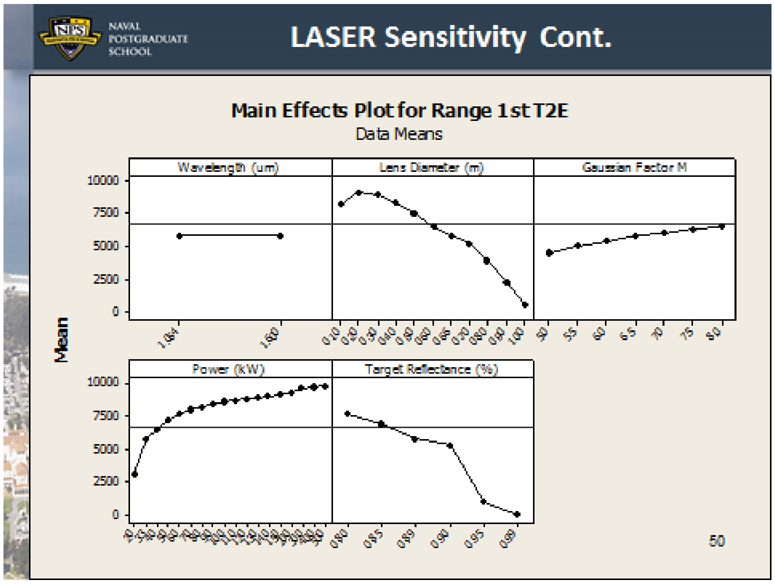
LASER Sensitivity Cont.

Main Effects Plot for Range 1st T1E
Data Means



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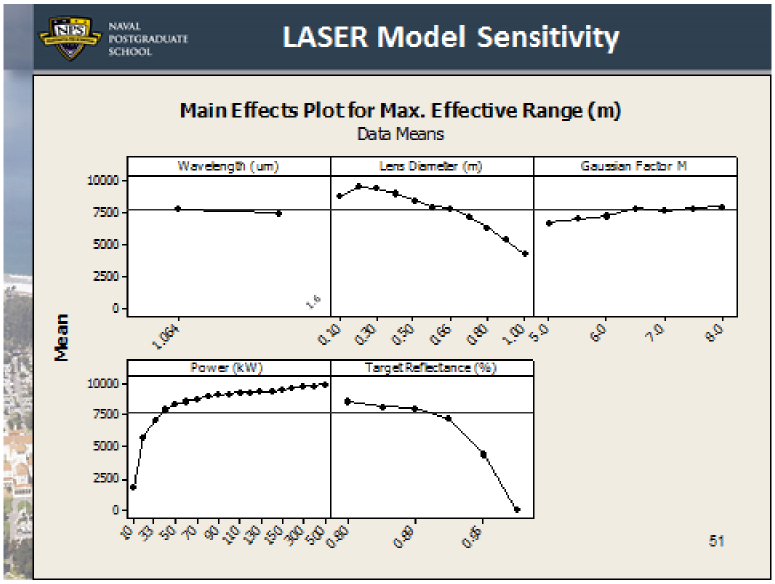
LASER Sensitivity Cont.

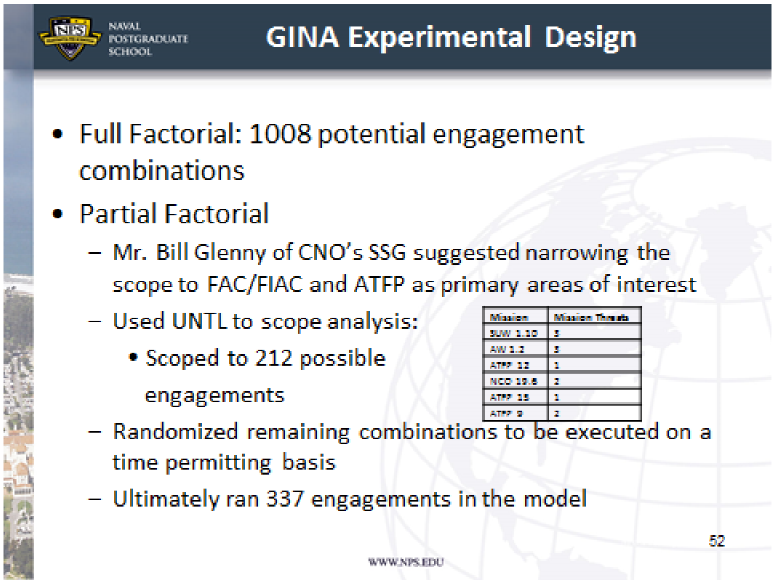
Main Effects Plot for Range 1st T2E
Data Means



LASER Model Sensitivity

Main Effects Plot for Max. Effective Range (m)

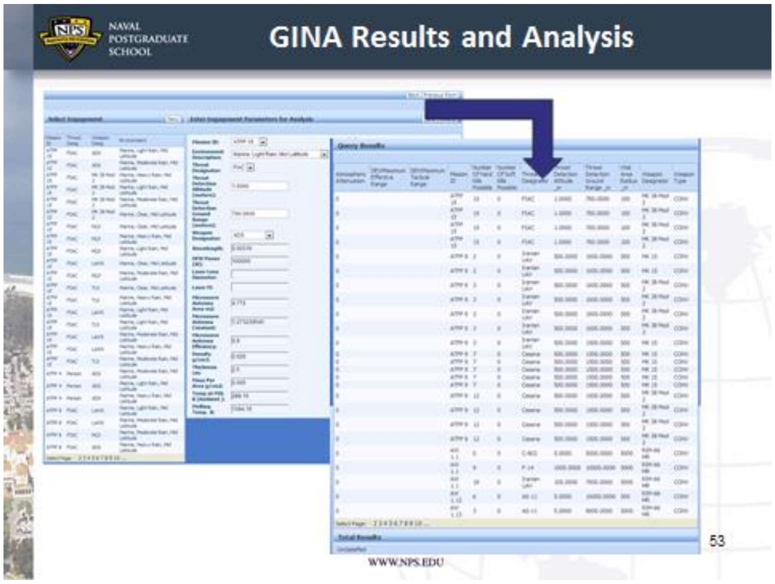
Data Means



GINA Experimental Design

- Full Factorial: 1008 potential engagement combinations
- Partial Factorial
  - Mr. Bill Glenny of CNO's SSG suggested narrowing the scope to FAC/FIAC and ATFP as primary areas of interest
  - Used UNTL to scope analysis:
    - Scoped to 212 possible engagements
  - Randomized remaining combinations to be executed on a time permitting basis
  - Ultimately ran 337 engagements in the model

Mission	Mission Threats
SUW 1.10	3
AW 1.2	3
ATFP 12	1
NCO 19.8	2
ATFP 15	1
ATFP 9	2



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GINA Results and Analysis

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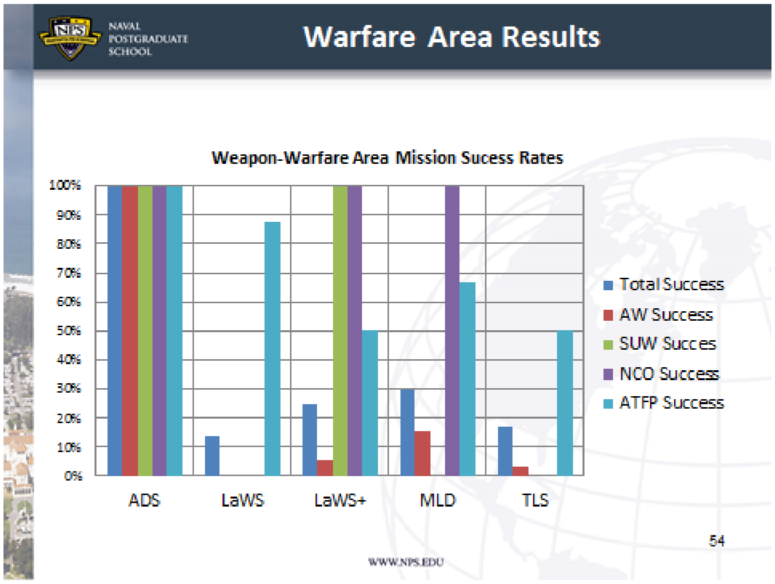

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Warfare Area Results

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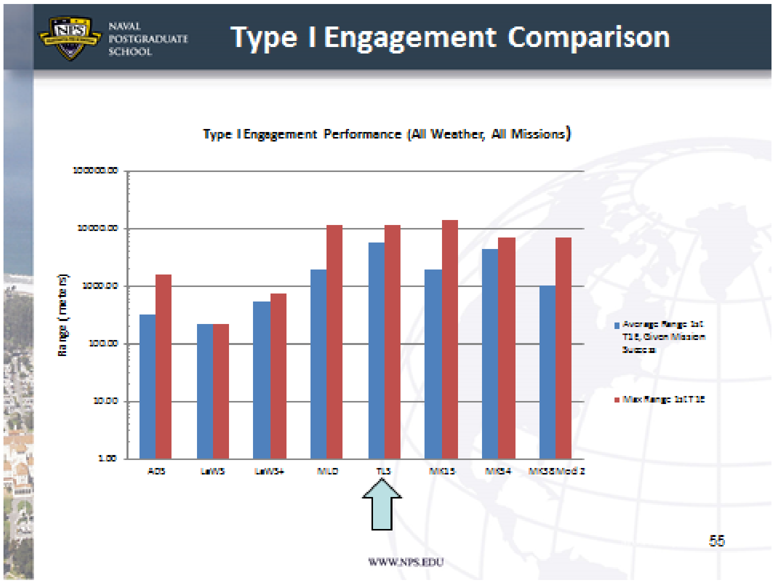

