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Expeditionary Warfare — Force Protection

by

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In 2003, the Systems Engineering and Analysis students were tasked to develop a system of systems conceptual solution to provide force protection for the Sea Base conceptualized in the 2002 Expeditionary Warfare study. The Systems Engineering and Analysis Team used the Systems Engineering and Management process as the primary methodology to complete this multidisciplinary task. Survivability was identified as the most critical factor for evaluating the protection of the Sea Base and its transport assets. Threats to the Sea Base were reviewed, analyzed, and prioritized. System design and analysis focused on preliminary analyses of various sensors, search concepts, and weapons. These preliminary analyses identified capability gaps that were translated into functional concepts and proposed architectures for detailed modeling and analysis. These proposed architectures were identified as either Point or Distributed. In order to adequately determine the relative performance of the proposed architectures generated by the team, a thorough and systematic design of experiments was developed and applied in the Naval Simulation System and EXTEND. Based on the results obtained, the Systems Engineering and Analysis Team determined that a Distributed Sensor and Weapons architecture would significantly increase the survivability of future Expeditionary Warfare forces.

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I. EXECUTIVE SUMMARY

The 2003 Expeditionary Warfare Force Protection Integrated Project represents the combined efforts of approximately 60 students and 15 faculty members from different Naval Postgraduate School departments. The Systems Engineering and Analysis (SEA-4) Team integrated these efforts into the final product, a system of systems conceptual solution for expeditionary warfare force protection. The project began in 2002 with the office of the Deputy Chief of Naval Operations for Warfare Requirements and Programs (OPNAV N7) requesting an examination of future expeditionary warfare operations in terms of current and emerging operational concepts. The 2002 study identified and defined capability gaps, developed platform solutions, and generated conceptual design requirements for an expeditionary warfare family of ships, a heavy lift aircraft, and other systems designed to be capable of fully implementing the Ship to Objective Maneuver and Sea Basing doctrines identified as the future concepts of operation. The 2003 Expeditionary Warfare Force Protection Integrated Project was tasked to develop a system of systems conceptual solution to provide force protection for the Sea Base developed in the 2002 study. SEA-4 accomplished the task by employing a distinct Systems Engineering methodology, defining the problem, creating a scenario, conducting analyses, and using modeling and simulation tools to draw conclusions and determine the results.

Conclusions, results, and recommended system architecture were based on the attributes of force composition, sensor architecture, weapons architecture, and weapons type. The key findings of this study were:

- ***The distributed sensor and weapons architectures improve force survivability*** by providing increased available reaction times and more engagement opportunities. These architectures are particularly effective against Undersea Warfare (USW) threats because submarines can be detected and engaged prior to closing within effective torpedo ranges. Limited torpedo defense capabilities were identified as the primary cause of mission kills in the point sensor architecture.
- ***Conceptual weapons when paired with distributed sensors, improve survivability*** by increasing available reaction time. Conceptual weapons included higher-speed, longer-range variants of existing weapons, and a free-electron laser. Detecting threats at greater ranges provides commanders with more time to evaluate threats before committing weapons.

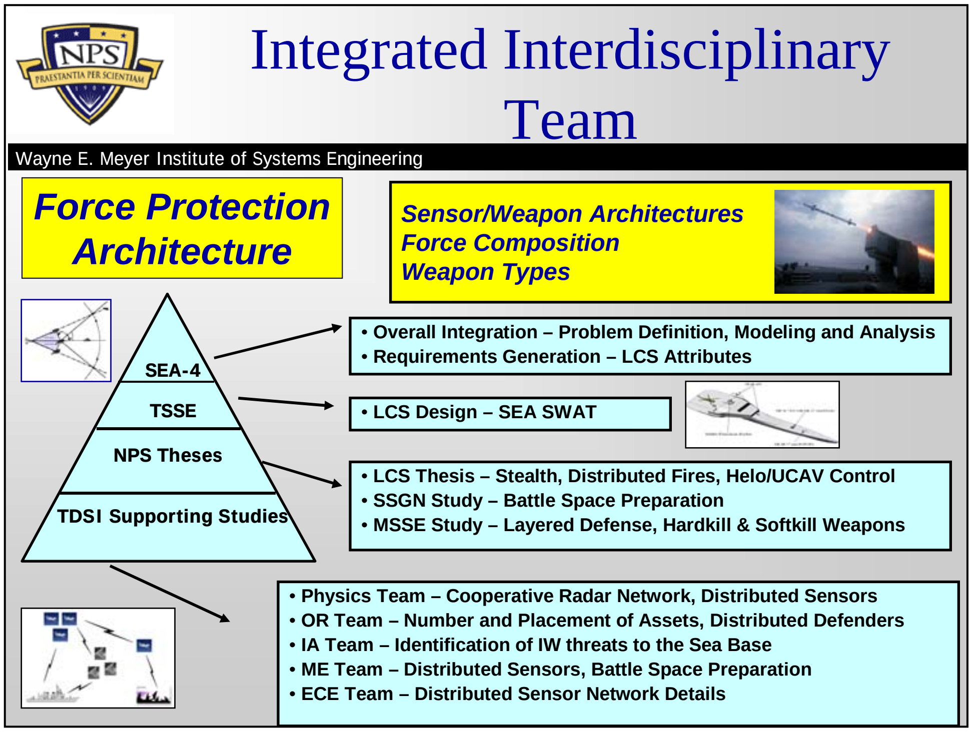
- ***The distributed architecture conserves weapons*** by detecting targets at ranges close to the maximum range of the interceptor. The longer detection ranges, in conjunction with the increased maximum ranges of the conceptual weapons, allow threat platforms to be engaged before they can launch their weapons. For example, if an aircraft capable of launching four anti-ship cruise missiles is destroyed before launching those missiles, then only one interceptor is used instead of four. Also, the greater reaction time provided by the distributed sensors allows for improved targeting, which contributes to the conservation of weapons.
- ***The selected cruiser-destroyer (CRUDES)-based and the Littoral Combat Ship (LCS)-based force compositions were tactically equivalent.*** Ultimately, another measure of effectiveness, such as manning, life cycle costs, etc., would have to be used to select a preferred concept.

The Systems Engineering and Management Process was used as the primary methodology to complete this multidisciplinary task and is an iterative, four-phase process designed as an organized approach to solving complex engineering problems. The four phases are: problem definition, design and analysis, decision-making, and implementation. Within each phase there are several iterative steps. Because this study was an academic exercise, the implementation phase was omitted.

Defining the problem was the most critical task in this study. In defining the problem, the team outlined critical assumptions, identified the primary functions of the system, addressed critical issues, assessed the threat environment, and generated system requirements. Survivability was determined to be the most critical factor in the protection of the Sea Base and its transport assets. Survivability is the measure of all defensive actions and consists of two components: susceptibility and vulnerability. Survivability can be increased by reducing susceptibility (probability of being hit) and reducing vulnerability (probability of kill given a hit). Threats to the Sea Base were reviewed, analyzed, and prioritized. The problem was scoped by generalizing threats in the form of threat categories, and by identifying and focusing force protection efforts on the primary threats identified by the analysis. Due to resource limitations, the threat analysis did not encompass the full range of threats that the Sea Base might face in the future, but it was able to provide a realistic basis, with regards to the capabilities and characteristics, of the types of threats that future architectures will have to counter in order to be successful.

After defining the problem, system design and analysis focused on detailed analyses of sensor concepts, search concepts, and weapons engagement concepts. An important part of effectively countering any threat is the ability to detect it. The analysis began by assessing the ability of various sensors (radar, lidar, infrared, and sonar) to detect threats as the first step in defending the Sea Base. Analysis of sensors showed that a distributed sensor network offers greater detection ranges by extending the sensors' horizons and by achieving greater target aspects. The analysis also provided insight into which sensors were best in detecting a specific threat. For example, the infrared sensor performed better than radar when detecting a high-diving, supersonic, anti-ship cruise missile. From this, various threat-sensor pairs were developed, studied, and analyzed in order to determine potential detection ranges of the sensors against associated threats. The search analysis applied search detection models based on area or volume covered and beam spread or field of view for each sensor to determine probabilities of detection for each threat-sensor pair. First principal probability of detection equations were applied in addition to the detection ranges calculated in the sensor analysis to provide insight into the type of sensor architecture needed to best protect the Sea Base. These preliminary analyses identified a capability gap that drove the need for a sensor system that would be capable of detecting threat platforms at long range and with ample time to counter them before reaching their weapons' maximum effective ranges. The functional analysis identified the basic functions of deploy, detect, defeat, prevent, and withstand as individual capabilities needed to protect the Sea Base. Using these factors, the team proposed architectures based on characteristics of force composition, sensor architecture, weapons architecture, and weapons type.

Supporting studies from individual student theses and student faculty teams, including those from the Temasek Defense Systems Institute, were used as a basis for developing these characteristics and the associated architectures. A breakdown of the teams and brief descriptions of their contributions is shown in Figure I-1.



Integrated Interdisciplinary Team

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Force Protection Architecture

Sensor/Weapon Architectures
Force Composition
Weapon Types

- Overall Integration – Problem Definition, Modeling and Analysis
- Requirements Generation – LCS Attributes

- LCS Design – SEA SWAT

- LCS Thesis – Stealth, Distributed Fires, Helo/UCAV Control
- SSGN Study – Battle Space Preparation
- MSSE Study – Layered Defense, Hardkill & Softkill Weapons

- Physics Team – Cooperative Radar Network, Distributed Sensors
- OR Team – Number and Placement of Assets, Distributed Defenders
- IA Team – Identification of IW threats to the Sea Base
- ME Team – Distributed Sensors, Battle Space Preparation
- ECE Team – Distributed Sensor Network Details

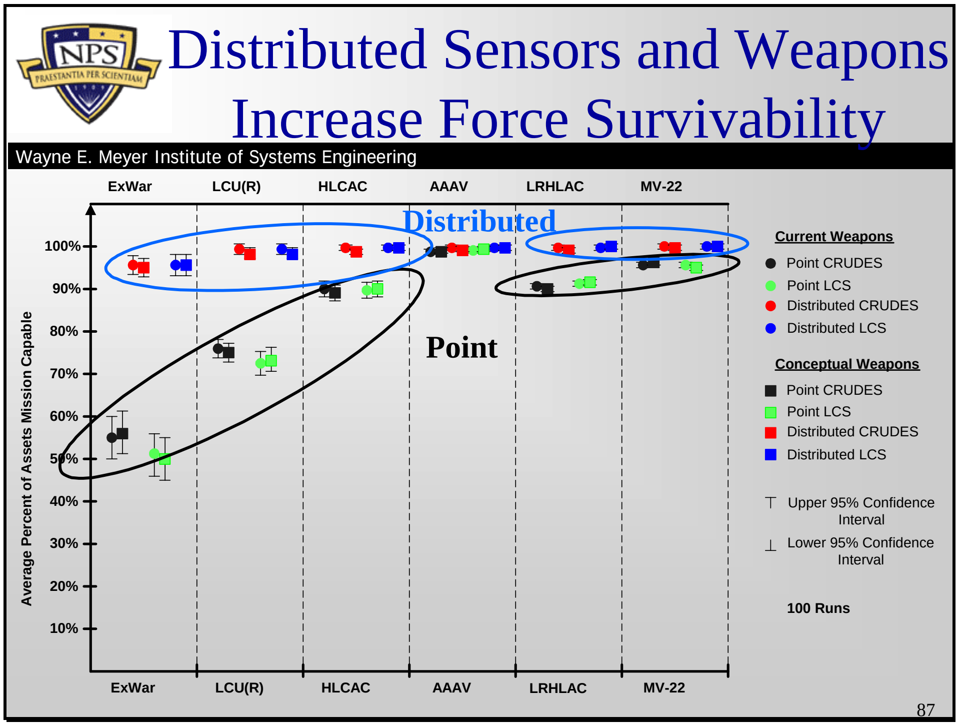
Figure I-1 Overview of Supporting Studies

Understanding the complex nature of force protection of the Sea Base required the use of modeling and simulation tools. The tools initially assessed included: Joint Army Navy Uniform Simulation (JANUS), Joint Theater Level Simulation (JTLS), Naval Simulation System (NSS), Enhanced ISSAC (Irreducible Semi-Autonomous Adaptive Combat) Neural Simulation Toolkit (EINSTein), EXTEND, and Microsoft Excel. After completing a detailed risk analysis, the team decided to include NSS, EINSTein, EXTEND, and Microsoft Excel as parts of the study.

In order to adequately determine the relative performance of the proposed architectures developed by the team, a thorough and systematic design of experiments was developed to maximize the model runs. The primary characteristics of the proposed architectures are force composition, sensor and weapons architecture, and weapon types. Using the notion of a 2^n factorial design, two levels of each characteristic were developed. The force composition levels are courses of action (COA) A and B. COA A is a CRUDES-based protection force comprised of three CGs, three DDGs, three FFGs, and one SSN. COA B is a LCS-based force protection force comprised of one CG, one DDG, 12 LCSs, and one SSGN. The sensor and weapons architecture are point and distributed. Weapon types are current and conceptual weapons.

From the functional analysis, survivability was determined to be the key function in force protection of the Sea Base. The primary measure of effectiveness (MOE) of protecting the Sea Base, therefore, was determined to be the survivability of the Sea Base and its transport assets. The output of each of the models was designed to facilitate the collection of information needed to determine the survivability of the Sea Base and its transport assets.

EXTEND, a process-based, discrete-event modeling and simulation tool, provided a macro-view of sensor-weapon architecture-threat interactions. Results from the EXTEND model (see Figure I-2) demonstrated that distributed sensors increase the survivability of the Sea Base and its transport assets, that an LCS-based protection force is tactically equivalent to a CRUDES-based protection force; and that current weapons are not statistically different with respect to survivability when compared to conceptual weapons. Additionally, the submarines and torpedoes were by far the highest threats to the Sea Base. Torpedoes, which in this model made up roughly 10% of the threat, caused approximately 90% of the mission kills (see Figure I-3).