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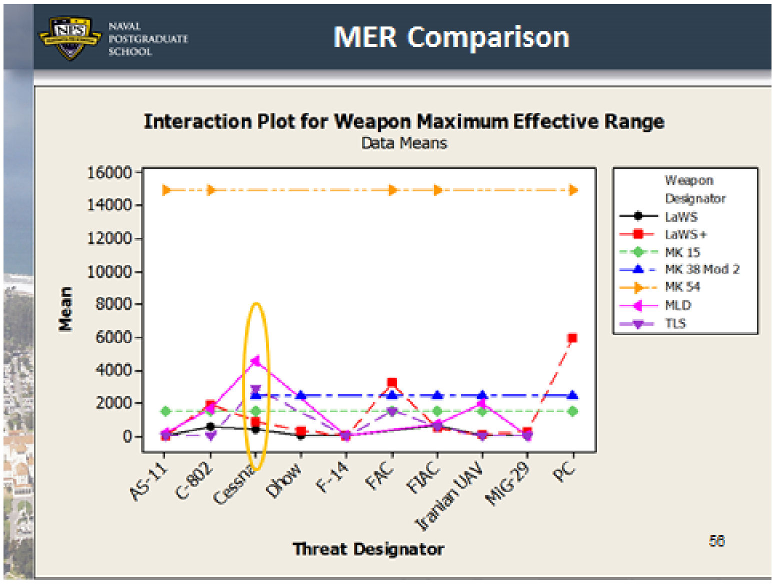
Type I Engagement Comparison



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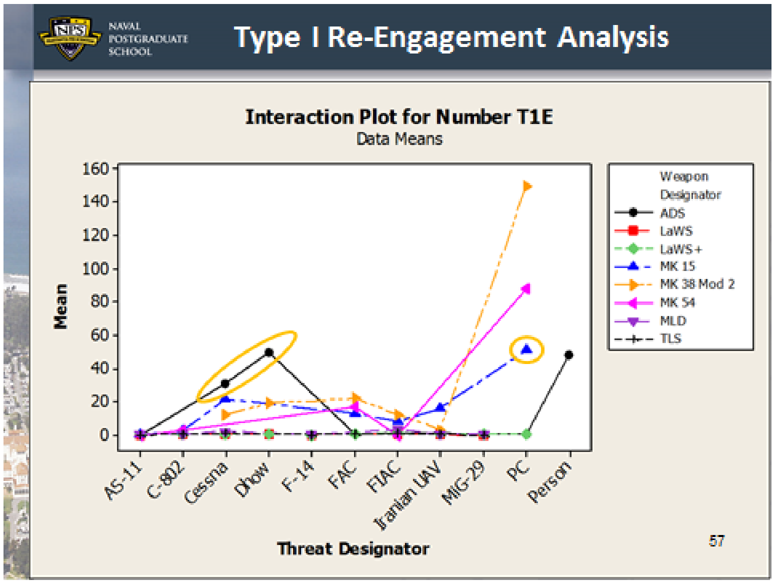
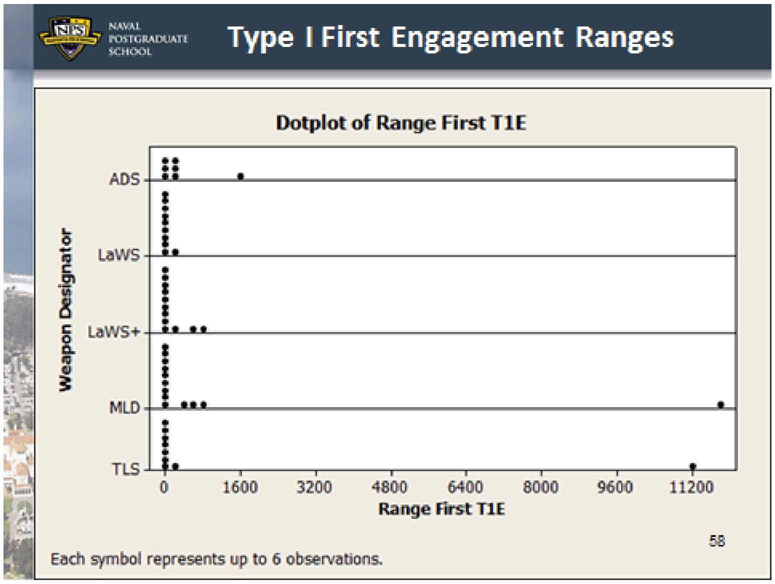
MER Comparison



Type I Re-Engagement Analysis

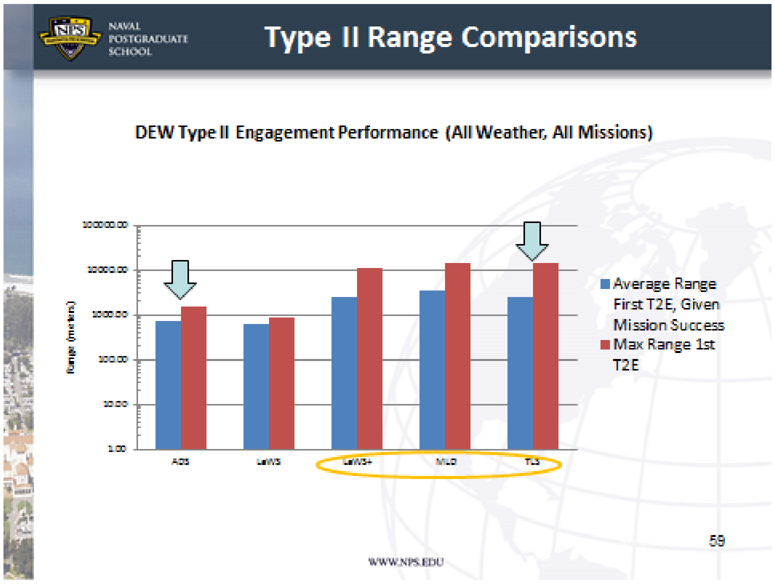
57



Type I First Engagement Ranges

58

Each symbol represents up to 6 observations.



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Type II Range Comparisons

DEW Type II Engagement Performance (All Weather, All Missions)

59

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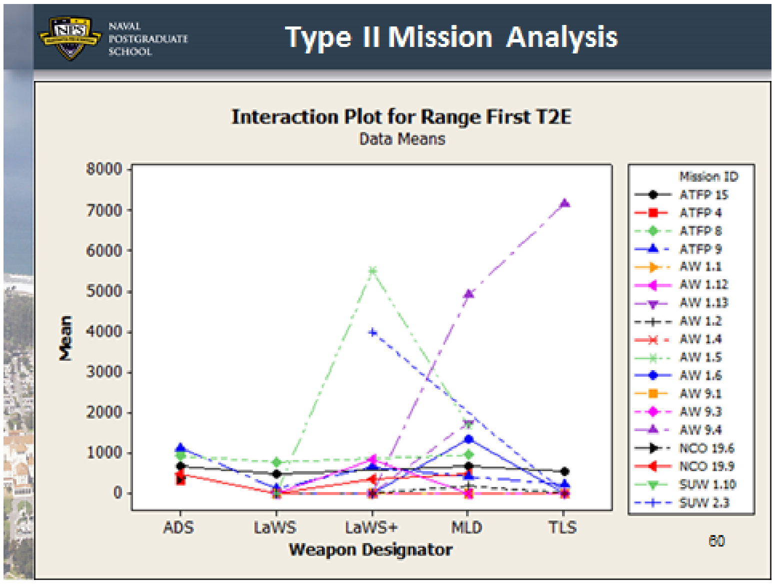

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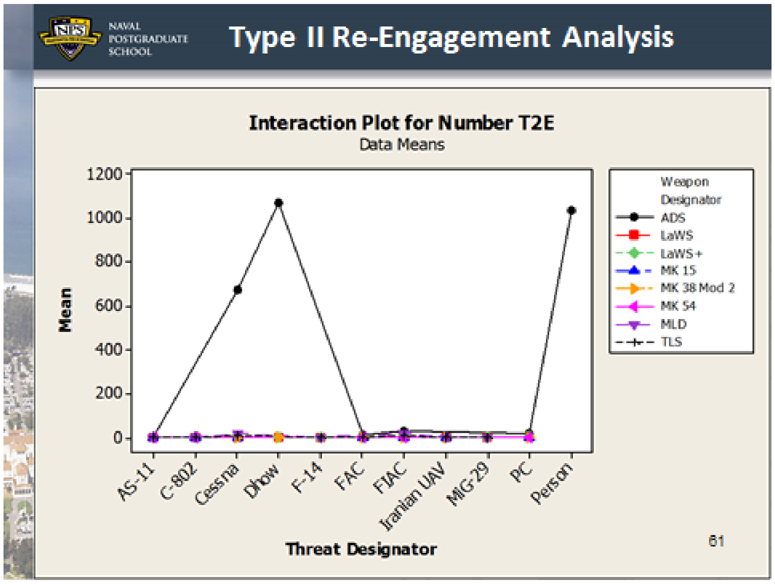
Type II Mission Analysis

Interaction Plot for Range First T2E

Data Means

60



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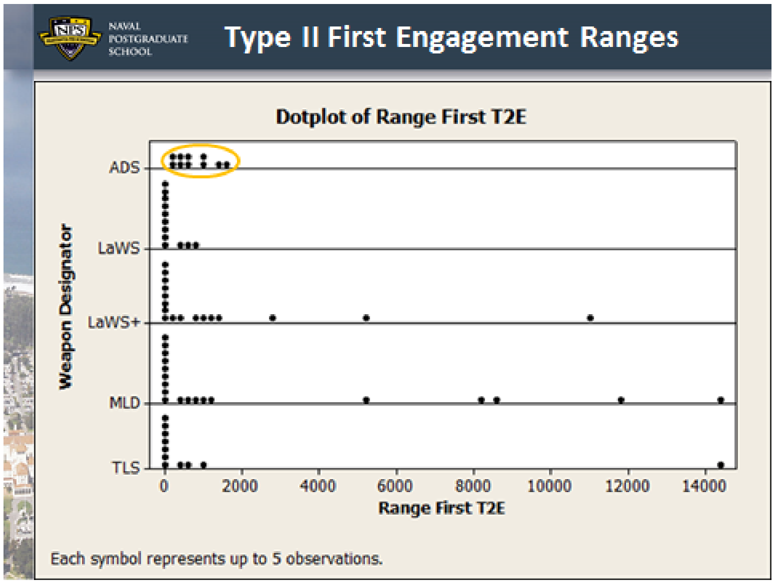
Type II Re-Engagement Analysis

Interaction Plot for Number T2E

Data Means

61

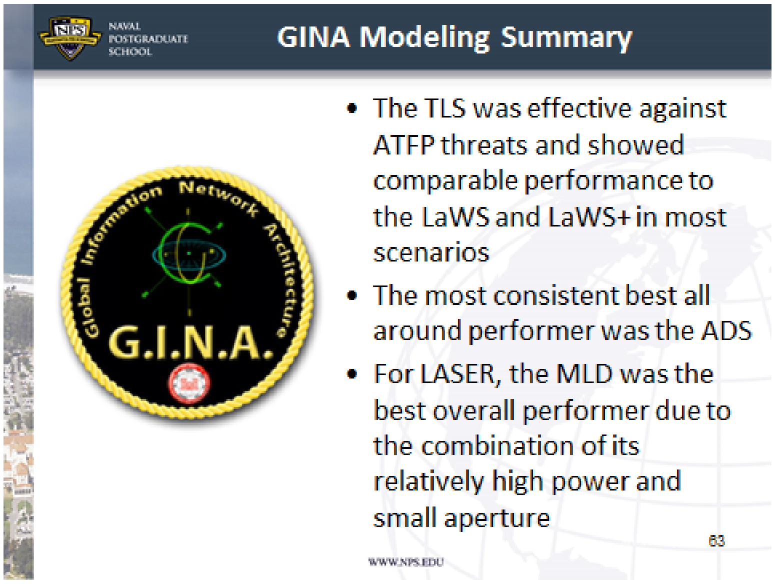


NAVAL POSTGRADUATE SCHOOL

Type II First Engagement Ranges

Dotplot of Range First T2E

Each symbol represents up to 5 observations.



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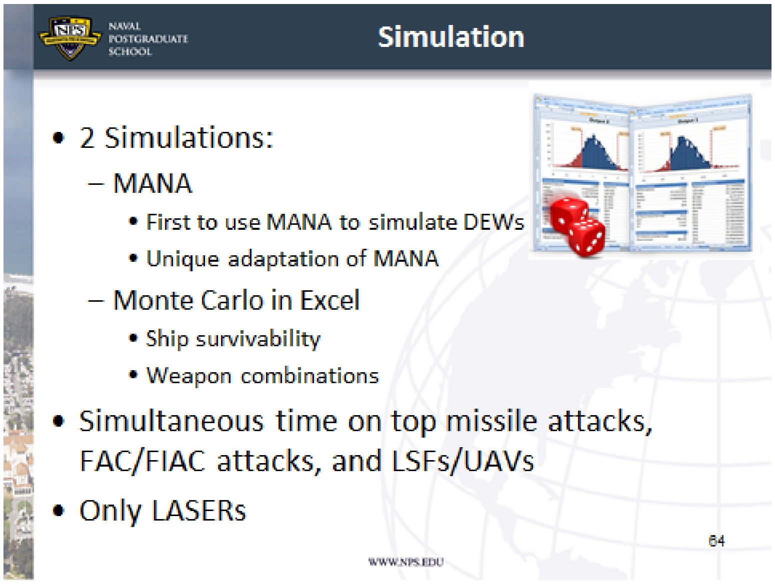
GINA Modeling Summary

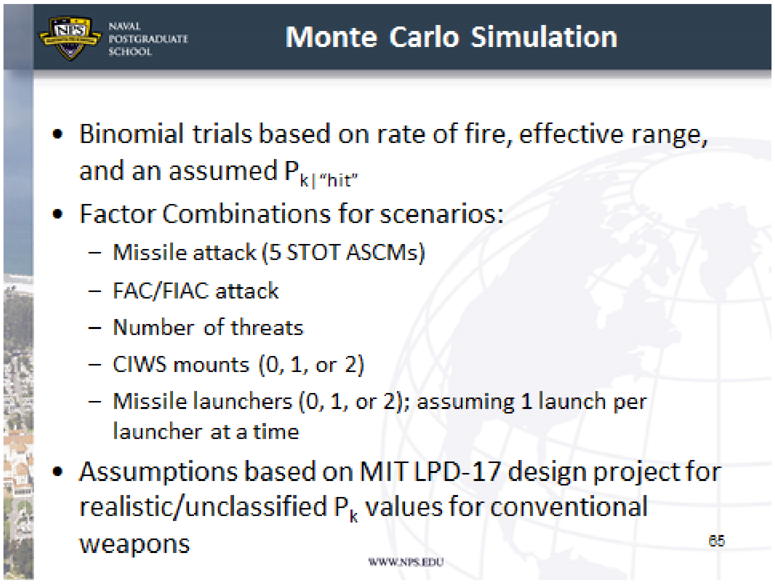
- The TLS was effective against ATFP threats and showed comparable performance to the LaWS and LaWS+ in most scenarios
- The most consistent best all around performer was the ADS
- For LASER, the MLD was the best overall performer due to the combination of its relatively high power and small aperture



NAVAL POSTGRADUATE SCHOOL

Simulation

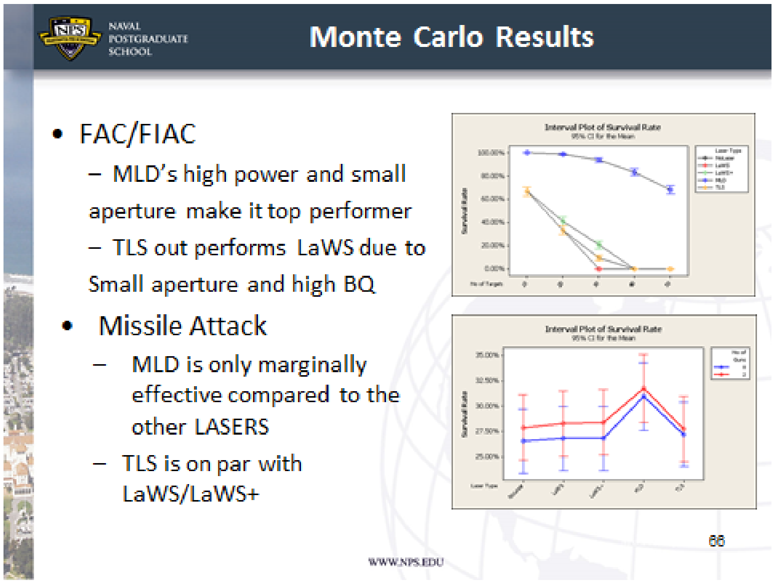
- 2 Simulations:
  - MANA
    - First to use MANA to simulate DEWs
    - Unique adaptation of MANA
  - Monte Carlo in Excel
    - Ship survivability
    - Weapon combinations
- Simultaneous time on top missile attacks, FAC/FIAC attacks, and LSFs/UAVs
- Only LASERs



NAVAL POSTGRADUATE SCHOOL

Monte Carlo Simulation

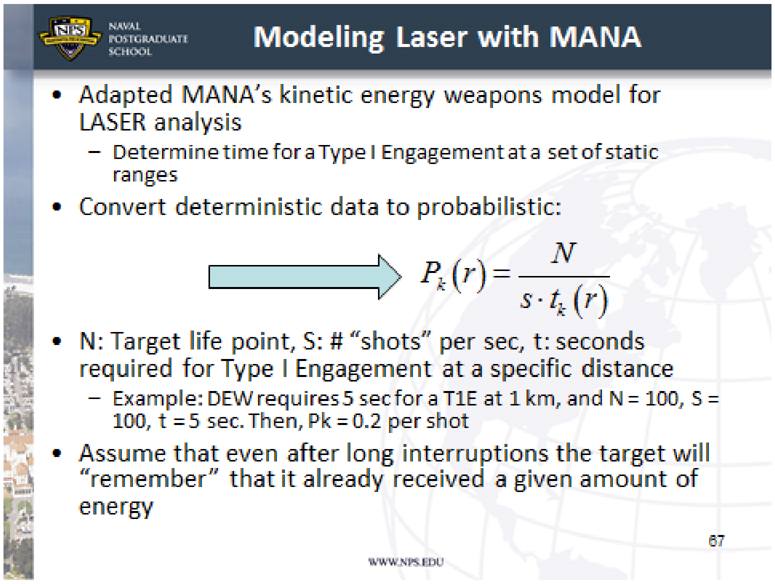
- Binomial trials based on rate of fire, effective range, and an assumed $P_{k\,|\,\text{“hit”}}$
- Factor Combinations for scenarios:
  - Missile attack (5 STOT ASCMs)
  - FAC/FIAC attack
  - Number of threats
  - CIWS mounts (0, 1, or 2)
  - Missile launchers (0, 1, or 2); assuming 1 launch per launcher at a time
- Assumptions based on MIT LPD-17 design project for realistic/unclassified P_k values for conventional weapons



NAVAL POSTGRADUATE SCHOOL

Monte Carlo Results

- FAC/FIAC
  - MLD’s high power and small aperture make it top performer
  - TLS out performs LaWS due to Small aperture and high BQ
- Missile Attack
  - MLD is only marginally effective compared to the other LASERS
  - TLS is on par with LaWS/LaWS+

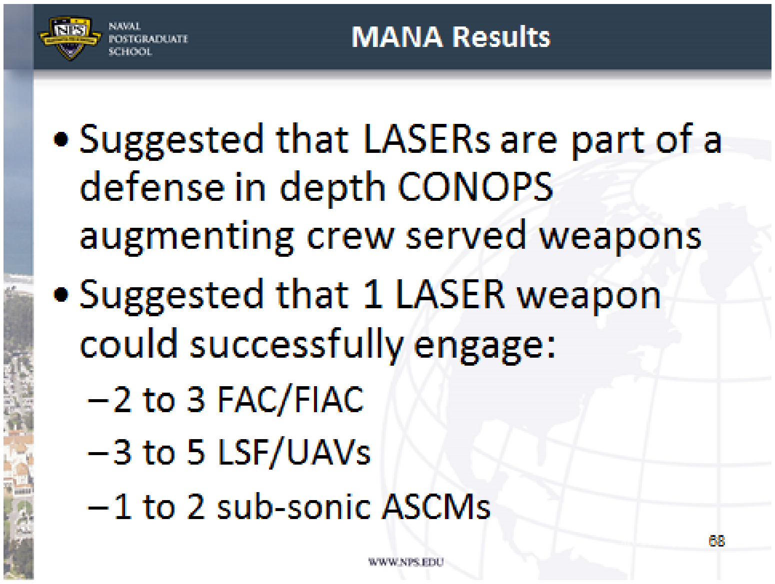


Modeling Laser with MANA

- Adapted MANA's kinetic energy weapons model for LASER analysis
  - Determine time for a Type I Engagement at a set of static ranges
- Convert deterministic data to probabilistic:

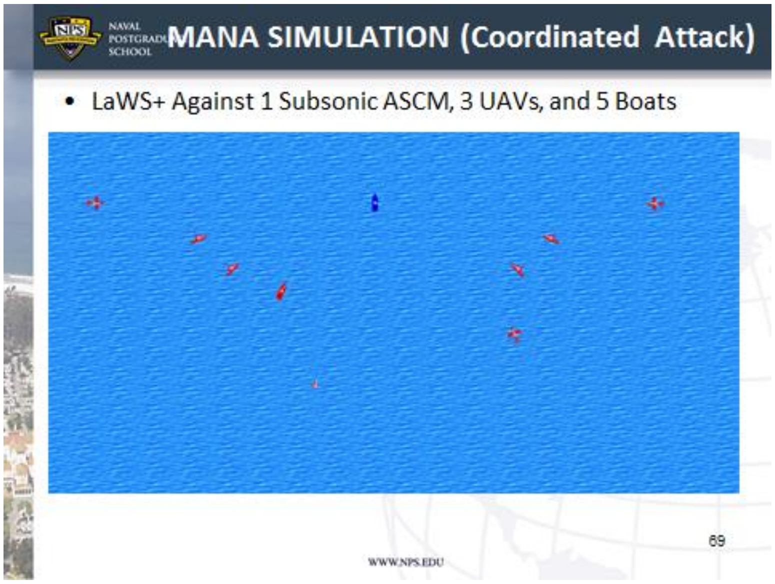
$$\Rightarrow \quad P_k(r) = \frac{N}{s \cdot t_k(r)}$$

- N: Target life point, S: # "shots" per sec, t: seconds required for Type I Engagement at a specific distance
  - Example: DEW requires 5 sec for a T1E at 1 km, and N = 100, S = 100, t = 5 sec. Then, Pk = 0.2 per shot
- Assume that even after long interruptions the target will "remember" that it already received a given amount of energy



MANA Results

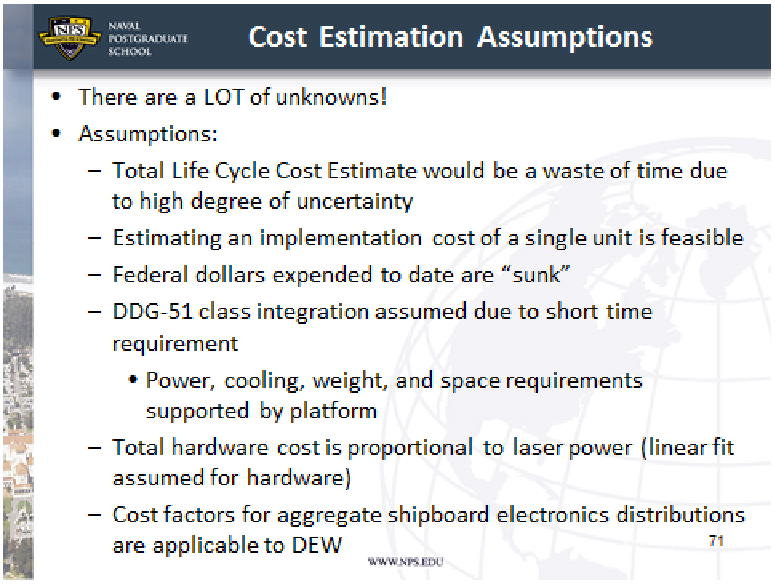
- Suggested that LASERs are part of a defense in depth CONOPS augmenting crew served weapons
- Suggested that 1 LASER weapon could successfully engage:
  - 2 to 3 FAC/FIAC
  - 3 to 5 LSF/UAVs
  - 1 to 2 sub-sonic ASCMs



MANA SIMULATION (Coordinated Attack)

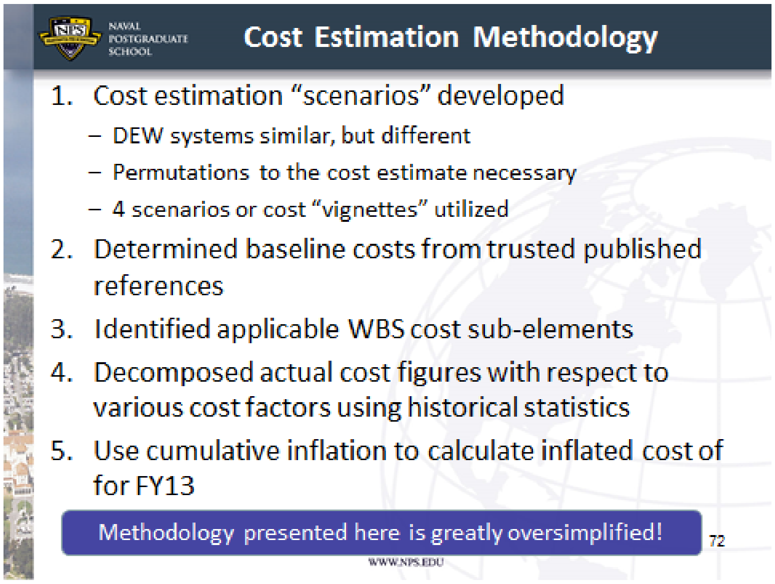
- LaWS+ Against 1 Subsonic ASCM, 3 UAVs, and 5 Boats

Cost Estimation



Cost Estimation Assumptions

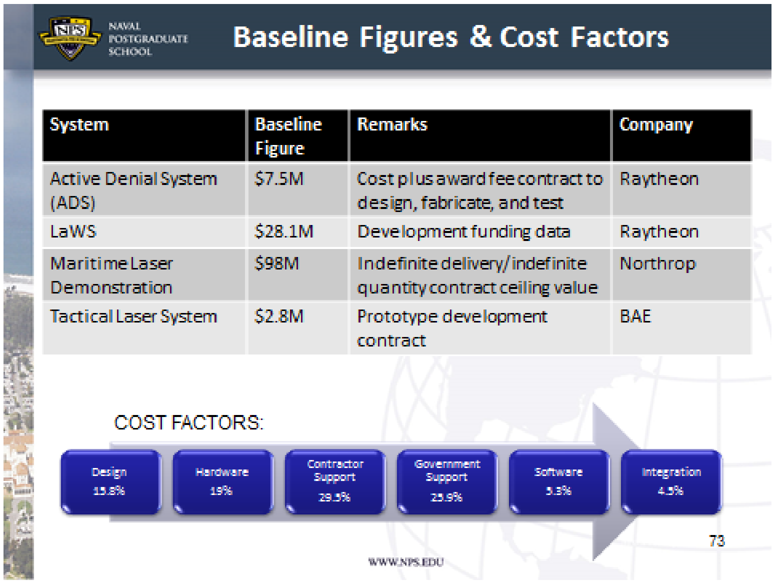
- There are a LOT of unknowns!
- Assumptions:
  - Total Life Cycle Cost Estimate would be a waste of time due to high degree of uncertainty
  - Estimating an implementation cost of a single unit is feasible
  - Federal dollars expended to date are “sunk”
  - DDG-51 class integration assumed due to short time requirement
    - Power, cooling, weight, and space requirements supported by platform
  - Total hardware cost is proportional to laser power (linear fit assumed for hardware)
  - Cost factors for aggregate shipboard electronics distributions are applicable to DEW



Cost Estimation Methodology

1. Cost estimation “scenarios” developed
   - DEW systems similar, but different
   - Permutations to the cost estimate necessary
   - 4 scenarios or cost “vignettes” utilized
2. Determined baseline costs from trusted published references
3. Identified applicable WBS cost sub-elements
4. Decomposed actual cost figures with respect to various cost factors using historical statistics
5. Use cumulative inflation to calculate inflated cost of for FY13

Methodology presented here is greatly oversimplified!

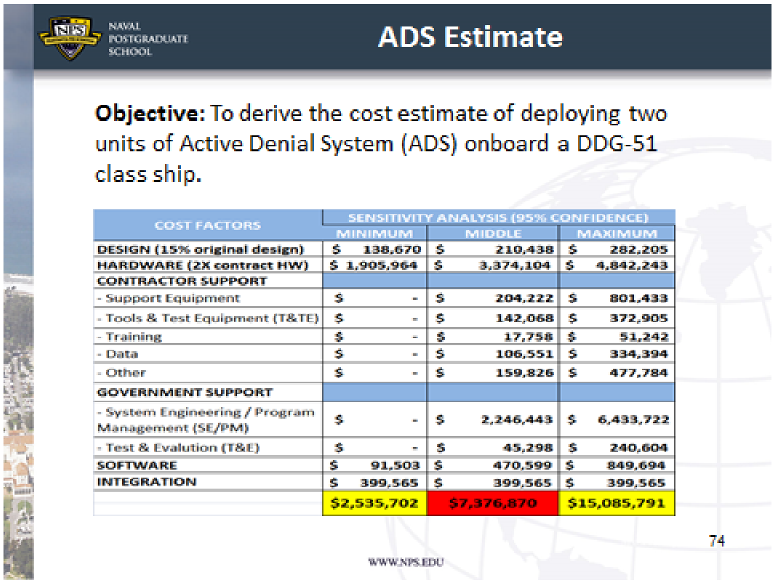


Baseline Figures & Cost Factors

System	Baseline Figure	Remarks	Company
Active Denial System (ADS)	$7.5M	Cost plus award fee contract to design, fabricate, and test	Raytheon
LaWS	$28.1M	Development funding data	Raytheon
Maritime Laser Demonstration	$98M	Indefinite delivery/indefinite quantity contract ceiling value	Northrop
Tactical Laser System	$2.8M	Prototype development contract	BAE

COST FACTORS:

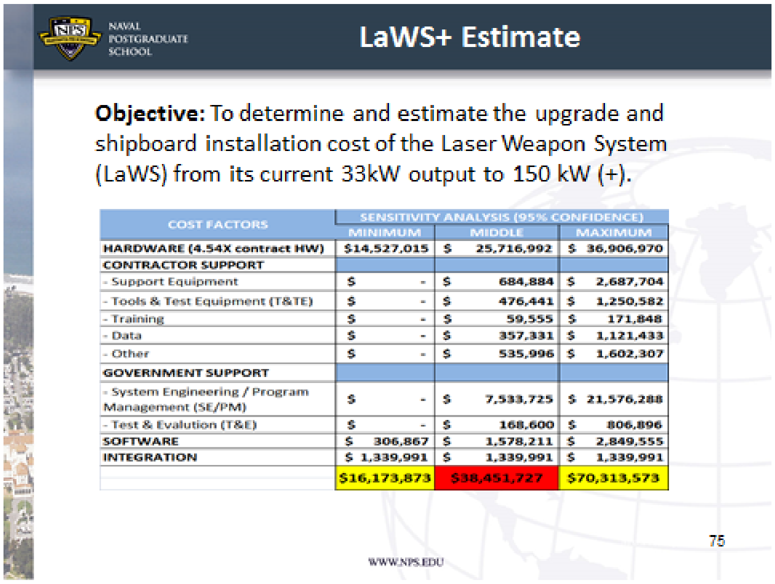
- Design 15.8%
- Hardware 19%
- Contractor Support 29.5%
- Government Support 25.9%
- Software 5.3%
- Integration 4.5%



ADS Estimate

Objective: To derive the cost estimate of deploying two units of Active Denial System (ADS) onboard a DDG-51 class ship.