Distributed Sensors and Weapons Increase Force Survivability

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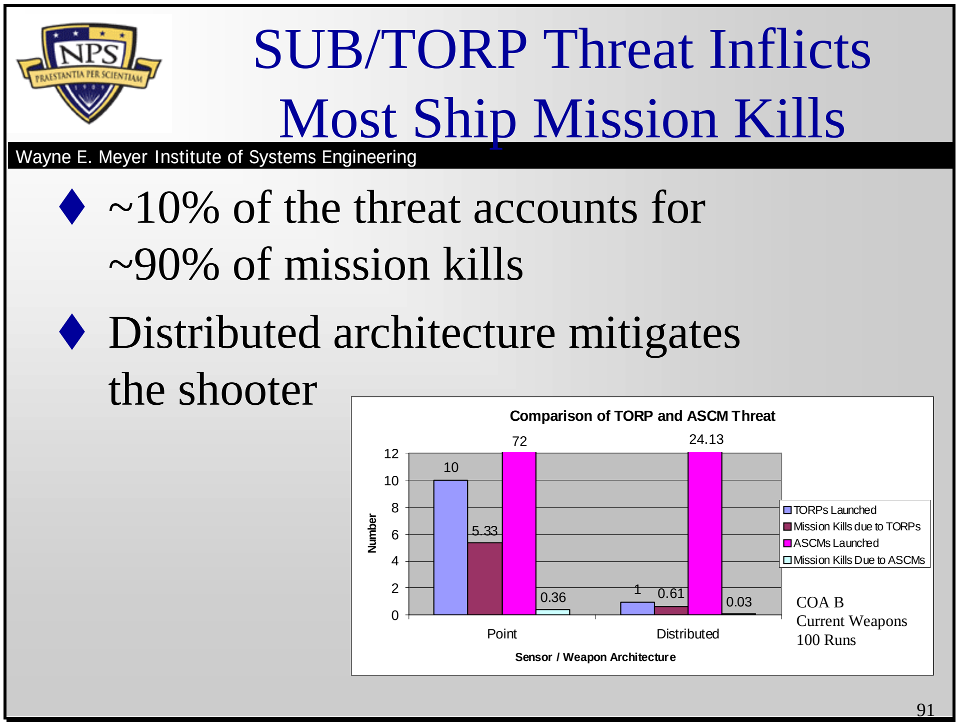
Figure I-2 Comparison of Alternate Force Architectures



SUB/TORP Threat Inflicts Most Ship Mission Kills

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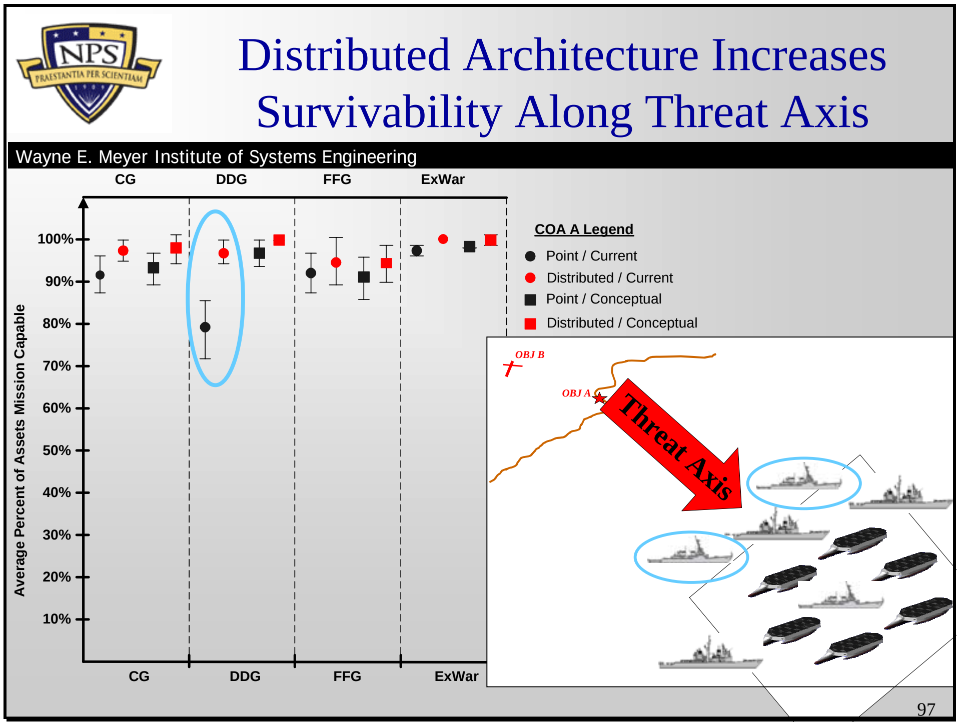
- ~10% of the threat accounts for ~90% of mission kills
- Distributed architecture mitigates the shooter

Figure I-3 Comparison of Torpedo and ASCM Threats

NSS, an object-oriented Monte Carlo modeling and simulation tool, provided a means of analyzing the characteristics of the two proposed force protection architectures. NSS model results showed that the distributed architecture provides improved survivability for defending assets placed along the threat axis (see Figure I-4). The model also showed that the distributed architecture seems to facilitate a quicker drawdown of threats. Additionally, the NSS model showed that the distributed architecture is more effective in its use of weapons because of its ability to provide better targeting information and more effective threat-weapon assignments. Furthermore, the distributed architecture was able to detect and defeat threat platforms before they were able to launch their weapons.



Distributed Architecture Increases Survivability Along Threat Axis

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COA A Legend

- ● Point / Current
- ● Distributed / Current
- ■ Point / Conceptual
- ■ Distributed / Conceptual

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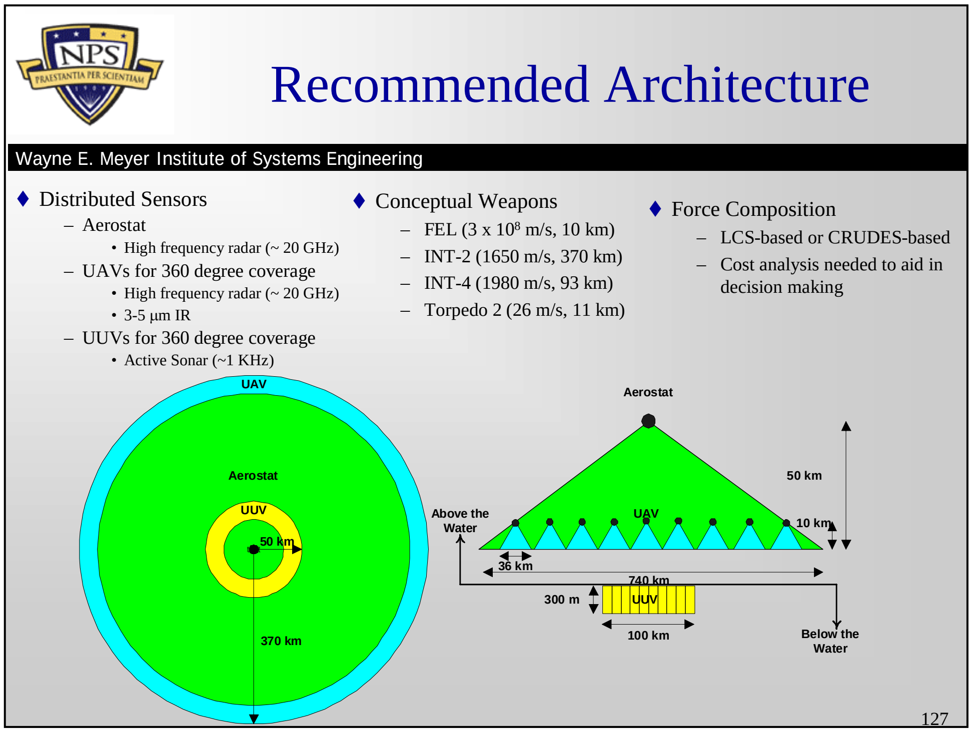
Figure I-4 Distributed Architecture Increases Survivability Along Threat Axis

From the models analyzed, the key factor in attaining higher survivability for the Sea Base and its transport assets was the ability of the sensor system to provide more reaction time, and therefore more engagement opportunities, to the weapons systems. The distributed sensor architecture allows the weapons systems to take fewer shots, thereby conserving the force’s fighting potential. As a result of these analyses, the proposed architecture can be either LCS- or CRUDES-based and possess either current or conceptual weapons. Ultimately, the decision to use an LCS-based or CRUDES-based force and the decision to use the given current or conceptual weapons must be based on a measure of effectiveness other than survivability. Figure I-5 summarizes the system of systems conceptual solution for Sea Base force protection.



Recommended Architecture

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- Distributed Sensors
  - Aerostat
    - High frequency radar (~ 20 GHz)
  - UAVs for 360 degree coverage
    - High frequency radar (~ 20 GHz)
    - 3-5 µm IR
  - UUVs for 360 degree coverage
    - Active Sonar (~1 KHz)

- Conceptual Weapons
  - FEL (3 x 10^8 m/s, 10 km)
  - INT-2 (1650 m/s, 370 km)
  - INT-4 (1980 m/s, 93 km)
  - Torpedo 2 (26 m/s, 11 km)

- Force Composition
  - LCS-based or CRUDES-based
  - Cost analysis needed to aid in decision making

Figure I-5 Proposed System Solution for Sea Base Force Protection

Because the analysis itself was broad, the results are broad-based as well. Further study efforts should be conducted to provide more thorough analyses of areas of particular concern. Some suggested areas include actual sensor and weapon capabilities, emerging technologies, reliability and maintainability factors, acquisition strategies, realistic timelines for deployment, associated trade-offs, and COA analyses. Finally, research into existing classified systems, emerging technologies, and non-lethal weapons technologies is recommended to provide additional options for protecting the Sea Base.

II. BACKGROUND

A. PROJECT ASSIGNMENT

In the Winter Quarter of 2002, students in the Systems Engineering and Integration (SEI) program provided project inputs to the board of advisors for the Wayne Meyer Institute of Systems Engineering. This board, made up of flag officers and distinguished civilians, assisted the Institute in choosing project work that is academically challenging, as well as relevant to Department of Defense (DOD) interests and needs. The board selected Expeditionary Warfare as an area of interest. Subsequently, in April 2002, the office of the Deputy Chief of Naval Operations for Warfare Requirements and Programs (OPNAV N7) tasked the Institute to conduct an Expeditionary Warfare study (McGinn, 2002). In the first year of this two-year project, the SEI-3 students used a "system of systems" approach to engineer an architecture with an overarching set of system requirements for a system of systems to conduct expeditionary operations in littoral regions; explore interfaces and system interactions; and compare current, proposed, and conceptual sea-based platforms against these requirements. The SEI-3 group also completed excursions to examine the effects of speed, reduced footprint ashore, Sea Basing, modularity of design, and reduced manning.

As part of their final report, the SEI-3 group made several recommendations for areas of further study. As with similar studies, the resources dictated the depth of the study. The amount of time and available number of students focused the scope of their examination on new ways to conduct Expeditionary Warfare. Their examination also raised several questions. Their recommendations were intended to describe areas where further study will enhance the understanding of Expeditionary Warfare from a system of systems perspective. One recommendation was to conduct a more thorough analysis of Force Protection. Based on input from OPNAV N7, advisor recommendations, time constraints, the number of students available, and other factors, the Wayne Meyer Institute of Systems Engineering faculty decided that further analysis of Force Protection would be the best subject for this year's follow-on study. This year's team consisted of students in the revised Systems Engineering and Analysis (SEA) program, this team was designated SEA-4. The SEA-4 Team endeavored to "develop a system of systems conceptual solution to provide force protection for the Sea Base and its transport assets while performing forced entry and Ship to Objective Maneuver (STOM) operations in support of the Ground Combat Element (GCE) of a Marine Expeditionary Brigade (MEB)." (Calvano, 2003, 1) The SEA-4 Team was also tasked to work closely with the Total Ship Systems Engineering (TSSE) students on a LCS (Littoral Combat Ship) design specifically suited for Force Protection of the Sea Base, as well as incorporating work completed by the Temasek Defense Systems Institute (TDSI) students into the conceptual system of systems solution to the Force Protection problem.

B. EXPEDITIONARY MANEUVER WARFARE

An expeditionary force is an armed force organized to accomplish a specific mission in foreign lands far from a supportable home base. This force is supported by a temporarily established means and will leave the foreign land when the mission is complete. Expeditionary Maneuver Warfare is the conduct of that specific mission by those established means. The concept of Expeditionary Warfare is the driving force that is being used to shape the future of the Marine Corps and Naval Amphibious Forces. The future of Expeditionary Maneuver Warfare is based on the tenets of Operational Maneuver from the Sea (OMFTS) and STOM. OMFTS employs the capability to use the sea as a maneuver space. STOM is the tactical application of OMFTS. STOM depends on ships located offshore, beyond the range of most threats, to support the landing forces. Sea Basing of command and control, logistics, combat service support, and operational support is the backbone of STOM.

C. SEA BASING

The concept of Sea Basing is designed to revolutionize the projection, protection, and sustainment of sovereign warfighting units around the world. Sea Basing capitalizes on the inherent mobility, security, and flexibility of naval forces to overcome the emerging military and political limitations to overseas access. The mobility of the Sea Base allows it to maneuver as part of the Expeditionary Task Force to support sustained operations ashore. This capability should reduce the need to build up logistical stockpiles ashore that may burden or endanger allies and drastically complicate force-protection requirements. By employing direct replenishment from ship-to-objective, the build up of forces ashore ("Iron Mountain") and operational pause can be reduced or eliminated. In addition, there is no need to allocate resources to protect this Iron Mountain. The thrust of the force protection efforts now lies in protecting transport assets at sea, and airborne assets between the Sea Base and the objective. Sea Basing will provide afloat positioning of command and control, and logistics support will strengthen force protection and free airlift-sealift to support missions ashore. It will also reduce early demands on the national strategic lift assets. Sea Basing will enable the Navy to conduct sustained, persistent combat operations from the sea, and when fully implemented will provide a viable option to eliminate the limitations imposed by reliance on overseas shore-based support. Figure II-1 shows a graphic illustration of the Sea Base concept as defined by the SEI-3 group.

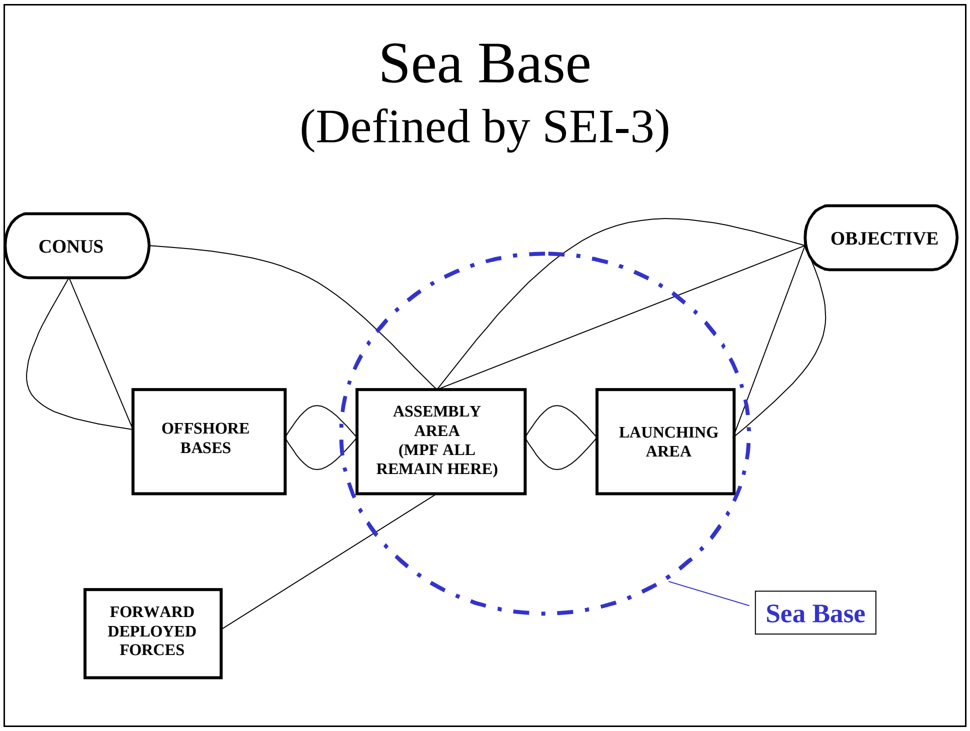


Figure II-1 Sea Base Diagram

D. FORCE PROTECTION

The Navy-Marine Corps team has been executing expeditionary operations since its inception. Few of these operations have been unopposed. Future adversaries will continue to probe perceived weaknesses, and will develop plans to deny access to their regions. Conventional and asymmetric strategies will be employed to conduct attacks on the Sea Base, landing craft, and aircraft components of the Expeditionary Warfare Force. Although Sea Basing reduces overall force protection requirements, it focuses those requirements on protecting the ships of the Sea Base and its airborne and seaborne transport assets. Chapter IV, Section C, details specific threats that will pose considerable challenges to the Sea Base in the 2015-2020 timeframe.

The term "Force Protection" can have several definitions. The SEA-4 Team, with stakeholder approval, adopted the following definition of Force Protection from the DOD dictionary: actions taken to prevent or mitigate hostile action against the Sea Base to include resources, facilities, and critical information. These actions conserve the force's fighting potential so it can be applied at the decisive time and place and incorporate the coordinated and synchronized offensive and defensive measures to enable the effective employment of the joint force while degrading opportunities for the enemy. Force Protection does not include actions to defeat the enemy or protect against accidents, weather, or disease.

E. CONCEPTUAL ARCHITECTURE

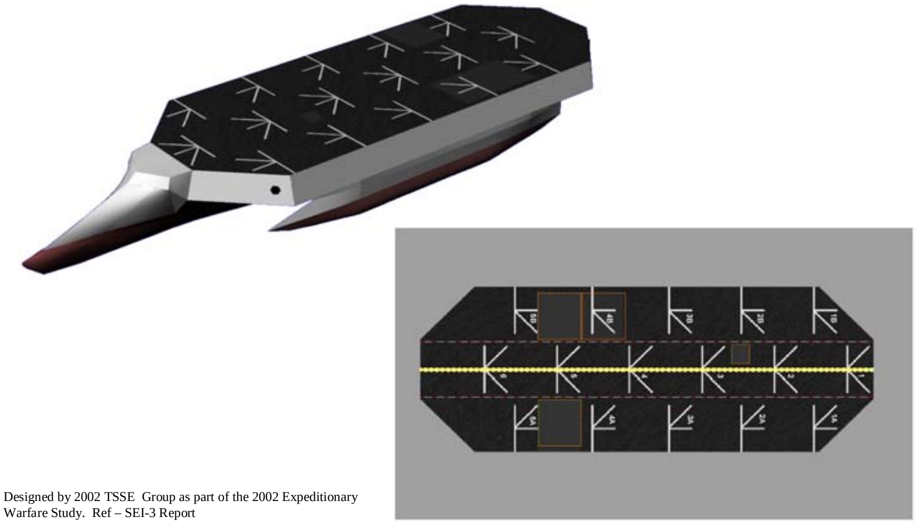
The conceptual architecture addressed in the SEI-3 report was developed as an alternative to the planned architecture of the United States Marine Corps (USMC) Marine Air Ground Task Force (MAGTF) in the 2015-2020 timeframe. This conceptual architecture includes new ships designed for the purpose of future Expeditionary Warfare operations considering the tenets of OMFTS and STOM, and the elimination of the traditional Iron Mountain. The SEI-3 Team used the systems engineering process to generate requirements for, and design, a force that includes new amphibious assault ship designs, logistic ship designs, and the design of a heavy lift aircraft that would successfully accomplish the Expeditionary Warfare mission. The resulting conceptual architecture incorporates conceptual, planned, and existing assets.

1. Expeditionary Warfare Ships (ExWar)

The ExWar ships created by the 2002 TSSE group were designed to be self-deployed and self-sustained platforms. They were an amalgamation of LHA, MPF, and LMSR ships with a transoceanic capability, and speeds greater than 27 knots. The design provided the needed maneuverability at sea for the Expeditionary Strike Group to conduct OMFTS and STOM. The flight deck of the ExWar ship provides 16 aircraft spots from which to conduct air operations.

All aircraft require one spot, with the exception of the Heavy Lift Aircraft, which requires two spots. A family of six ExWar ships form the Sea Base; Figure II-2 is a conceptual illustration of one of these six ships and its flight deck. Additionally, three other ships with the same hull form are used as logistics ships to transit back and forth from an offshore base to resupply the Sea Base.

Expeditionary Warfare Ship



Designed by 2002 TSSE Group as part of the 2002 Expeditionary Warfare Study. Ref – SEI-3 Report

Figure II-2 Expeditionary Warfare Ship Design

The ExWar ship was designed with basic combat systems capabilities required for self-defense. Naval Gun Fire Support (NGFS) was considered to be an extremely important mission because of the need to provide the forces ashore with effective fires in a STOM environment. Therefore, an Electromagnetic Rail Gun (ERG) was added to provide that capability. This was the only combat systems capability that could be considered offensive in nature. Some other weapon systems included a Free-Electron Laser (FEL) and Unmanned Underwater and Aerial Vehicles. Consideration was given to stealth technology as a means of reducing the radar cross section of the ship as a means of defense. Figure II-3 illustrates the major weapon systems incorporated in the ExWar ship design.

Figure II-3 Expeditionary Warfare Ship Weapon and Sensor Systems

2. Aircraft

The aircraft of the Sea Base include the MV-22, AH-1Z, UH-1, the Joint Strike Fighter (JSF), and the Heavy Lift Aircraft (HLAC) designed by the 2002 Aerospace Engineering Team. The MV-22 and HLAC are used for transport of assets to the objective and/or landing area.

a. MV-22

The MV-22 Osprey is a multi-engine, dual-piloted, self-deployable, medium lift, Vertical Takeoff and Landing (VTOL) tiltrotor aircraft designed for combat, combat support, combat service support, and Special Operations missions worldwide. It is scheduled to replace the CH-46E and CH-53D medium lift helicopters. The tiltrotor combines the speed, range and fuel efficiency normally associated with turboprop aircraft with the vertical takeoff and landing and hover capabilities of helicopters. The MV-22 is designed to have a cruise speed of 240 knots and to take up to 24 fully loaded combat troops up to a range of 200 nm. The MV-22 can be air refueled to increase its range and can carry up to 20,000 lbs. The MV-22 is shown in Figure II-4.

Figure II-4 MV-22 Osprey

b. Long Range Heavy Lift Aircraft (LRHLAC)

The Heavy Lift Aircraft was designed with the capability to carry an external payload of 37,500 lbs 300 nm from the Sea Base to the Objective, offload its payload, and return to the Sea Base without refueling. Additionally, the Heavy Lift Aircraft was designed to carry an internal load of 20,000 lbs for 300 nm, offload, and return to the Sea Base without refueling.

The Heavy Lift Aircraft combat survivability was also addressed in the SEI-3 report. At the time, the primary threat to the troop and material transport aircraft was considered to be shoulder-fired, infrared-guided surface-to-air missiles (SAM) with contact warheads, and small caliber (7.62mm and 12.7mm), armor-piercing, anti-aircraft artillery (AAA) platforms. Based on this, the aircraft was designed to be capable of sustained operations in a threat environment consisting of man-portable SAMs, small caliber AAA, and small arms fire with minimum impact on mission capability. The Heavy Lift Aircraft design concept is shown in Figure II-5.

Figure II-5 2002 Heavy Lift Aircraft Design

c. Joint Strike Fighter

The Marine Corps Joint Strike Fighter (JSF) is a single engine, multi-role Short Take-Off and Vertical Landing (STOVL) strike fighter designed to replace the AV-8B and F/A-18A/C/D. The JSF has more than twice the range of the AV-8B on internal fuel, operates at supersonic conditions, incorporates low observable characteristics, and houses internal weapons. The JSF is designed to fulfill USMC air-to-air and air-to-ground combat requirements for the battlefield of the future. It will also provide tactical air control and tactical reconnaissance capabilities and be able to perform the Suppression of Enemy Air Defenses (SEAD) mission. JSF requirements focused on readiness, expeditionary capability, combined-arms operations, and the conduct of Expeditionary Maneuver Warfare. The USMC JSF, recently designated the F-35B, is shown in Figure II-6.

USMC Joint Strike Fighter
F-35B

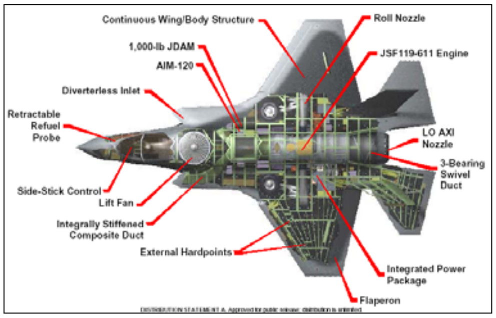


Figure II-6   USMC Joint Strike Fighter

d. AH-1Z

The AH-1Z upgrade was designed to be a very capable and flexible multi-mission attack helicopter. It was designed with state-of-the-art dynamics, weapons, and avionics suites that incorporate the latest survivability equipment available. The AH-1Z will have enhanced survivability characteristics and the capability to fully support Expeditionary Warfare operations. Features will include improved weapons capability, improved survivability and crashworthiness, use of modern technology, improved targeting system, improved air-to-air combat capability, enhanced maintainability, a modern cockpit design, and commonality with the UH-1Y. The AH-1Z is shown in Figure II-7.

Figure II-7 AH-1Z Super Cobra

e. UH-1Y

The UH-1Y tactical utility helicopter was designed as an upgrade to one of the oldest helicopters in the Marine Corps inventory. New features will include dramatically improved survivability, maneuverability, and supportability using the most modern technologies available. A new four-bladed main rotor system replaces the older two-bladed system. Airframe improvements, improved engines, a "glass" cockpit, and other advanced systems, are designed to deliver substantial increases in tactical capability. It will also have an increased payload capacity, while increases in range and speed will allow faster delivery of combat assets to the landing area and/or objective. Survivability improvements will be made in the form of increased self-protection capability and improved crashworthiness. The UH-1Y is shown in Figure II-8.

Figure II-8 UH-1Y Tactical Utility Helicopter

3. Landing Craft

The landing craft of the Sea Base include the Heavy Lift Landing Craft Air Cushioned (HLCAC), the Landing Craft Utility (Replacement) (LCU(R)), and the Advanced Amphibious Assault Vehicle (AAAV).

a. HLCAC

The HLCAC beam will measure approximately the same as the current LCAC's, but it will be half its length longer, giving the new LCAC a 1.5 greater payload capacity than its predecessor. The HLCAC will also have improved engines, which will make it faster and more reliable. The proposed craft would increase in both length and cargo area—by 33%—over the present LCAC and would have double the payload (144 tons). The HLCAC would be capable of carrying two M1A1 tanks or 10 Light Armored Vehicles (LAV). The LCAC is shown in Figure II-9; the HLCAC will be similar in appearance, only larger.

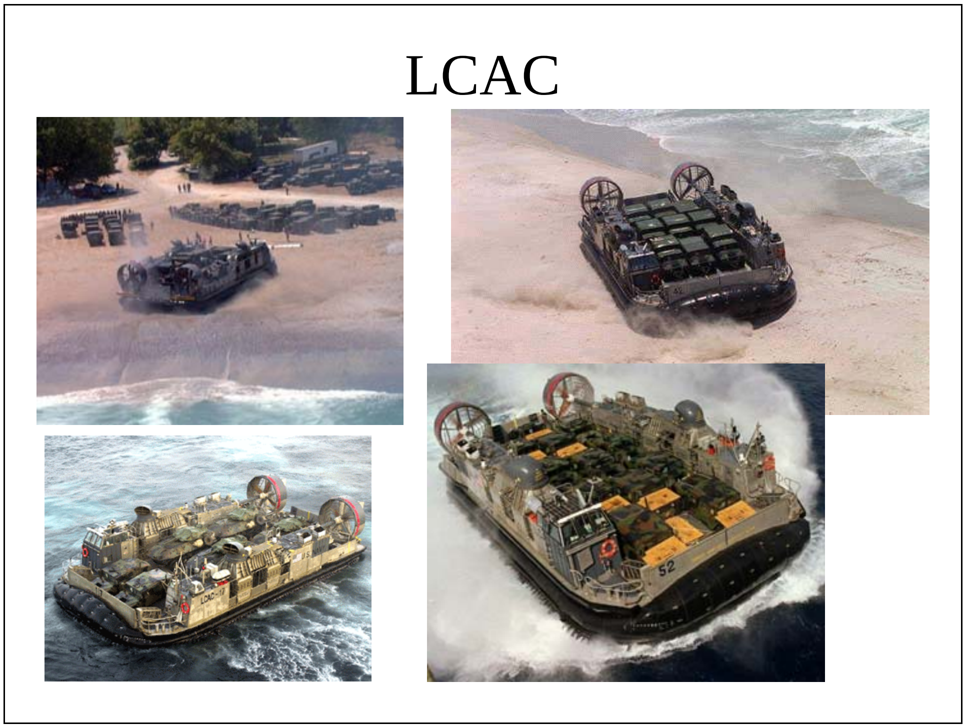


Figure II-9 LCAC

b. LCU(R)

The LCU(R) is designed to replace the LCU 1600 Class Utility Craft. It will provide a technologically advanced, heavy lift, utility landing craft to complement the high-speed, over-the-horizon (OTH), ship-to-objective amphibious lift required to support OMFTS. For purposes of this study, the LCU(R) will be able to operate from the well deck of the TSSE 2002-designed Expeditionary Warfare ship described in this Chapter, Section E. The craft will have higher operational speeds, and improved OTH lift capability. LCU(R) will have the capability to conduct sustained, independent operations for up to 10 days with an operational range of 1,000 nautical miles. The LCU(R)'s enhanced characteristics will greatly reduce ship-to-beach cyclic time, and will include a drive through design with forward and aft ramps to improve vehicle and cargo load out and discharge time when offloading equipment. The craft will have a secondary mission to serve as an alternative launch, recovery, and salvage platform for the Marine Corps' new Advanced Amphibious Assault Vehicle (AAAV). The LCU and a computer model of an LCU(R) are shown in Figure II-10.

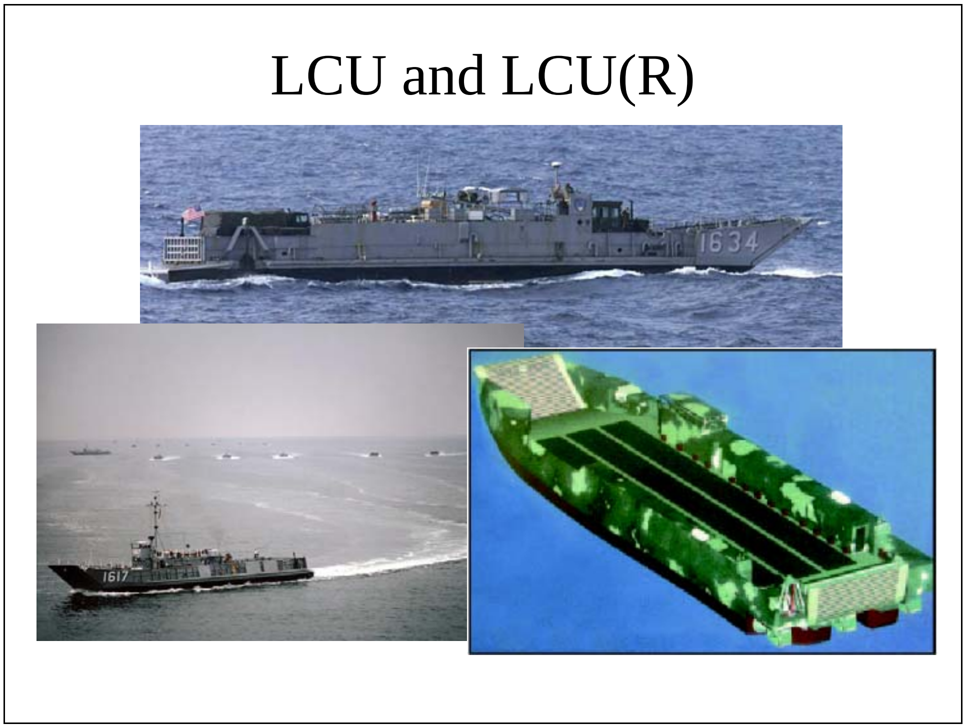


Figure II-10   LCU and LCU(R)

c. AAAV

The AAAV is designed to transport 18 Marines and a crew of three over water at speeds of 29 miles per hour up to a range of 65 miles; the design uses a planning hull propelled by two water jets. On land, the AAAV will achieve speeds of 45 miles per hour at a range of up to 300 miles, with cross-country mobility equal to an M1 Abrams tank. A command and control variant of the AAAV will provide access to information from satellite and computer-based intelligence sources, as well as from ships, aircraft, and other vehicles, while controlling operations at sea or on land. The AAAV is shown in Figure II-11.