COST FACTORS	SENSITIVITY ANALYSIS (95% CONFIDENCE)		
	MINIMUM	MIDDLE	MAXIMUM
DESIGN (15% original design)	$ 138,670	$ 210,438	$ 282,205
HARDWARE (2X contract HW)	$ 1,905,964	$ 3,374,104	$ 4,842,243
CONTRACTOR SUPPORT			
- Support Equipment	$ -	$ 204,222	$ 801,433
- Tools & Test Equipment (T&TE)	$ -	$ 142,068	$ 372,905
- Training	$ -	$ 17,758	$ 51,242
- Data	$ -	$ 106,551	$ 334,394
- Other	$ -	$ 159,826	$ 477,784
GOVERNMENT SUPPORT			
- System Engineering / Program Management (SE/PM)	$ -	$ 2,246,443	$ 6,433,722
- Test & Evalution (T&E)	$ -	$ 45,298	$ 240,604
SOFTWARE	$ 91,503	$ 470,599	$ 849,694
INTEGRATION	$ 399,565	$ 399,565	$ 399,565
	$2,535,702	$7,376,870	$15,085,791



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LaWS+ Estimate

Objective: To determine and estimate the upgrade and shipboard installation cost of the Laser Weapon System (LaWS) from its current 33kW output to 150 kW (+).

COST FACTORS	SENSITIVITY ANALYSIS (95% CONFIDENCE)		
	MINIMUM	MIDDLE	MAXIMUM
HARDWARE (4.54X contract HW)	$14,527,015	$ 25,716,992	$ 36,906,970
CONTRACTOR SUPPORT			
- Support Equipment	$ -	$ 684,884	$ 2,687,704
- Tools & Test Equipment (T&TE)	$ -	$ 476,441	$ 1,250,582
- Training	$ -	$ 59,555	$ 171,848
- Data	$ -	$ 357,331	$ 1,121,433
- Other	$ -	$ 535,996	$ 1,602,307
GOVERNMENT SUPPORT			
- System Engineering / Program Management (SE/PM)	$ -	$ 7,533,725	$ 21,576,288
- Test & Evalution (T&E)	$ -	$ 168,600	$ 806,896
SOFTWARE	$ 306,867	$ 1,578,211	$ 2,849,555
INTEGRATION	$ 1,339,991	$ 1,339,991	$ 1,339,991
	$16,173,873	$38,451,727	$70,313,573

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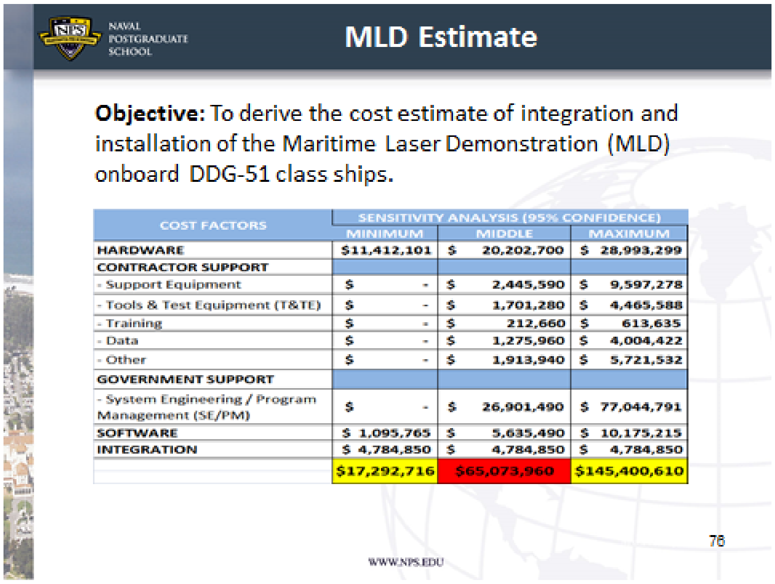

NAVAL POSTGRADUATE SCHOOL

MLD Estimate

Objective: To derive the cost estimate of integration and installation of the Maritime Laser Demonstration (MLD) onboard DDG-51 class ships.

COST FACTORS	SENSITIVITY ANALYSIS (95% CONFIDENCE)		
	MINIMUM	MIDDLE	MAXIMUM
HARDWARE	$11,412,101	$ 20,202,700	$ 28,993,299
CONTRACTOR SUPPORT			
- Support Equipment	$ -	$ 2,445,590	$ 9,597,278
- Tools & Test Equipment (T&TE)	$ -	$ 1,701,280	$ 4,465,588
- Training	$ -	$ 212,660	$ 613,635
- Data	$ -	$ 1,275,960	$ 4,004,422
- Other	$ -	$ 1,913,940	$ 5,721,532
GOVERNMENT SUPPORT			
- System Engineering / Program Management (SE/PM)	$ -	$ 26,901,490	$ 77,044,791
SOFTWARE	$ 1,095,765	$ 5,635,490	$ 10,175,215
INTEGRATION	$ 4,784,850	$ 4,784,850	$ 4,784,850
	$17,292,716	$65,073,960	$145,400,610

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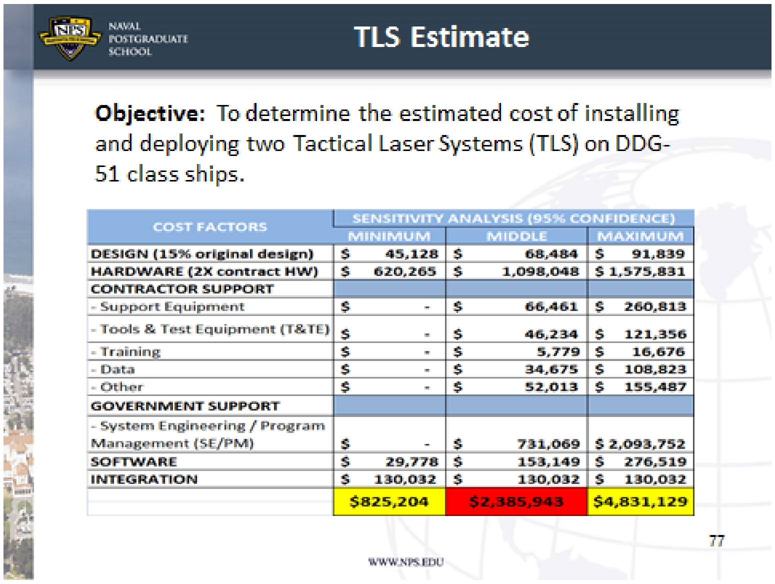

NAVAL POSTGRADUATE SCHOOL

TLS Estimate

Objective: To determine the estimated cost of installing and deploying two Tactical Laser Systems (TLS) on DDG-51 class ships.

COST FACTORS	SENSITIVITY ANALYSIS (95% CONFIDENCE)		
	MINIMUM	MIDDLE	MAXIMUM
DESIGN (15% original design)	$ 45,128	$ 68,484	$ 91,839
HARDWARE (2X contract HW)	$ 620,265	$ 1,098,048	$ 1,575,831
CONTRACTOR SUPPORT			
- Support Equipment	$ -	$ 66,461	$ 260,813
- Tools & Test Equipment (T&TE)	$ -	$ 46,234	$ 121,356
- Training	$ -	$ 5,779	$ 16,676
- Data	$ -	$ 34,675	$ 108,823
- Other	$ -	$ 52,013	$ 155,487
GOVERNMENT SUPPORT			
- System Engineering / Program Management (SE/PM)	$ -	$ 731,069	$ 2,093,752
SOFTWARE	$ 29,778	$ 153,149	$ 276,519
INTEGRATION	$ 130,032	$ 130,032	$ 130,032
	$825,204	$2,385,943	$4,831,129

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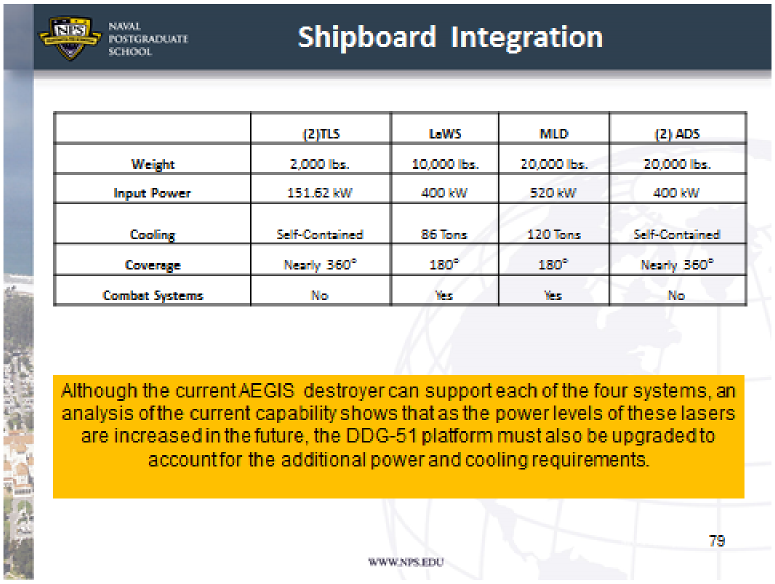
Integration

(www.educollaborators.com)