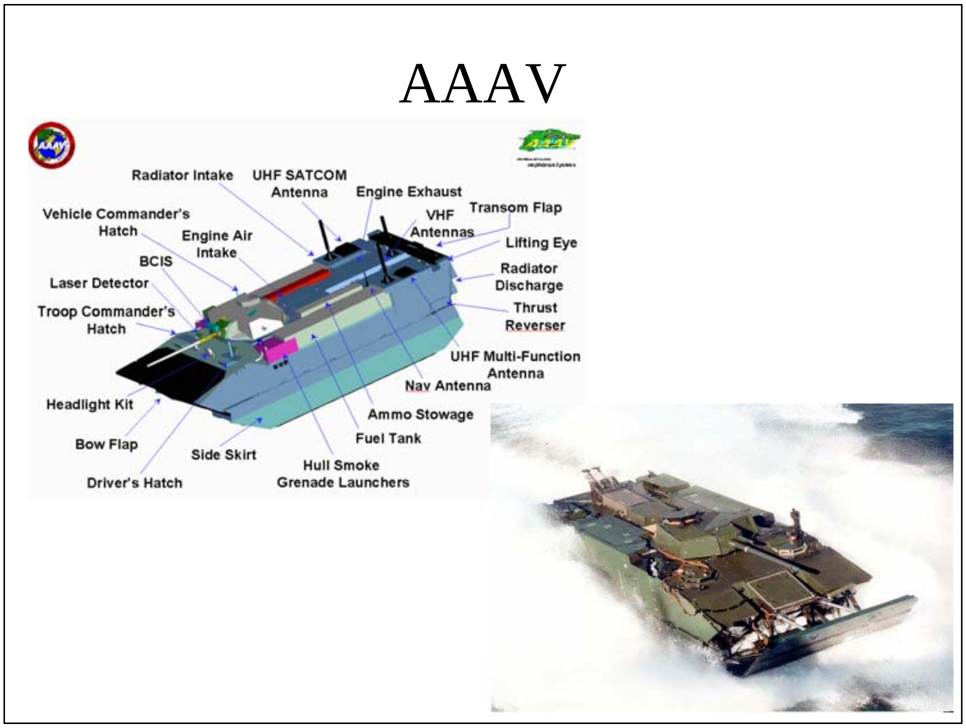


Figure II-11 Advanced Amphibious Assault Vehicle

F. SUMMARY

The information contained in this chapter provides the foundation from which this study was conceived, and is intended to give the reader a basic understanding of Expeditionary Warfare; the future Naval-Marine Corps tactics desired to be employed in the 2015-2020 timeframe; and the friendly assets that will execute those tactics. Protecting those assets is the main focus of this study's efforts. This study, as a continuation of past efforts, began with the constraints defined by the SEI-3 Team. Those constraints were the mission area, the concepts, the platforms, and the assumptions. Efforts to clearly define these constraints using open-source information, and what conceptual system of systems will best serve the Navy-Marine Corps Team with regards to accomplishing the force protection mission, will be discussed in greater detail in the following chapters.

III. SYSTEMS ENGINEERING METHODOLOGY

A. OVERVIEW

A system is a set of interrelated components working together toward a common objective. The International Council on Systems Engineering (INCOSE) defines Systems Engineering as:

> “An interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem:
>
> - Operations
> - Performance
> - Test
> - Manufacturing
> - Cost & Schedule
> - Training & Support
> - Disposal
>
> Systems Engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs.”

This definition shows that the function of Systems Engineering is essentially to guide the engineering and development of multidisciplinary systems. Nowhere is this more critical than in the design and implementation of joint combat systems.

There are several processes that can be used for guidance in these efforts. Systems Engineers have developed several formal methodologies for accomplishing this task, many of which are tailored for specific uses. The common thread in each of these methodologies is a basic framework that includes a structured method for defining the problem. Some methods also include processes to generate alternative solutions, analyze the alternatives, and then select the best alternative. This basic framework is appropriate for multidisciplinary engineering systems such as those that address large-scale, complex military problems. The design methodology, called the Systems Engineering and Management Process (SEMP), was introduced as the methodology for use in this study. The SEMP is depicted in Figure III-1.

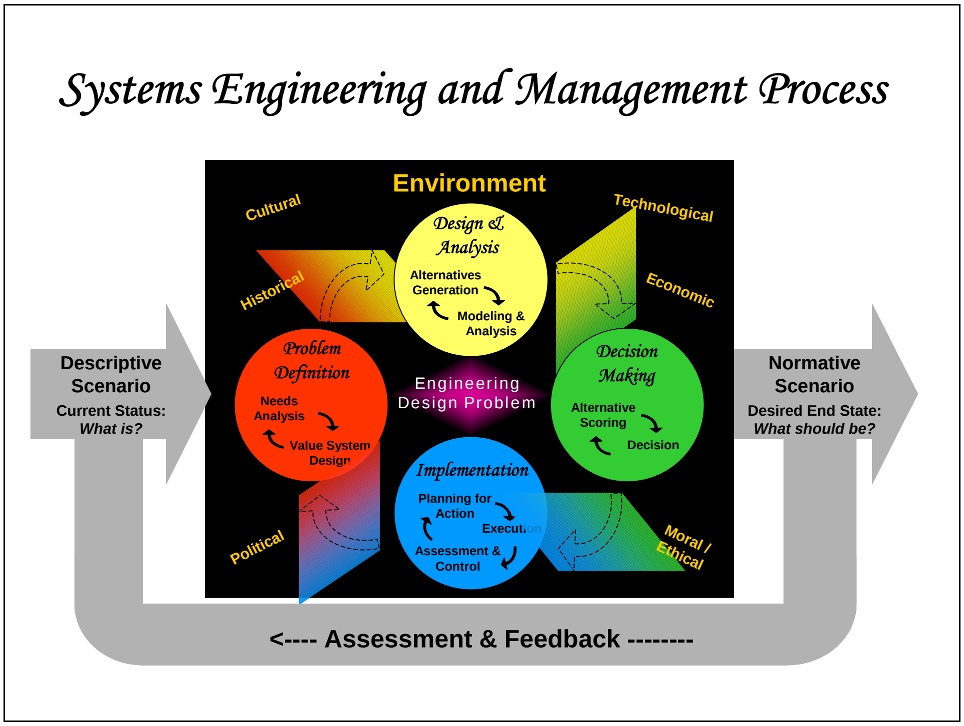


Figure III-1 The Systems Engineering and Management Process (SEMP)

The SEMP is a four-phase process designed as an organized approach to solving a complex engineering problem. The four phases are problem definition, design and analysis, decision-making, and implementation. The depiction of the SEMP shows that problem definition is the first phase of the process and that the other phases follow in order. Use of the SEMP must be tailored to the engineering design problem being addressed and therefore may require altering the order shown or movement into one phase prior to completion of another. Depending on the situation, the variables, and what already exists, extra time may be spent completing one step while other steps may be omitted. In addition, any step may be re-visited in an iterative way.

B. PROBLEM DEFINITION

This phase's purpose is to ensure Systems Engineers have a clear understanding of the problem at hand. The client's needs, wants, and desires must be captured. In some cases, the clients themselves may not have a clear understanding of the problem to be solved. The problem definition phase addresses these issues and allows the Systems Engineers to define the problem in a logical manner. This requires two major steps: needs analysis and value system design.

1. Needs Analysis

The engineering design process begins with a problem statement developed by the client. This statement may, in some cases, be vague. Again, the client may not have a clear understanding of the problem or may not be sure what they want or need. They also may not have a clear vision of where they are or where they are going.

To gain an understanding of the problem, Systems Engineers must thoroughly research the problem area; interact with the client to determine their objectives; and interact with users, manufacturers, maintainers, and all other relevant stakeholders to determine their needs as well. This research and interaction, shown in Figure III-2, should culminate in the development of an effective need statement, which the client, stakeholders, and analysts all agree clearly defines the problem to be solved. This statement must outline the objectives that the design intends to meet.

Figure III-2 Needs Analysis

There are several tools available to support a needs analysis and help the Systems Engineers to better understand the problem. The SEMP focuses on three primary tools: stakeholder analysis, functional analysis, and futures analysis.

2. Stakeholder Analysis

The purpose of stakeholder analysis is to identify the people and/or organizations that are relevant to the problem and to determine their needs, wants, and desires with respect to the problem to be solved. These groups are referred as stakeholders because they have a considerable stake or vested interest in the problem and its eventual solution. Typical stakeholder classes include clients, sponsors, decision-makers, users and analysts.

The stakeholder analysis allows Systems Engineers to begin identifying critical assumptions and constraints on the problem. These assumptions and constraints set the boundaries that Systems Engineers have to work within to solve the problem. These boundaries come from a variety of sources and may include assumptions ranging from strategic to tactical. Resources such as time, personnel, and funding are the most typical constraints; however, there may be physical, legal, environmental, social, and technological constraints to consider as well.

3. Functional Analysis

The primary purpose of functional analysis is to identify and decompose critical system functions, and to organize them in such a way as to facilitate a better understanding of the system functional requirements. In other words, it describes what the system must do, but not how it will be implemented. Functions are purposeful actions of the system that involve the transformation or alteration of material, energy, information, and/or other resources. A function also implies some input that undergoes a transformation process to produce a desired output.

Functional analysis is a two-step process. The beginning of this process is functional decomposition. The purpose of functional decomposition is to identify and decompose the system's critical functions. System decomposition contains four elements: system functions, system components, hierarchical structure, and system states. System functions are purposeful actions of the system that involve the transformation or alteration of material, energy, information, and/or other resources. This function implies some input that undergoes a transformation process to produce a desired output. System components can be structural (static elements of the system that do not change as the system performs its transformation function), operating (dynamic elements that perform the processing), or flow components (transformed elements that are changed by the system). The system's components, or the system as a whole, may assume different quantitative and/or qualitative values that describe the current state of the system. These values are variables used to describe the components or to measure the system state. As the system performs its function, the values of the state variables will change to reflect an instantaneous condition (or state) of the system. The hierarchical structure is the physical and/or functional relationship between components.

The result of a functional decomposition is a list of functions and subfunctions required of the proposed system. The most difficult part of the functional decomposition is avoiding the tendency to develop solutions based on existing systems. Thinking in terms of existing systems limits the range of possible solutions. The Systems Engineer needs to focus on the purpose of the intended system and avoid preconceived solutions. After completing the functional decomposition and development of a list of functions and subfunctions, the next step of functional analysis is to organize this list in a meaningful way. One method of doing this is by creating a functional hierarchy. This hierarchy, or tree, captures the results of the functional decomposition by showing the top-level functions required of the system broken down into subfunctions. Each of these functions and subfunctions in the hierarchy must be well defined to ensure a common understanding. Figure III-3 shows a generic functional hierarchy.

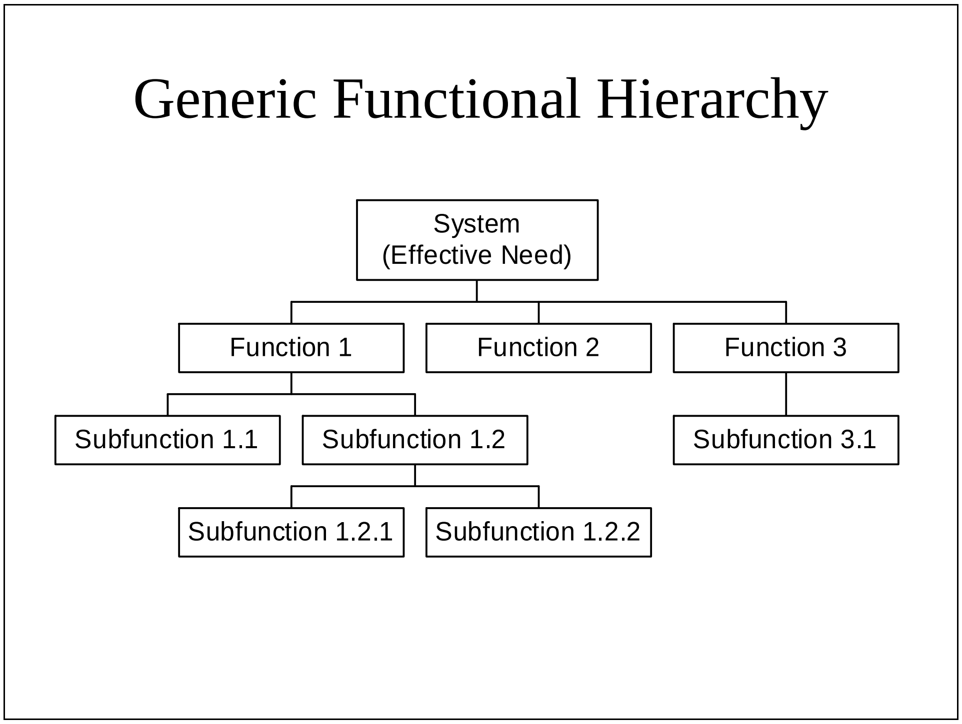


Figure III-3 Generic Functional Hierarchy

Another method of organizing the list of functions and sub functions from the functional decomposition is a functional flow diagram. The functional flow diagram's purpose is to lay out in a sequential manner the order in which functions are performed in a system using a flow chart. Figure III-4 is an example of a functional flow diagram for a fire request.

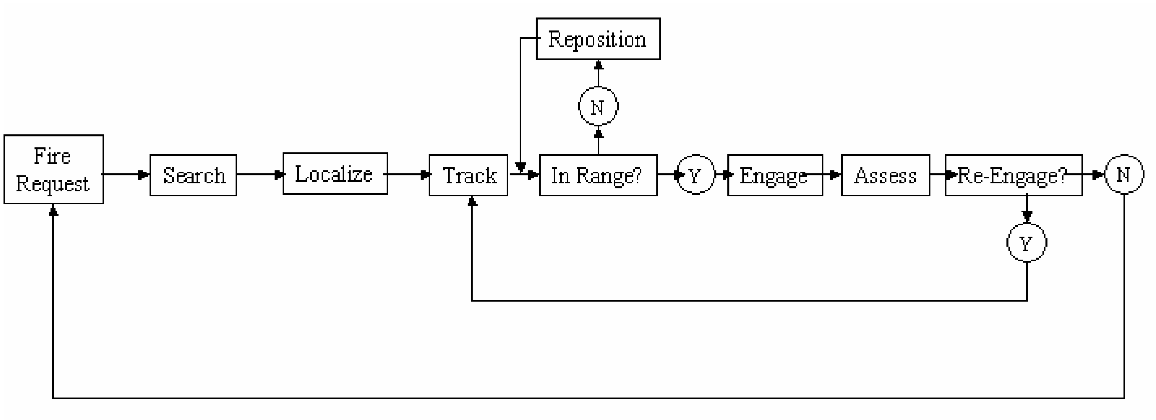


Figure III-4 Functional Flow Diagram

Functions are diagrammed in series and parallel to depict the relationship between functions. As with a functional hierarchy, an ideal functional flow diagram is logical and helps in the design process without implying particular solutions. This method of organizing the system functions allows the systems engineer to identify critical interfaces between system functions that may later be used to develop alternative subsystems that will function together as an integrated system. Functional flow diagrams may identify functions that are repeated and present opportunities to combine or reorder functions as appropriate.

Depending on the problem, either or both functional hierarchy or a function flow may be used. Functional flow diagrams may be more appropriate for a system when the functions are ordered or sequential. Those systems whose functions do not flow in a sequential manner are better suited for a functional hierarchy. In some cases, both can be used.

The functional analysis' results are used in the next phase of the SEMP, which is the design and analysis phase. The design of alternative systems will depend on the system functions identified in the functional analysis.

C. FUTURES ANALYSIS

The futures analysis' purpose is to analyze the environment in which the system will be operating. This phase requires making several projections and predictions about the future from many different aspects. The primary objective is to identify the key variables that will shape the future environment and ultimately drive the system and/or organizations that use the system. These factors, or drivers, will aide in the design of a system better prepared to operate in the future. As a result, the completed system should be robust enough to meet both the present and future needs of the stakeholders and operate successfully in the present and in future environments.

1. Value System Design

The value system design's primary purpose is to develop a value hierarchy that will be used to evaluate potential alternative solutions and ultimately select the best of the proposed alternatives. A value hierarchy is a pictorial representation of the structure of the functions, objectives, and evaluation measures for a given system. It is developed from efforts completed during the needs analysis and should be a reflection of the needs and objectives of the stakeholders.

Development of the value hierarchy begins with the effective need statement developed during the needs analysis. Major critical functions form the next layer, much like the functional analysis. As with the functional analysis, functions and/or objectives are decomposed into subfunctions. The primary difference between the value hierarchy and the functional hierarchy is the identification of objectives for each bottom level subfunction. These objectives should be specific and measurable. Evaluation measures are then developed for each objective as a metric that can be used as a measure of how well a proposed alternative meets that objective. Figure III-5 is a generic example of a value hierarchy.

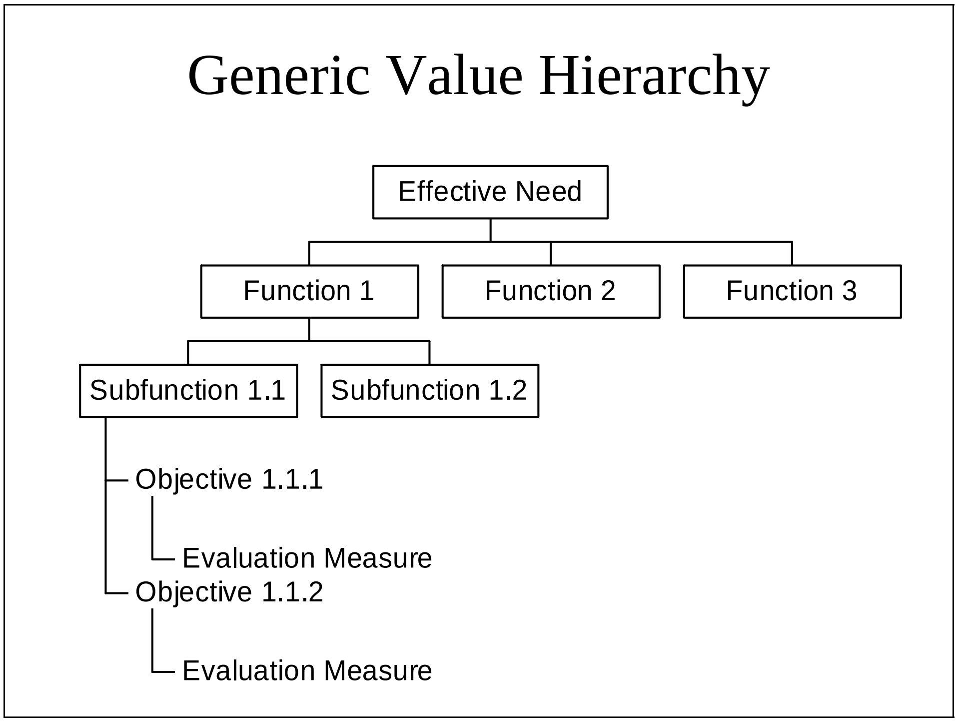


Figure III-5 Generic Value Hierarchy

As the value hierarchy is refined, it is important to note that the values and objectives should reflect the stakeholders' values. These values should be approved and accepted by the client and then presented to the stakeholders before proceeding further. Ultimately, it is the client that will use the value hierarchy to aid in any decisions regarding the best alternative system that will be designed to solve their problem.

D. DESIGN AND ANALYSIS

The SEMP's design and analysis phase designs and proposes alternative solutions to the problem identified in the problem definition phase and then analyzes the performance of these proposed solutions. The two steps in this phase are alternatives generation and modeling and analysis.

1. Alternatives Generation

Alternatives generation is the process of bringing system alternatives into being. It is the creative mental process of producing concepts and ideas in order to solve problems. In the previous steps of the SEMP, it was important to avoid introducing preconceived solutions into the process. Since there is no single solution to most systems engineering problems, one of the goals in this step is to avoid considering only known or traditional alternatives. Some complex problems are best solved using non-traditional means, so the creation of those means should not be influenced by traditional methods.

This process is creative, yet structured. Several alternatives will be created, as well as a structured approach to selecting the best ones for analysis. Best is defined as those alternatives that will satisfy the needs of the stakeholders using the resources available to the client. Several alternatives may meet the stakeholders' needs. The job of the Systems Engineers is to propose alternatives, recommend a preferred alternative, qualify that recommendation, and allow the client to choose which alternative to implement.

Approaches to generating alternatives vary, but each relies on the identification of critical functions that that system must perform. Research and brainstorming are good methods to develop alternative ways to perform each function and subfunction. Alternatives for each function and/or subfunction can then be packaged as a complete system alternative. It is important that each alternative be significantly different from one another. Each alternative should offer the client a markedly different method to meet the effective need. Alternatives should be detailed to allow sufficient means of comparison and to facilitate modeling efforts in later steps. In general, alternatives will fall into four categories:

- Do Nothing
- Off the shelf
- Adaptation
- New and Unique

Using these four categories can help in the process of alternatives generation. It gives the Systems Engineers a place to start and a method of organizing potential alternatives.

2. Modeling and Analysis

The modeling and analysis phase's purpose is to predict or estimate the performance of the proposed alternatives with respect to the evaluation measures developed in the value hierarchy. The alternatives were developed with sufficient detail to provide a clear picture in terms of system parameters and variables to allow accurate modeling and facilitate prediction of performance based on those evaluation measures. The first step in the process is to select the models that will be used to evaluate the proposed alternatives. The models, either existing or developed, must be properly formulated, applied, and interpreted so that the results accurately reflect the real system's characteristics.

Models come in three basic forms: physical, visual, and mathematical. Physical models are simply scaled physical representations of an object or system. Visual models are graphical or pictorial representations of an object or system. Mathematical models use symbols of math and logic to represent the various components, subsystems, functions and their relationships in an object or system.

Once modeling and analysis for each alternative is complete, the next step is to compile and organize the data in a useful manner. The organization of the data should present all of the information necessary to analyze and compare each proposed alternative. This should serve as the basis for presenting the information to the client in a format suitable for decision-making.

Ultimately, the data will be converted to a decision-making format that will be used to recommend the best alternative to the client. The proper implementation of this phase is very important as a significant error in modeling could lead to the wrong recommendation and ultimately to the wrong decision.

E. DECISION MAKING

The purpose of the decision-making phase is to use the information from previous phases to select the best proposed alternative, and present that alternative to the client as a recommendation of the best method to meet their effective need. Once approved by the client, the next phase of the SEMP can begin. The two steps in this phase are: alternative scoring and the decision.

1. Alternative Scoring

The purpose of alternative scoring is to use a structured method to compare the results of modeling dissimilar alternatives with respect to the evaluation measures developed in the value systems design. Scores for each alternative are calculated using information obtained from research and modeling efforts in the modeling and analysis phase. Scores are based on performance in respect to each evaluation measure and the relative importance of those measures as delineated in the value system design. This process involves constructing a utility relationship for each evaluation measure and using that relationship to calculate a total score for each alternative. The total score for each alternative reflects its aggregate performance with respect to all of the evaluation measures. These scores are then used as a basis for making a recommendation and ultimately driving the final decision. Generally, the alternative with the highest score is the one recommended to the client.

2. Decision

This step of the SEMP represents the decision from the client based on the recommendation from alternative scoring. The recommendation may be presented to the client in person or in a written report. To aid in conveying the recommendation, performance data for each alternative must be gathered and presented in a succinct manner. Matrices can be used for comparisons and graphs can be used to depict the sensitivity of decision variables. All should be focused to support the recommended alternative. The most important part of this phase is to present the recommendation in a clear, convincing, and concise manner.

F. IMPLEMENTATION

Normally, this phase would begin once the client has made a decision. The construction of the selected system is planned and executed. Construction entails nonrecurring engineering efforts, prototypes, test and evaluation, and manufacturing and production. This step ultimately solves the problem presented by the client. Although there are various steps in this phase, they do not apply for a paper study. As this study is a paper study only, it would ideally end with the presentation of the recommended system to the client, and the acceptance and approval of the system by the client and the stakeholders.

G. SUMMARY

It should be noted that use of the SEMP will normally be tailored to the individual project and that the phases of the SEMP are iterative in nature. For a given project, some steps may be omitted and extra time may be spent on others. Some phases and/or steps may be repeated as necessary to ensure that the requirements of that particular phase of the process are met and to ensure that the solution to the engineering design problem best meets the needs of the client and stakeholders. Most importantly, the SEMP as a whole is iterative, meaning that it too should be repeated as necessary to readdress the system solution and how it meets the needs of the client.

The SEMP is integral to this study’s approach to force protection of the Sea Base. It was important to start with this process, as there were several supporting teams working a project that was not clearly understood in the beginning. The SEMP allowed the SEA-4 Team to methodically approach the problem to be solved and integrate the previous study and the efforts of several supporting teams. Chapter IV will discuss the SEA-4 Team’s use of the SEMP and how it was tailored to meet the needs of this study.

IV. PROBLEM DEFINITION

A. OVERVIEW

This section will review plan of action and milestone (POA&M) development and problem definition for the Expeditionary Force Protection Study. The SEA-4 Team started by identifying the ultimate driver—graduation day. Using this as a guideline and working backwards, the team identified critical tasks and chose attainable milestones for each. From this "strawman," an overall plan was developed. The POA&M illustrated in Figure IV-1 became the standard that was used to govern the project.

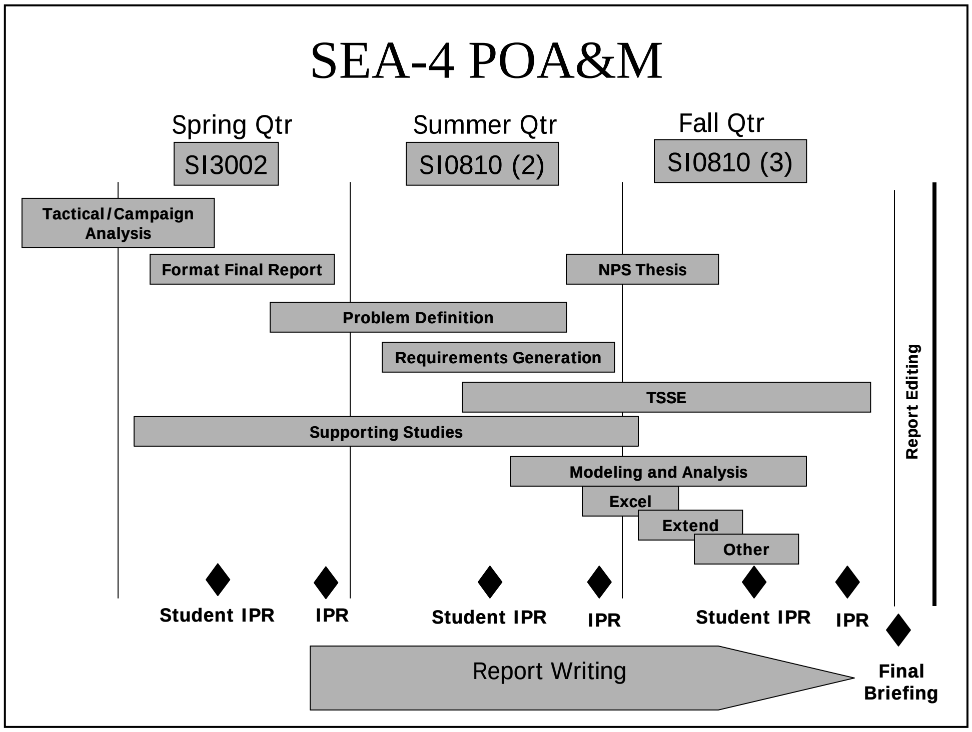


Figure IV-1 Plan of Action and Milestones

After POA&M development, the next task for the SEA-4 Team was to define the problem in a logical manner and ensure a clear understanding of the task. Using the Systems Engineering and Management Process (SEMP) described in Chapter III, this study initiated a top-down analysis of expeditionary force protection. The needs analysis and value systems design processes provided the structure by which the SEA-4 Team was able to scope and bound the problem at hand and is described in detail in the following sections.

B. NEEDS ANALYSIS

The SEA-4 Team began the Needs Analysis with the official "Project Guidance" provided by the Meyer Institute, which states:

> "You will develop a system of systems conceptual solution, supported by other teams on campus in various discipline areas, to provide force protection for the Sea Base and its transport assets while performing forced entry and STOM operations in support of the Ground Combat Element of a Marine Expeditionary Brigade. … The practical impact is that your study must address protection of the ships of the Sea Base while at sea in the operating area as well as the protection of the airborne transport assets moving between the Sea Base and the objective and the surface assets moving between the Sea Base and the beach or a port." (Calvano, 2003, 1)

The primitive need was developed using the project guidance and defined to be:

- Protect the Sea Base while at sea in the operating area
- Protect airborne transport assets from Sea Base to objective
- Protect surface transport assets from Sea Base to beach or port

To gain a thorough understanding of the problem, this study conducted additional research by reviewing the governing documents referenced in the SEI-3 report and by reviewing specific areas of the SEI-3 report itself. While conducting this research, several challenging issues were uncovered that would need to be addressed before proceeding further. These issues were discussed with the stakeholders to the satisfaction of all parties involved. The following chapter speaks to those issues.