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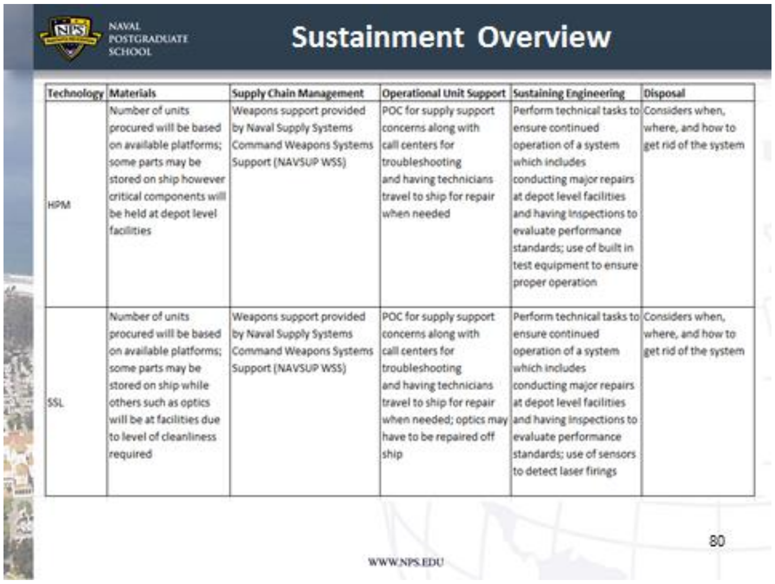
Shipboard Integration

	(2)TLS	LaWS	MLD	(2) ADS
Weight	2,000 lbs.	10,000 lbs.	20,000 lbs.	20,000 lbs.
Input Power	151.62 kW	400 kW	520 kW	400 kW
Cooling	Self-Contained	86 Tons	120 Tons	Self-Contained
Coverage	Nearly 360°	180°	180°	Nearly 360°
Combat Systems	No	Yes	Yes	No

Although the current AEGIS destroyer can support each of the four systems, an analysis of the current capability shows that as the power levels of these lasers are increased in the future, the DDG-51 platform must also be upgraded to account for the additional power and cooling requirements.



NAVAL POSTGRADUATE SCHOOL

Sustainment Overview

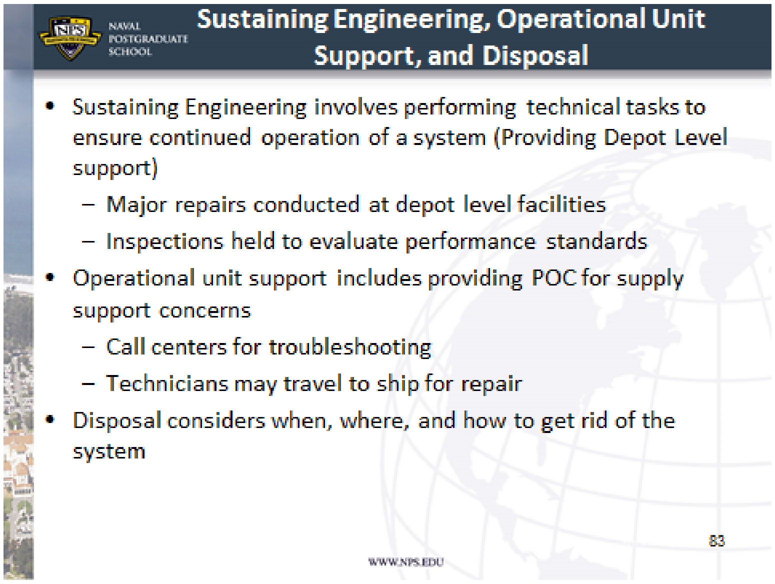
Technology	Materials	Supply Chain Management	Operational Unit Support	Sustaining Engineering	Disposal
HPM	Number of units procured will be based on available platforms; some parts may be stored on ship however critical components will be held at depot level facilities	Weapons support provided by Naval Supply Systems Command Weapons Systems Support (NAVSUP WSS)	POC for supply support concerns along with call centers for troubleshooting and having technicians travel to ship for repair when needed	Perform technical tasks to ensure continued operation of a system which includes conducting major repairs at depot level facilities and having inspections to evaluate performance standards; use of built in test equipment to ensure proper operation	Considers when, where, and how to get rid of the system
SSL	Number of units procured will be based on available platforms; some parts may be stored on ship while others such as optics will be at facilities due to level of cleanliness required	Weapons support provided by Naval Supply Systems Command Weapons Systems Support (NAVSUP WSS)	POC for supply support concerns along with call centers for troubleshooting and having technicians travel to ship for repair when needed; optics may have to be repaired off ship	Perform technical tasks to ensure continued operation of a system which includes conducting major repairs at depot level facilities and having inspections to evaluate performance standards; use of sensors to detect laser firings	Considers when, where, and how to get rid of the system

Sustainment

- Materials
  - Requirements
    - Initial Needs/Projections
  - Personnel
- Supply Chain Management
  - Procurement
  - Distribution
  - Software
- Sustaining Engineering
  - Depot Level Support
  - Performance Standards Analysis for Continued Use
- Operational Unit Support
- Disposal

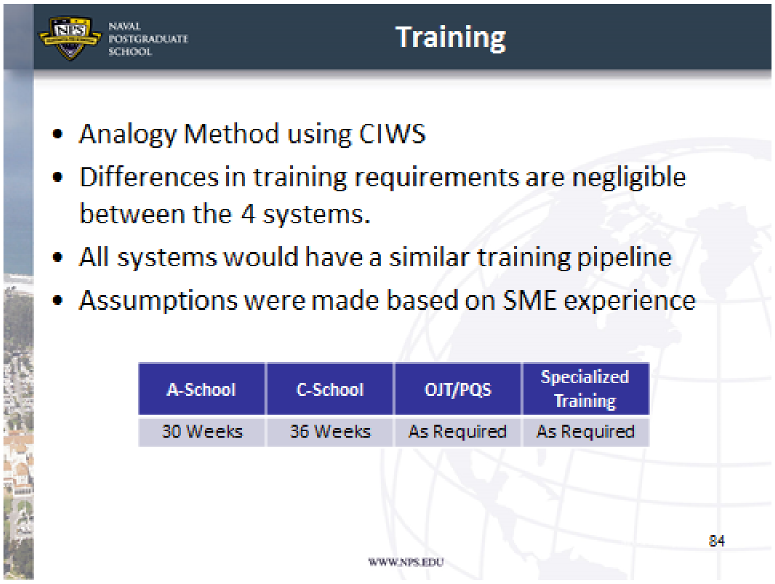
Materials and Supply Chain Management

- Material involves developing supply requirements, storing components needed for repair and replacement, and providing personnel for warehouse functions
  - Number of units acquired will be based off of number of available platforms
  - Considerations made for operating in marine environment include protective coverings, stabilizers, and lubricants
  - Minor components stored on ship and major components stored at facilities
- Supply chain managements includes the procurement and distribution of materials
  - Weapons support provided by Naval Supply Systems Command Weapons Systems Support (NAVSUP WSS)



Sustaining Engineering, Operational Unit Support, and Disposal

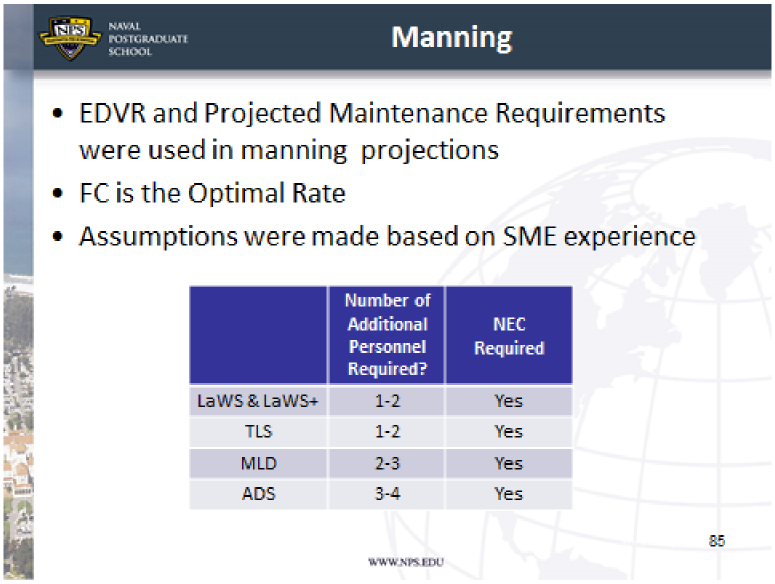
- Sustaining Engineering involves performing technical tasks to ensure continued operation of a system (Providing Depot Level support)
  - Major repairs conducted at depot level facilities
  - Inspections held to evaluate performance standards
- Operational unit support includes providing POC for supply support concerns
  - Call centers for troubleshooting
  - Technicians may travel to ship for repair
- Disposal considers when, where, and how to get rid of the system



Training

- Analogy Method using CIWS
- Differences in training requirements are negligible between the 4 systems.
- All systems would have a similar training pipeline
- Assumptions were made based on SME experience

A-School	C-School	OJT/PQS	Specialized Training
30 Weeks	36 Weeks	As Required	As Required



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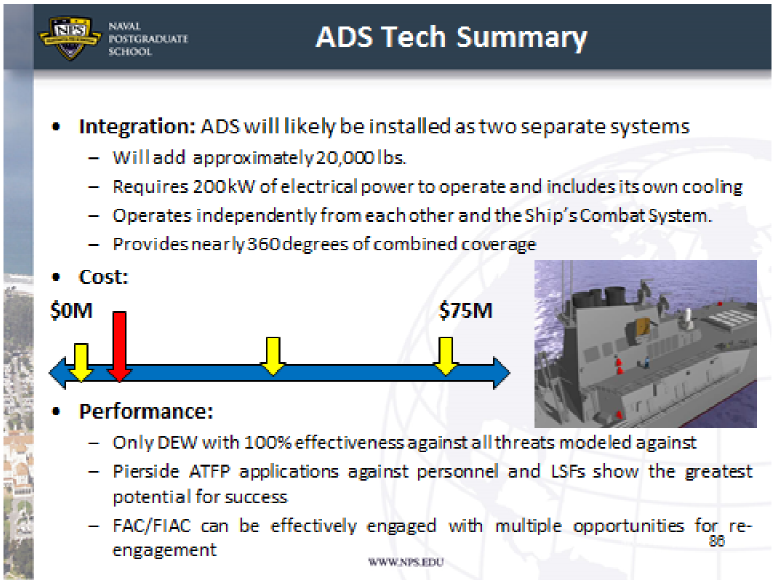
Manning