1. Force Protection Issues

The charter given to the SEA-4 Team was to "develop a system of systems conceptual solution to provide force protection for the Sea Base and its transport assets while performing forced entry and Ship To Objective Maneuver (STOM) operations in support of the Ground Combat Element (GCE) of a Marine Expeditionary Brigade (MEB)." (Calvano, 2003, 2) As part of the needs analysis, this study examined the concept of force protection by assessing the threat, the environment, the mission, and the forces required to accomplish that mission.

This step in the systems engineering process helped the team to identify four primary issues in developing a system of systems to provide force protection for the Sea Base and its airborne and seaborne transport assets:

- Key Assumptions
- Composition of the Sea Base
- Distance from Objective and/or Shore
- Carrier Strike Group (CSG) Role

a. Key Assumptions

The results of any study are affected by the assumptions made by the participants conducting the study. Carefully crafted assumptions help to scope the problem and yield realistic results. The SEA-4 Team and their stakeholders agreed on the key assumptions needed to provide a system of systems architecture capable of protecting the Sea Base and its transport assets in the selected timeframe. The overarching assumptions governing this study are as follows:

- MEB operations occur in the 2015-2020 timeframe.
- MEB size Marine Air Ground Task Force (MAGTF) composition and sustainment requirements remain constant between the present and 2015-2020.
- The United States Marine Corps (USMC) adopts STOM doctrine.
- SEI-3's conceptual expeditionary warfare architecture is operationally available in 2015-2020.
- All current United States Navy (USN) and USMC legacy platforms will remain operational through 2015-2020 and will not retire early.
- All proposed USN and USMC acquisitions of new aircraft and land vehicles will be operationally available in 2015-2020.
- MEB forces may be projected as far as 200 nm inland. The ships of the Sea Base may be as far as 200 nm offshore, but not to exceed 275 nm from Sea Base to objective.
- A CSG is available for battle space preparation.
- Expeditionary warfare force protection is modeled and analyzed in the SEA-4 Sea Base defined region only.

Obviously many more assumptions were made as the study proceeded through the SEMP; those assumptions pertaining to specific analysis will be addressed in later sections in much greater detail.

b. Composition of the Sea Base

As stated in the Naval Transformation Roadmap, Sea Basing is a transformational concept that will revolutionize the projection, protection, and sustainment of sovereign warfighting capabilities around the world for the United States Navy and Marine Corps. Sea Basing will capitalize on the inherent mobility, security, and flexibility of naval forces to overcome the emerging military and political limitations to overseas access. This future capability will reduce the need to build up logistical stockpiles ashore that may burden or endanger allies and drastically complicate force protection requirements.

There are several similar definitions for the Sea Base but they all have one thing in common—they define the Sea Base as a concept and not as a "thing." Since it would be difficult to design a system of systems to protect a concept, this study defined the Sea Base (for force protection purposes) in terms of a finite number of specific platforms. Composition of the Sea Base was derived from two sources: Chapter XII of the SEI-3 report, which stated "The Sea Base will be formed by merging at a minimum of two Marine Expeditionary Unit (MEU)-sized Amphibious Ready Groups (ARGs), their escorts, logistics and pre-positioned equipment support ships, and associated CSG"; and the Project Guidance Memorandum, that directed this study to focus on the "conceptual architecture" developed in the SEI-3 report when developing a proposed solution to the force protection problem. With this, the Sea Base (for purposes of this study) was defined as:

- 6 Expeditionary Warfare (ExWar) Combat Ships
    - 6 Joint Strike Fighters (JSFs) per ship
    - 6 Aero Design Heavy Lift Aircraft (HLACs) per ship
    - 18 Advanced Amphibious Assault Vehicle (AAAVs) per ship
    - 14 MV-22s per ship
    - 4 AH-1Zs per ship
    - 4 UH-1Ys per ship
    - 2 Landing Craft Utility (Replacement) (LCU(Rs)) per ship
    - 3 Heavy Lift Landing Craft Air Cushioned (HLCACs) per ship
- 3 Expeditionary Warfare Logistic Ships

Though force protection requirements might eventually dictate the addition of combatants such as CG, DDG, and Littoral Combat Ship (LCS), they were not considered as part of the initial Sea Base. Therefore, for purposes of this study, the force to be protected is defined as the Sea Base ships, their surface transfer assets, and their air transfer assets.

After defining the Sea Base, an additional challenge arose. The disposition of the logistics ships raises questions regarding the "expansion and contraction" of the Sea Base as these assets enter and depart the operating area to resupply. When do they become part of the Sea Base and thus fall under the force protection umbrella? Do they become part of the Sea Base as soon as they leave the Continental United States (CONUS)? At 300 miles? Are they still part of the Sea Base while loading supplies at an overseas base? Will they have to be protected by Sea Base assets while they are in port? Will they need escorts? What procedures are involved in joining or departing the Sea Base? After discussion with the stakeholders, it was determined that these questions were relevant, but difficult to answer. Further discussion concluded that those questions would best be addressed in further study efforts and would be considered beyond the scope of this study. For the purposes of this study, the expansion and/or contraction of the Sea Base would not be addressed, nor would circumstances involving ships entering or leaving the Sea Base, or the protection of assets while in port.

2. Distance from Objective and/or Shore

The distance of the Sea Base from the objective and distance from shore will have an impact on force protection. For example, small boats may not be a threat 200 nm offshore, but may be the primary threat if the Sea Base is 10 nm offshore. As noted in the Key Assumptions section, the land force could be as far as 200 nm inland, while the ships of the Sea Base may be as far as 200 nm offshore. Force protection postures may be significantly different based on distance from the objective and distance from shore. To address these differences, the SEA-4 Team elected to split expeditionary operations into phases, and concentrated on the relative difficulty of force protection in each phase.

After researching the basic tactics employed during STOM operations, the SEA-4 Team divided an expeditionary warfare mission into three distinct phases. Phase I encompasses the staging and buildup of the Sea Base forces offshore. In this phase there are no aircraft flying and there are no landing craft in the water. Phase I was assumed to be the least challenging in terms of force protection because it can be accomplished outside of the threat area and out of range of the enemy's weapons. Phase II covers the assault and the movement of troops and equipment from the Sea Base to the landing area and/or the objective. Phase II was assumed to be the most challenging phase because of the number of transport assets in the air and on the water. Also, the limited ranges of the landing craft force the Sea Base to move closer to shore and into enemy weapons envelopes. Phase III includes the sustainment of the troops and equipment ashore; it involves transfer of assets to the landing area and/or the objective, but only enough to sustain the forces ashore.

The threats were then apportioned by the likelihood of occurrence during each phase of the operation (See Threat Analysis). It then became clear that for each phase, the geography, the threats, and location of the objective dictated the relative location of the Sea Base. The team decided on the "worst-case" phase and designed the conceptual system of systems to address force protection in this situation only. Resource constraints did not allow for excursions into other scenarios or phases, therefore, this study chose to model force protection of the Sea Base during Phase II operating the Sea Base at a distance less than 75 nm from shore. Further study of different scenarios and distances is recommended later in this report.

3. CSG Role

The official project guidance stated that there would be a CSG in the vicinity. This raised several questions. What is "the vicinity" in terms of distance? Will the CSG be engaged in other activities or will it be in direct support of the expeditionary operation? What platforms make up the CSG? What are their capabilities? To bound these questions the team decided to make some assumptions and have the stakeholders validate those assumptions before moving forward. The team proposed a specific platform mix for the CSG. The capabilities of the platforms were considered to be inherent to the ship-type. For this study, the CSG consists of:

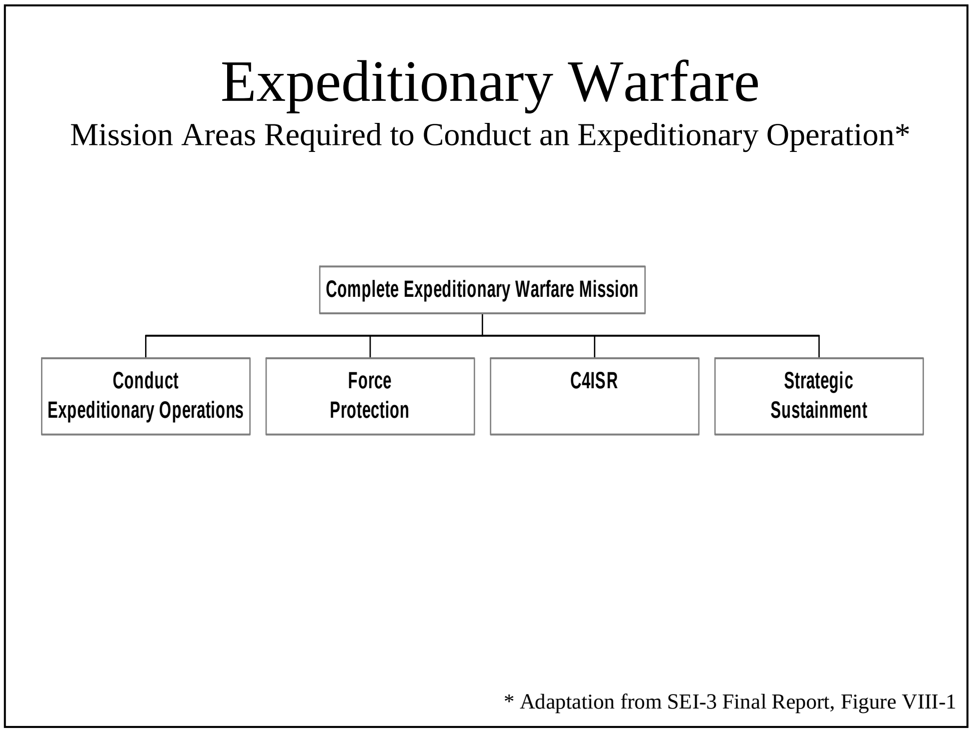
- 1 CVN
- 2 CGs or CG (Xs)
- 2 DDGs
- 1 DD (X)
- 1 SSN
- 1 AOE

Based on the current fleet and programs of record, the team believed that these platforms adequately represent a future CSG along with its required capabilities. The CSG was also given the sole responsibility for Theater Ballistic Missile Defense (TBMD) and responsibility for preparation of the battlefield as dictated by the expeditionary warfare force. Therefore, TBMD was not addressed in the system of systems concept for direct force protection of the Sea Base.

The team proposed to define a maximum and minimum distance from the CSG to the lead Sea Base ship and a specific platform mix for the CSG. The CSG will maintain a minimum distance of 20 nm from the Sea Base and a maximum distance of 200 nm. Additionally, CSG air assets must be able to strike the area in and around the objective, as well as any selected landing areas.

C. FUNCTIONAL ANALYSIS

Functional Analysis is viewed as one of the critical steps in completing the Needs Analysis. The primary purpose of the Functional Analysis is to identify and decompose critical system functions, and organize them in such a way to facilitate a better understanding of the system functional requirements. In other words, it graphically describes what the system must do, not how it will function. The first step in the Functional Analysis is to create a system decomposition. To start, the role of force protection in the overall expeditionary warfare mission had to be determined. Research into the SEI-3 study provided that relationship and a graphical adaptation is provided in Figure IV-2.


Expeditionary Warfare

Mission Areas Required to Conduct an Expeditionary Operation*

* Adaptation from SEI-3 Final Report, Figure VIII-1

Figure IV-2 Expeditionary Warfare Functions

Concentrating on the force protection function in Figure IV-2, this study then developed a general top-level functional hierarchy (Figure IV-3) in order to obtain a better understanding of the inherent functions required for force protection of a conceptual Sea Base and its transport assets.

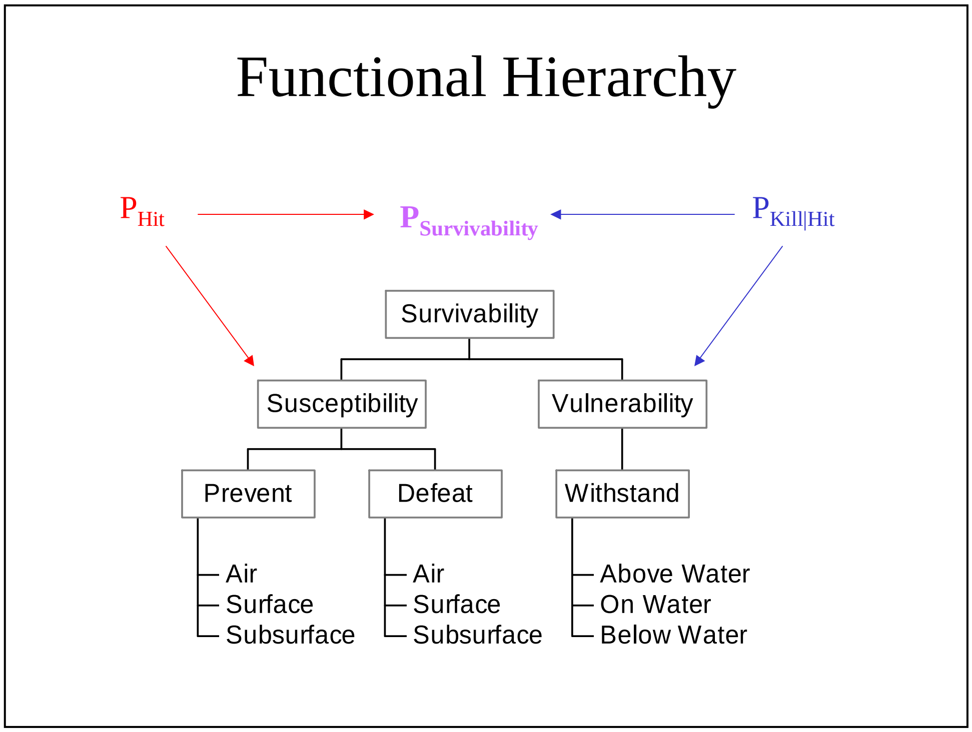


Figure IV-3 General Force Protection Functional Hierarchy

This general functional hierarchy indicates that survivability is the key function to force protection. The subfunctions of survivability are susceptibility and vulnerability. Definitions of the terms survivability, susceptibility, and vulnerability, as used in this study are:

- **Survivability** – The measure of all defensive actions, including design actions that reduce damage and its effects. The two components of survivability are susceptibility and vulnerability. The probability of survival is characterized by the following equation:

Equation (1) $P_{Survival} = (1 - P_{Hit} * P_{Kill|Hit})$

- **Susceptibility** – The inability of the platform to avoid being subjected to a hostile man-made environment. Susceptibility incorporates all factors that determine the probability that the platform will be damaged by a given threat and is characterized by the probability of being hit (P_{Hit}).
- **Vulnerability** – The inability of the platform to withstand damaging effects of a hostile man-made environment to which it has been subjected. Vulnerability includes all factors that determine the degradation of any given mission area given a damage mechanism and is characterized by the probability of kill given a hit ($P_{Kill|Hit}$).

The general force protection functional hierarchy was used to develop the functional hierarchy for protection of the Sea Base and its airborne and seaborne transport assets. Threats to the Sea Base were considered, along with specific mission areas, in order to develop the functional hierarchy shown in Figure IV-4.

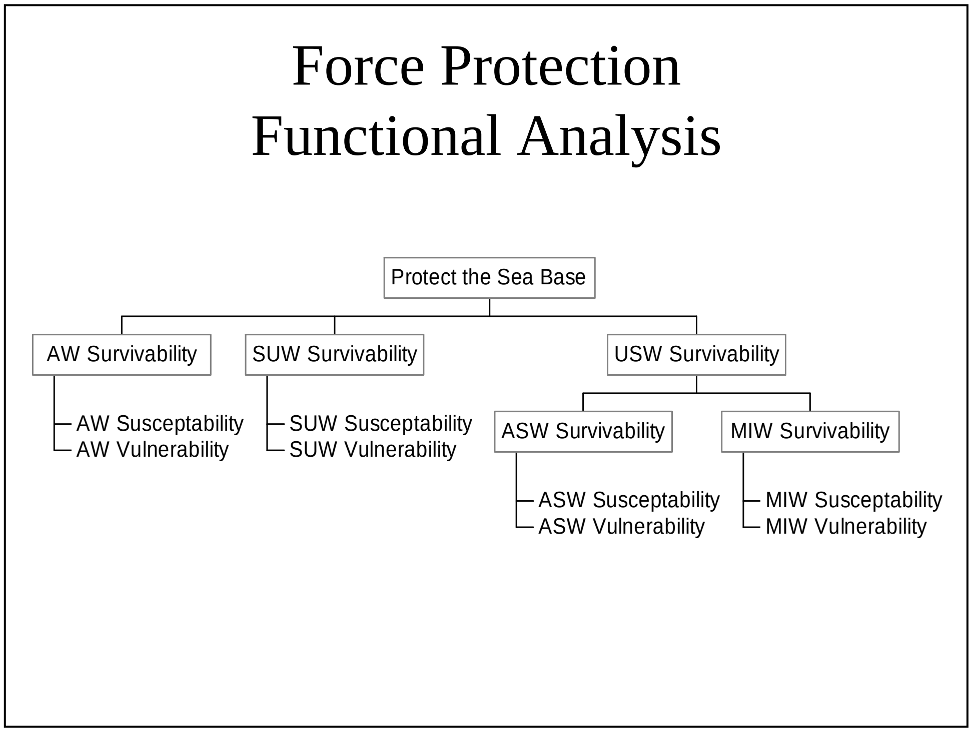
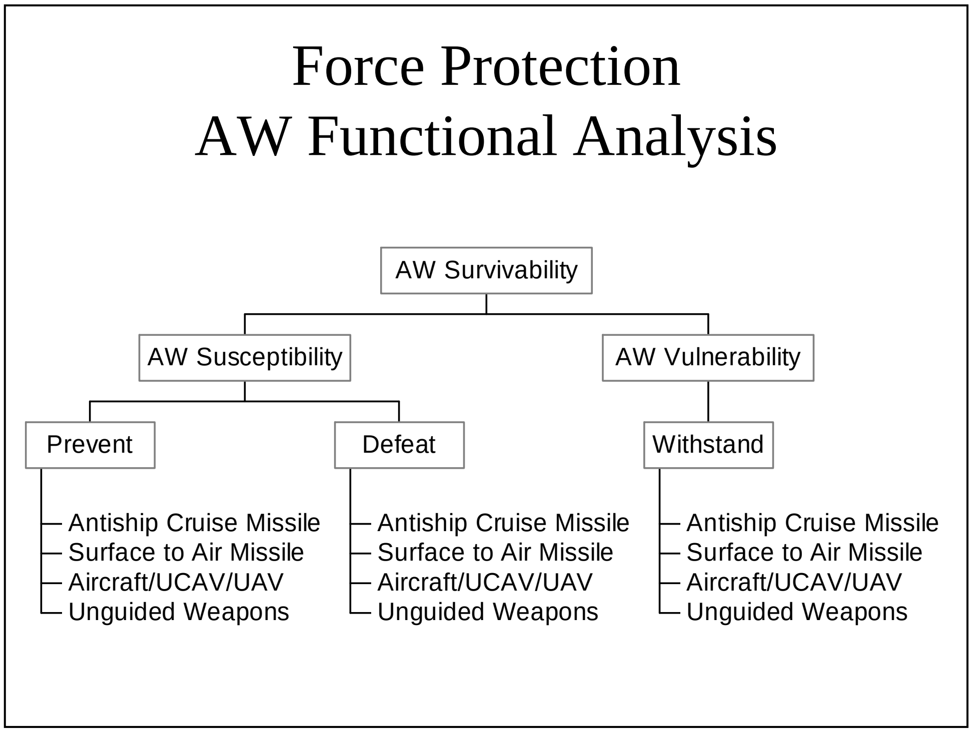


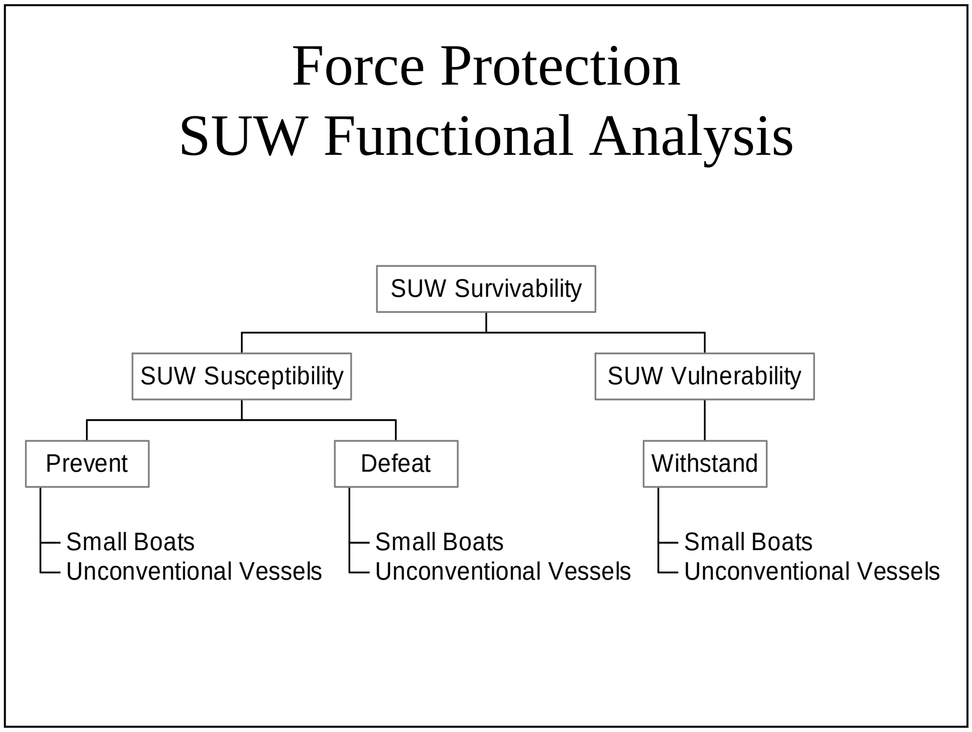
Figure IV-4 Expeditionary Warfare Force Protection Functional Hierarchy

Each warfare area was then examined and a separate more detailed, functional hierarchy was developed for each. Figure IV-5 shows the Air Warfare (AW) analysis; Figure IV-6 shows the Surface Warfare (SUW) analysis; and Figure IV-7 shows the Undersea Warfare (USW) analysis, which includes Anti-Submarine Warfare (ASW) and Mine Warfare (MIW). Initially, all threats were considered. After some iteration, only the primary threats to the Sea Base, as determined in the Threat Analysis, are listed in the following figures.



Force Protection
AW Functional Analysis

Figure IV-5 AW Functional Hierarchy



Force Protection
SUW Functional Analysis

Figure IV-6 SUW Functional Hierarchy

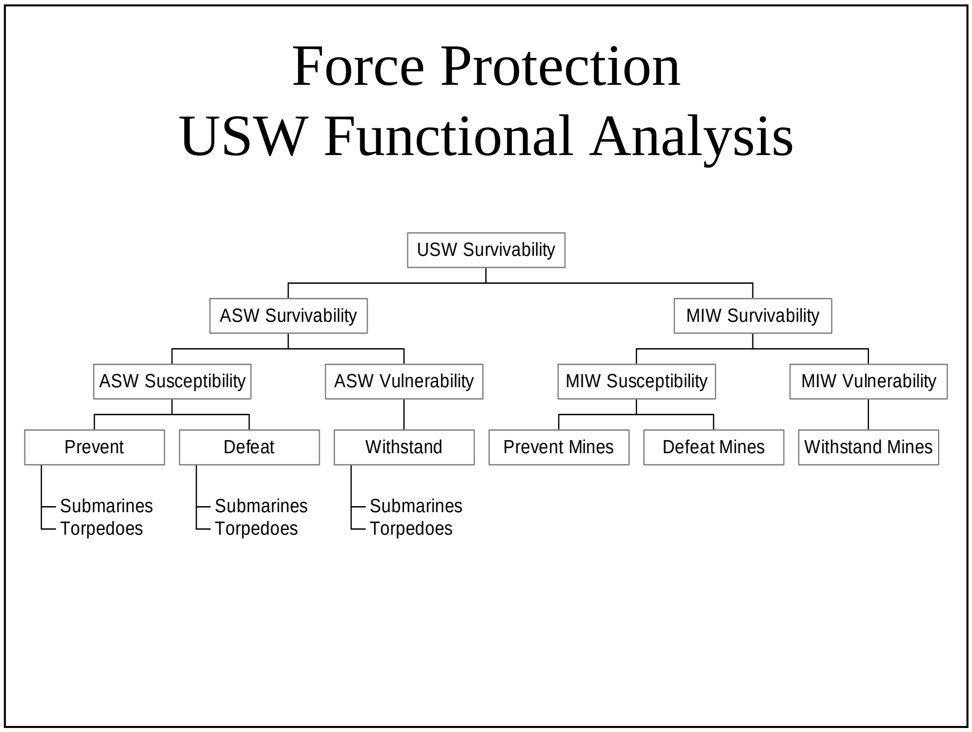


Figure IV-7 USW Functional Hierarchy

Because expeditionary warfare involves Navy and Marine Corps forces and assets, a physical decomposition of the conceptual expeditionary force was required to better understand the problem at hand. Based on conclusions from the Makeup of the Sea Base discussion earlier in this chapter, the Sea Base physical decomposition is illustrated in Figure IV-8.

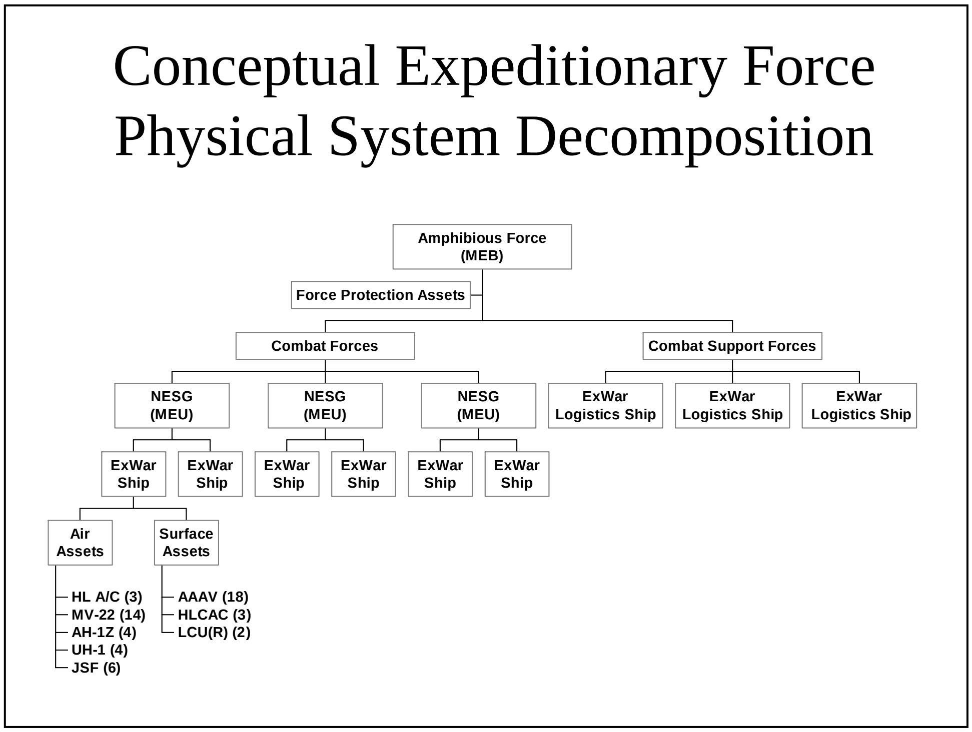


Figure IV-8 Physical System Decomposition

In this physical decomposition, force protection assets are not specifically defined because they will be varied as part of the study to determine the optimal mix of assets needed to protect the Sea Base. Those assets may be existing, planned, conceptual, or any combination of the three.

Another method of organizing the list of functions and subfunctions of a system is to employ a Functional Flow Diagram. The purpose of a functional flow diagram is to sequentially lay out the order in which functions are performed in a system through the use of a flow chart. Functions are diagrammed in series and parallel to depict the relationship between functions. Several functional flow diagrams were used to depict the various functions of force protection in an ordered and sequential manner. These were adapted from functional flow diagrams developed and used by the SEI-3 Team in the previous study. Figure IV-9 is an example of one of the functional flow diagrams used by this study.

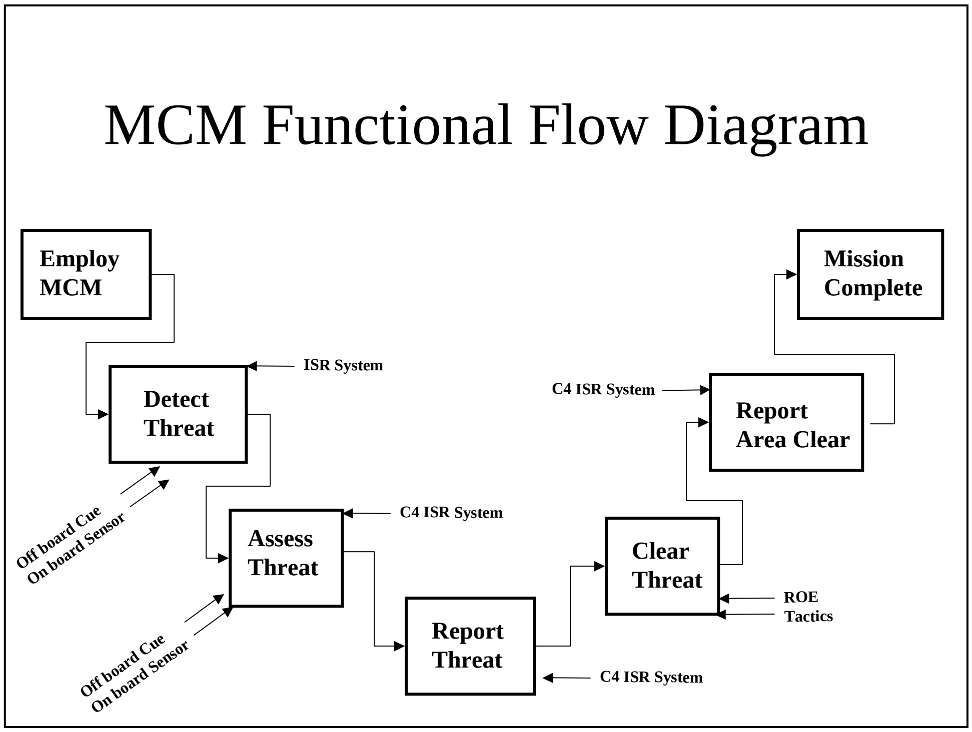


Figure IV-9 SEI-3 MCM Functional Flow Diagram Example

D. FUTURES ANALYSIS – DEFINING THE THREAT

Futures analysis is the final phase of the needs analysis. The futures analysis' purpose is to analyze the environment and develop plausible alternate future worlds in which a conceptual expeditionary force may have to function. The futures analysis conducted by this study did not intend to predict the future as much as it attempted to propose a plausible future in which to test the conceptual system of systems solution to the force protection issue. A detailed threat analysis was determined to be an integral part of the futures analysis. Once again, the goal was not to predict exact future weapons systems, but rather to identify plausible and challenging threats that the conceptual system of systems might have to defeat.