- EDVR and Projected Maintenance Requirements were used in manning projections
- FC is the Optimal Rate
- Assumptions were made based on SME experience

	Number of Additional Personnel Required?	NEC Required
LaWS & LaWS+	1-2	Yes
TLS	1-2	Yes
MLD	2-3	Yes
ADS	3-4	Yes

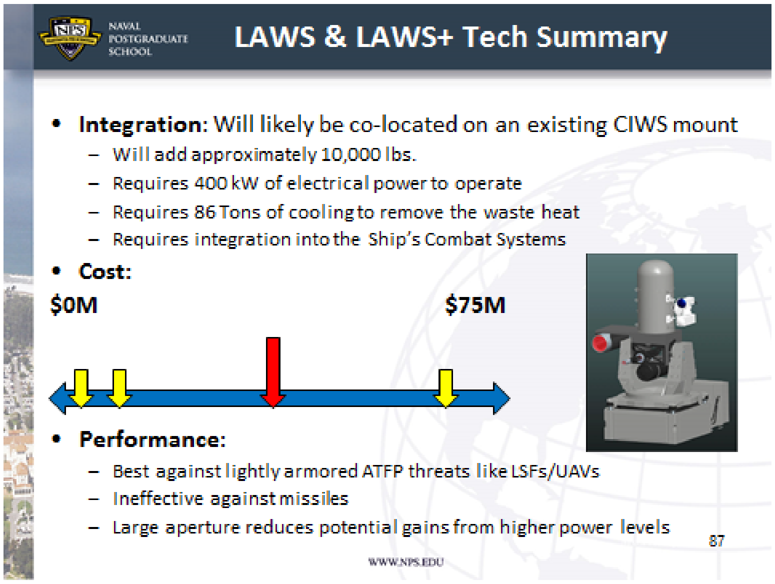


NAVAL POSTGRADUATE SCHOOL

ADS Tech Summary

- **Integration:** ADS will likely be installed as two separate systems
  - Will add approximately 20,000 lbs.
  - Requires 200kW of electrical power to operate and includes its own cooling
  - Operates independently from each other and the Ship's Combat System.
  - Provides nearly 360 degrees of combined coverage
- **Cost:**

- **Performance:**
  - Only DEW with 100% effectiveness against all threats modeled against
  - Pierside ATFP applications against personnel and LSFs show the greatest potential for success
  - FAC/FIAC can be effectively engaged with multiple opportunities for re-engagement



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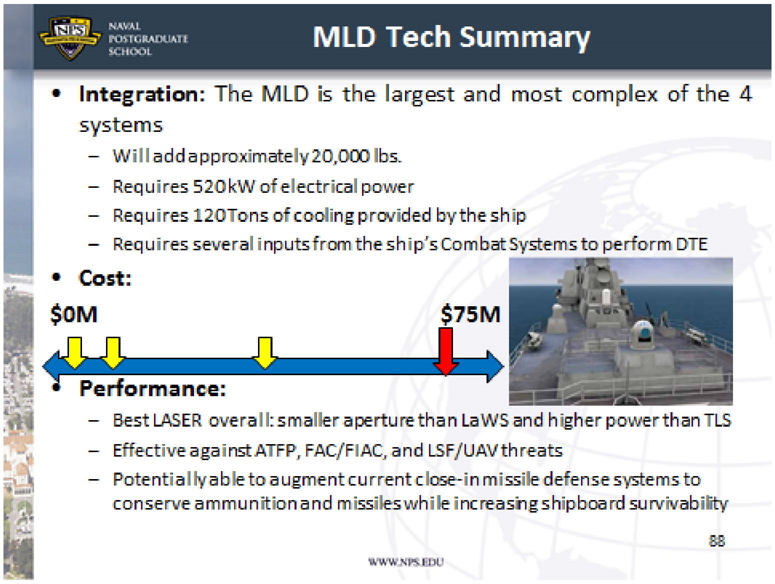
LAWS & LAWS+ Tech Summary

- **Integration**: Will likely be co-located on an existing CIWS mount
  - Will add approximately 10,000 lbs.
  - Requires 400 kW of electrical power to operate
  - Requires 86 Tons of cooling to remove the waste heat
  - Requires integration into the Ship's Combat Systems
- **Cost:**

$0M **$75M**

- **Performance:**
  - Best against lightly armored ATFP threats like LSFs/UAVs
  - Ineffective against missiles
  - Large aperture reduces potential gains from higher power levels



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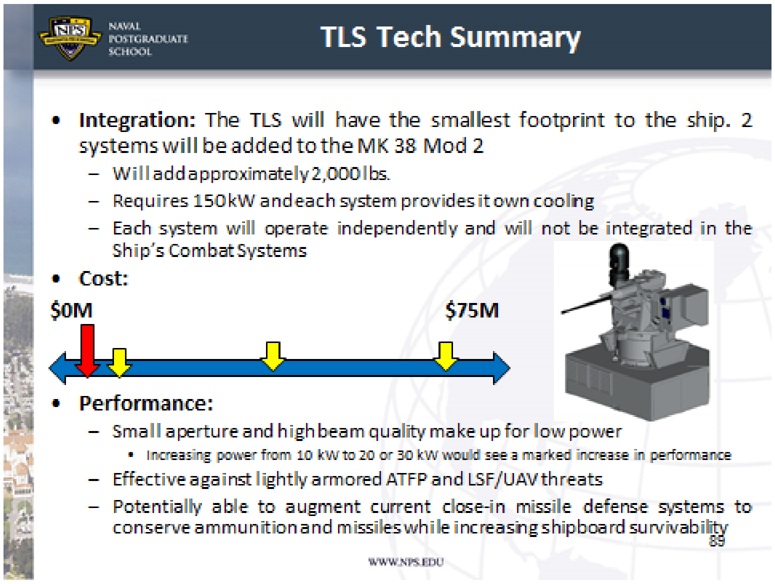
MLD Tech Summary

- **Integration**: The MLD is the largest and most complex of the 4 systems
  - Will add approximately 20,000 lbs.
  - Requires 520kW of electrical power
  - Requires 120Tons of cooling provided by the ship
  - Requires several inputs from the ship's Combat Systems to perform DTE
- **Cost:**

$0M **$75M**

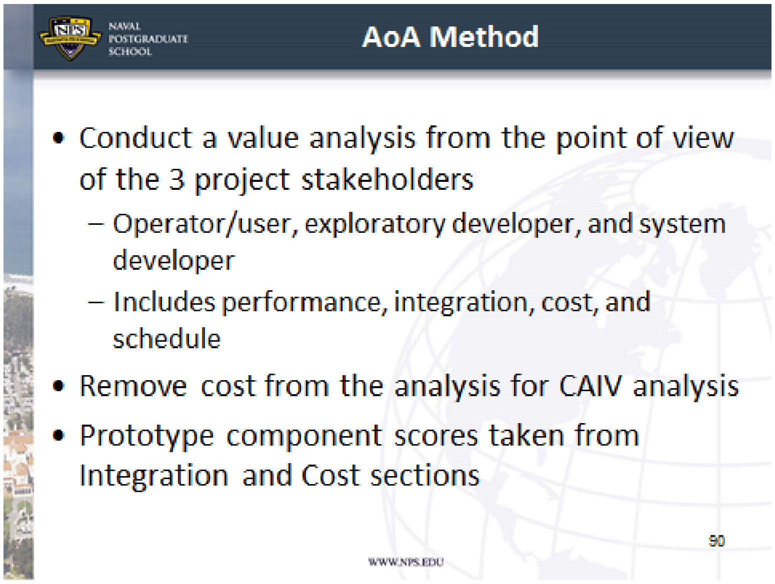
- **Performance:**
  - Best LASER overall: smaller aperture than LaWS and higher power than TLS
  - Effective against ATFP, FAC/FIAC, and LSF/UAV threats
  - Potentially able to augment current close-in missile defense systems to conserve ammunition and missiles while increasing shipboard survivability



TLS Tech Summary

- **Integration:** The TLS will have the smallest footprint to the ship. 2 systems will be added to the MK 38 Mod 2
  - Will add approximately 2,000 lbs.
  - Requires 150kW and each system provides it own cooling
  - Each system will operate independently and will not be integrated in the Ship's Combat Systems
- **Cost:**

- **Performance:**
  - Small aperture and high beam quality make up for low power
    - Increasing power from 10 kW to 20 or 30 kW would see a marked increase in performance
  - Effective against lightly armored ATFP and LSF/UAV threats
  - Potentially able to augment current close-in missile defense systems to conserve ammunition and missiles while increasing shipboard survivability



AoA Method

- Conduct a value analysis from the point of view of the 3 project stakeholders
  - Operator/user, exploratory developer, and system developer
  - Includes performance, integration, cost, and schedule
- Remove cost from the analysis for CAIV analysis
- Prototype component scores taken from Integration and Cost sections

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AoA Top Level

Overall

Operator/User
- Performance/Schedule (0.75)
- Integration (0.20)
- Cost (0.05)

Exploratory Developer
- Performance (0.55)
- Cost/Integration (0.35)
- Schedule (0.10)

System Developer
- Performance (0.33)
- Schedule (0.33)
- Cost/Integration (0.33)

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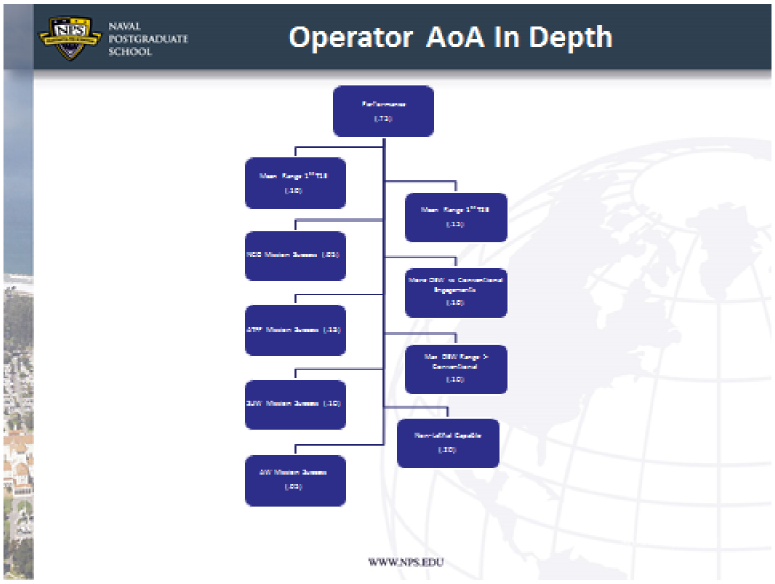

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Operator AoA In Depth

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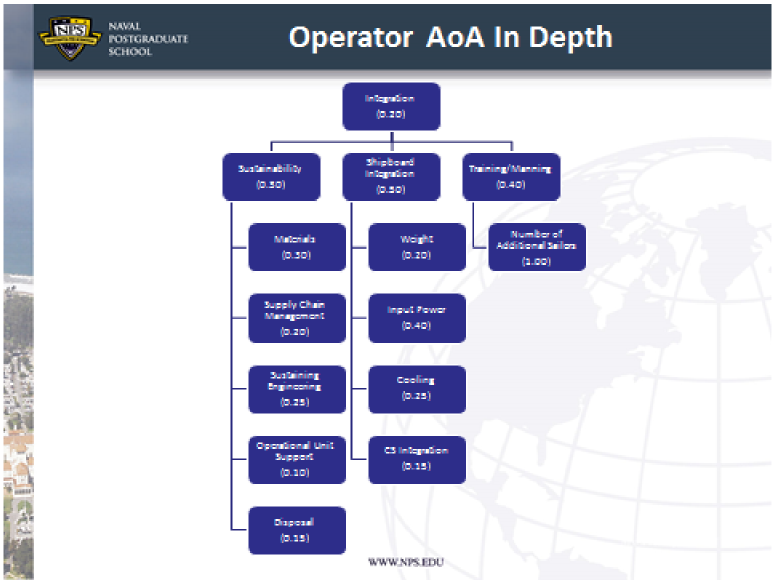

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Operator AoA In Depth

- Integration (0.20)
  - Sustainability (0.30)
    - Materials (0.30)
    - Supply Chain Management (0.20)
    - Sustaining Engineering (0.25)
    - Operational Unit Support (0.10)
    - Disposal (0.15)
  - Shipboard Integration (0.30)
    - Weight (0.20)
    - Input Power (0.40)
    - Cooling (0.25)
    - C5 Integration (0.15)
  - Training/Manning (0.40)
    - Number of Additional Sailors (1.00)

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Operator AoA In Depth

- Cost (0.05)
  - Per-Unit Cost (1.00)

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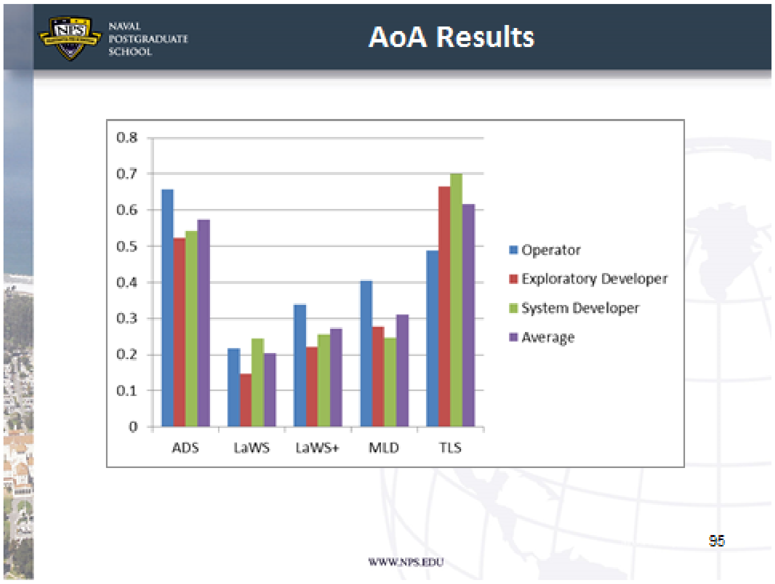

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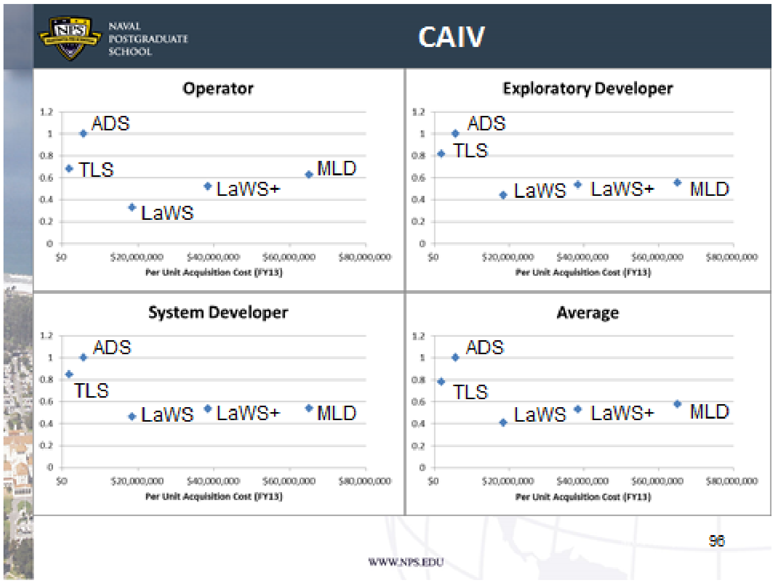
AoA Results



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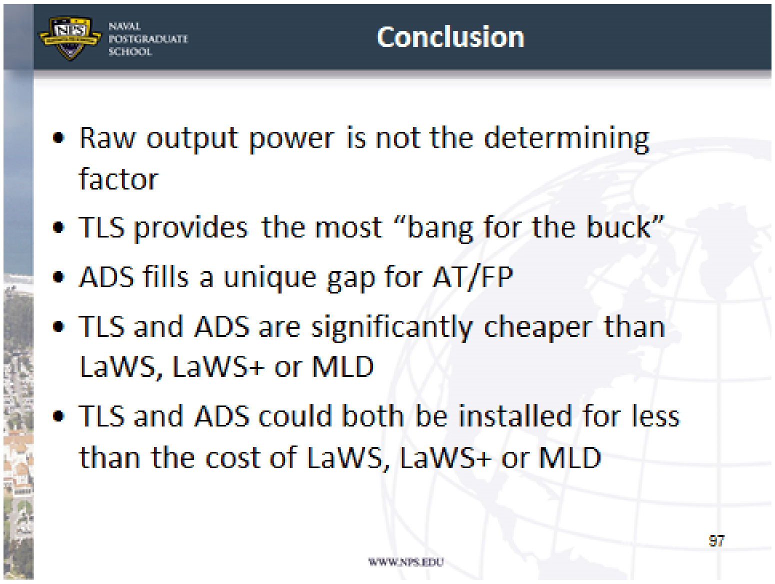
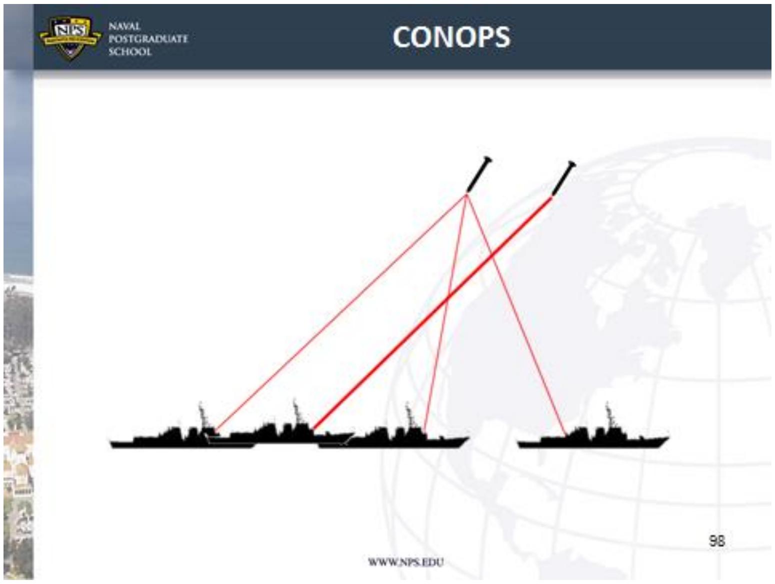
CAIV



Conclusion

- Raw output power is not the determining factor
- TLS provides the most “bang for the buck”
- ADS fills a unique gap for AT/FP
- TLS and ADS are significantly cheaper than LaWS, LaWS+ or MLD
- TLS and ADS could both be installed for less than the cost of LaWS, LaWS+ or MLD



CONOPS

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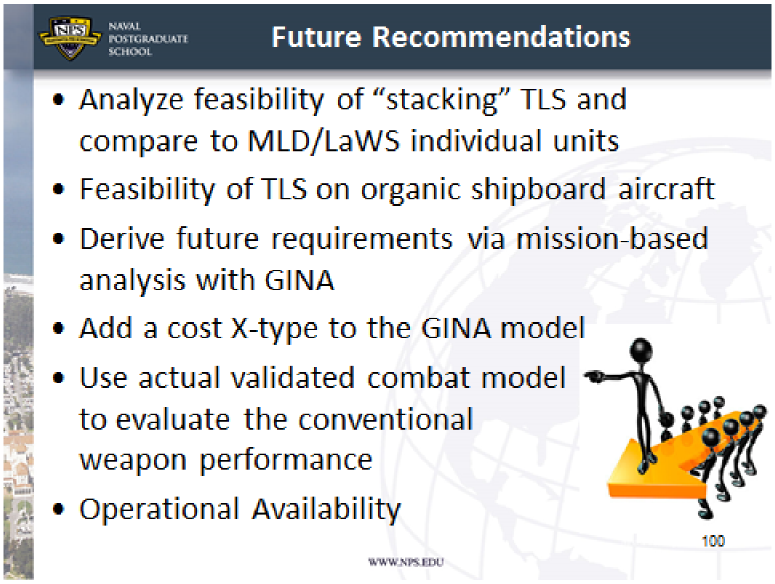
The Future



NAVAL POSTGRADUATE SCHOOL

Future Recommendations

- Analyze feasibility of "stacking" TLS and compare to MLD/LaWS individual units
- Feasibility of TLS on organic shipboard aircraft
- Derive future requirements via mission-based analysis with GINA
- Add a cost X-type to the GINA model
- Use actual validated combat model to evaluate the conventional weapon performance
- Operational Availability

Questions ?

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LIST OF REFERENCES

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