The primary objective of this phase was to identify the key variables that could shape the future environment and ultimately drive the system and/or organizations that use the system. These factors, or drivers, aid the design of the system so that it is better prepared to operate in the future. As a result, the final system should be robust enough to meet both the present and future needs of the stakeholders, as well as possess the operational capability to successfully function in present and future environments.

The futures analysis tool allowed the SEA-4 Team to determine several key drivers and characteristics of these future worlds. The following list is a summary of those drivers and characteristics:

- The number and nature of powerful political and economic actors
- Organizing principles of actors
- Centralized or decentralized power distribution
- Interest groups and constituents
- Population growth in developing countries
- Political and social will
- Global economic capability
- World economic conditions
- The relative economic strength of the United States
- U.S. competitive capability
- The size of the U.S. defense budget
- The degree of global economic integration
- The availability of energy and natural resources
- The degree of regionalism
- The degrees of cultural commonality and continuity that could be envisioned in the world
- Political instability in the third world
- The nature and extent of military alliances
- Terrorist disruption and disruptive potential
- Technology diffusion and proliferation
- The future vulnerability of data, hardware, and transmission
- The degree of conflict
- Biogenetic threats or havens
- The locale in which military activities will take place
- The type of available weaponry

From these various drivers and characteristics, four key dimensions and associated values were developed:

- Sovereign interconnectedness—low or high
- Weapons proliferation—low or high
- Hostile nations and organizations—few or many
- The will to oppose U.S. interests that would necessitate use of force—strong or weak

When analyzed with emerging strategic battle spaces, this study felt the worst-case scenario would involve a distant country seeking to oppose U.S. interests by creating regional instability. This instability would include the use of military aggression against U.S. allies, while rejecting the spirit of international cooperation. From this alternative future, the South China Sea 2016 scenario presented in SEA-4's Joint Campaign Analysis course (OA4602) was adopted and shaped to address these future concerns. Separate from this scenario, yet universally applicable to it, this study also conducted detailed research into future weapons systems and threats that will pose realistic and considerable challenges to U.S. platforms in the 2016 timeframe. The following sub-chapters will describe these efforts.

1. South China Sea 2016 Scenario

The South China Sea 2016 scenario places China in a unique position within the world order. Following China's integration into the World Trade Organization in 2001, its economy continued its rapid growth. In addition to enhancing educational and social programs, the China invested its windfall funds in military forces, focusing on strategic and naval forces capable of establishing a longer-range "sphere of influence" from its shores. In 2012, Taiwan and China signed a treaty formally recognizing each party's government and set a timetable for unification under a single government by 2018.

Strategic and naval forces growth was seen by China as a strategic necessity to affirm rights to the offshore oil reserves in the South China Sea. In 2015, China publicly claimed hegemony over the entire South China Sea—justifying its actions through claims of historical rights and economic requirements—and guaranteed the freedom of innocent merchant shipping through its economic zone. That same year, the People's Liberation Army (PLA) Navy reinforced its presence in the Spratly Islands (specifically on Mischief and Alison Reef) by creating three paved runways, pier and maintenance facilities, air defense area batteries, and installing ballistic missile sites. The Philippines, Vietnam, Indonesia, Malaysia, Australia, Singapore, Japan, and the United States all condemned China's announcement and Spratly development, but fell short of consensus on a combined response. Indonesia, Malaysia, and the Philippines, however, formed a hasty common defense treaty and again protested China's aggressive behavior in the area. The United States and the Philippines established a similar treaty in 2010.

China increased its naval presence in the South China Sea by deploying ships and aircraft from its northern fleets to augment the South China Fleet. Despite repeated protests, Chinese naval exercises frequently disregarded the territorial seas of the Philippines, Malaysia, and Indonesia. Early in 2016, a Philippine jet aircraft, after issuing a warning to clear its territorial waters, strafed a Chinese destroyer that was firing its gun within two miles of Palawan Island's (the Philippines) coast. Ten Chinese sailors were killed and the destroyer returned fire, but failed to hit the aircraft.

Two months later, claming self-defense and the need to establish a "safety" perimeter around the South China Sea, China invaded Kepulalian Natuna (Indonesia) with a division of Chinese infantry supported by an air defense regiment, and 10 shore-based, anti-ship cruise missile batteries. They further threatened to invade Palawan Island if any the Association of Southeast Asian Nations (ASEAN) reacted. In coordination, the PLA Navy established a quarantine on Puerta Princesa port (Palawan). This quarantine extended to the edges of the Sulu Sea. The Chinese government immediately called for a treaty with the Philippines and Indonesia to establish a New Era of South China Sea Cooperation among perimeter nations.

Led by the United States, ASEAN nations condemned China's action and submitted a joint United Nations resolution to establish sanctions against China. This resolution was vetoed in the Security Council. Reacting to the quarantine placed on Puerta Princesa, United States and ASEAN ships—claiming freedom of navigation—attempted to enter the Sulu Sea. PLA Navy missile-gun boats fired on the combined U.S./ASEAN patrol and sank two ASEAN vessels. Two days later, the PRC invaded Palawan Island and began fortifying their positions.

2. Threat Analysis

a. Introduction

As part of a systems approach to defending the Sea Base, the following Threat Analysis was derived from unclassified sources. This study reviewed the myriad of threats that threaten a Sea Base and its ability to project power. It endeavored to scope the problem by selecting certain generic, and thus universal, threats that will pose considerable challenges to U.S. platforms in the 2016 timeframe. By no means does this analysis encompass the full gamut of threats that the U.S. might face in the future, but it does provide a realistic basis, with regards to the capabilities and characteristics, of the types of enemy systems future architectures will have to counter in order to be successful. This Threat Analysis will demonstrate the flow by which this study came to these conclusions. This study first listed the threats posed to the Sea Base and categorized them by warfare type (see Table IV-1).

WARFARE	THREAT TO SEA BASE
Air Warfare (AW)	Unmanned Aerial Vehicle (UAV) Aircraft (sea based or air assets) Anti-Ship Cruise Missile (ASCM) Ballistic Missile Space-based Laser Low Slow Flyer
Surface Warfare (SUW)	Ships Small Boats (jet ski, PB, PGM, etc.) Unconventional Ships Unmanned Surface Vehicles (USV)
Undersea Warfare (USW)	Submarine (diesel, nuclear, midget) Mines Divers Mammals Unmanned Underwater Vehicles (UUVs)
Information Warfare (IW)	Viruses Computer Network Attack (CNA) Electronic Attack (EA) Chaff / Flares Sensor Overload
Land Warfare (LW)	Surface to Air Missiles (SAMs) Small Arms Anti-Aircraft Artillery (AAA) Rockets Mortars
Miscellaneous	Land-based Gunfire Chemical, Biological, Radiological-Nuclear Effects Land mines for Craft Landing Zones (CLZ)

Table IV-1 Warfare Areas and Associated Threats to the Sea Base

This study researched the basic tactics employed during STOM operations, and broke down a forced entry amphibious mission into the three phases discussed previously. Phase I encompasses the staging and buildup of the Sea Base forces offshore; Phase II covers the assault; and Phase III includes the sustainment of the troops and equipment ashore. The threats were then apportioned by the likelihood of occurrence during each phase of the operation. The difficulties of defeating these threats were also taken into account before prioritizing them. The reasoning behind prioritizing the threats per phase follows the reasoning behind the problem definition phase of the SEMP—what exactly is the problem at hand? The SEA-4 Team felt it necessary, and reasonable, to scope and bound the force protection problem in order to better define the problem by concentrating on certain threats rather than all. The likelihood of occurrence and prioritization of the threats stemmed primarily from research, the operational experience of the officers conducting the study, and the study's stakeholders' expert opinions. Table IV-2 lists the top five most likely threats the Sea Base might encounter by phase.

PHASE	TOP FIVE THREATS
I	Unconventional Vessels Submarine ASCM Small Boats Mines
II	Mines Small Boats SAMs Aircraft / UAV ASCM
III	ASCM Mines Unconventional Vessels SAMs Unguided Munitions

Table IV-2 Sea Base Operation Phases and Associated Threats

Further investigation into the prioritized threats revealed that some could be categorized as platforms and others as weapons. For example, a submarine is a platform that can employ torpedoes, mines, surface to air missiles, or anti-ship cruise missiles. The weapon the submarine employs is considered the threat, not the submarine itself (assuming the sub is not used as a battering ram). Therefore, weapons were linked with platforms (see Table IV-3).

PLATFORM	WEAPON
Submarine	Torpedo Mines Anti-Ship Cruise Missile Surface to Air Missile
Small Boat	Torpedo Mines Anti-Ship Cruise Missile Surface to Air Missile Unguided Munitions
Aircraft / UAV	Anti-Ship Cruise Missile Unguided Munitions Mines Torpedo
Unconventional Vessels	Torpedo Mines Anti-Ship Cruise Missile Surface to Air Missile Unguided Munitions
Land	Anti-Ship Cruise Missile Unguided Munitions Surface to Air Missile

Table IV-3 Threat Platforms and Associated Weapons Capable of Employment

This study then conducted detailed research into the history and range of capabilities and characteristics of the threats and platforms listed in Table IV-3. In order to scope the numerous variations of enemy assets that exist today, the three (and in some cases four) most capable threats or platforms from each category were chosen to serve as the “baseline” for future assets an enemy may employ or possess. These generic categories were set in order to keep this discussion on an unclassified level, and to provide a more universal feel to the study itself. After analyzing the characteristics and capabilities of platforms, representative threats a Sea Base may encounter in the 2016 timeframe were defined in the “Future” section of the subsequent paragraphs of the Threat Analysis.

The paragraphs (b, c, and d) are categorized by the medium in which these threats operate: below, on, or above the water. Each threat is then described in further detail by the following: its definition, how it specifically threatens the Sea Base, its history, and future representative threats.

b. Below the Water

(1) Mines

(a) Definition

This study defines a naval mine as an explosive device laid in the water with the intention of damaging or sinking ships or surface transport assets, such as the HLCAC, LCU(R), and AAAV. The term does not include devices attached to the bottoms of ships or to harbor installations by personnel operating underwater, nor does it include depth-charge type devices.

(b) Threat to Sea Base

Mines can be employed by hostile forces to disrupt Sea Base operations in littoral regions. Mines are not only capable of damaging and sinking Sea Base assets, but they can interfere with operations by channeling, blocking, or delaying ships and landing craft. The mere uncertainty of their presence may slow operations, limit mobility, and/or cause planners to redefine operating areas to avoid the mine threat. Due to their relatively low cost and ease of use, mines may play a prominent role in an adversary's sea denial arsenal.

(c) History

The idea of using mine warfare has been around since the Revolutionary War, when David Bushnell floated contact mines using barrels of gunpowder to attack British warships. During World War I (WW I) and World War II (WW II), simple mines were used to interdict shipping and to close vital ports. In WW I, a total of 966 ships and submarines were sunk or damaged by mines. In WW II, a total of 3,200 ships and submarines were sunk or damaged by mines. During the Korean War, an amphibious landing at Wonsan was delayed for eight days while United Nations mine countermeasure forces struggled to clear a channel. The commander of the amphibious task force at Wonsan, Rear Admiral Allan E. Smith stated, “We have lost control of the seas to a nation without a navy, using pre-World War I weapons, laid by vessels that were utilized at the time of the birth of Christ.” In the Gulf War (Operation Desert Storm), the USS Tripoli (LPH 10) and USS Princeton (CG 59) were damaged by mines off the coast of Kuwait. Amphibious forces threatened Iraq with a possible landing in Kuwait. This diversion greatly contributed to the ground war’s success. Intelligence reports after the war revealed Iraqi minefields were larger and denser than anticipated, and could potentially have caused a disaster for U.S. amphibious forces (Morris, 1997).

As shown in Figure IV-10, since 1950, mines have caused damage to 14 U.S. warships. This is significantly more than the damage caused by terrorist, missile, torpedo, and aerial attacks combined.

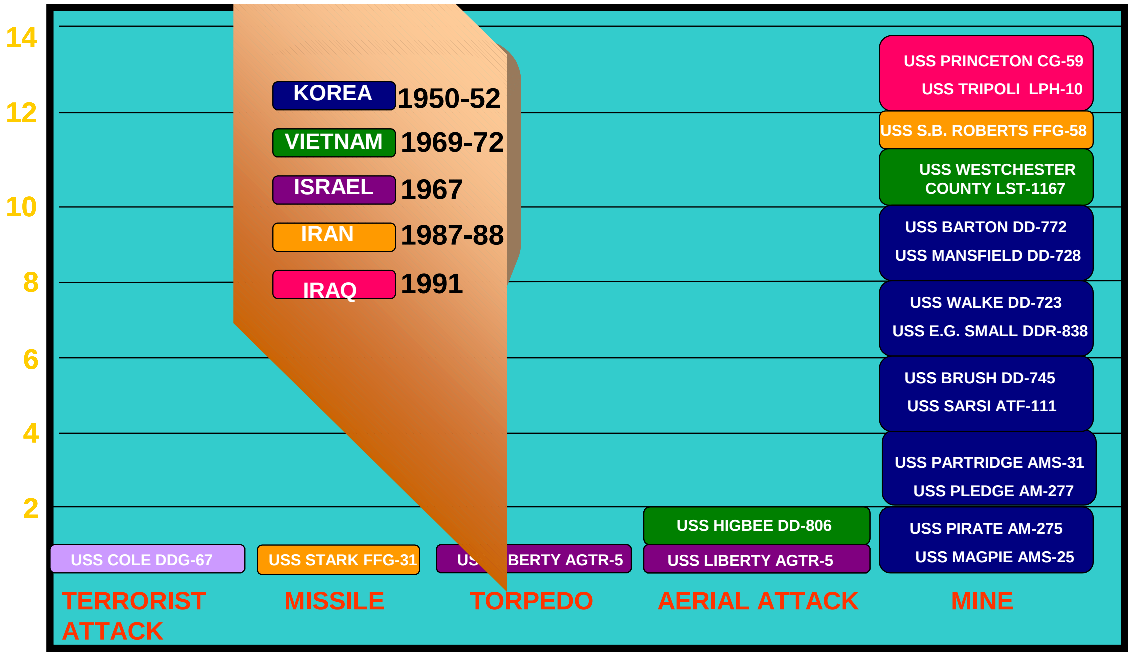


Figure IV-10 Damage to U.S. Warships Since 1950 (National Research Council, 2000, 6)

Mines are easily deployed, relatively inexpensive, and thus widely proliferated. More than 50 countries have mining capabilities with more than 300 types of mines (Morison, 2000). One appealing aspect of mines is their cost effectiveness. Table IV-4 shows the costs to transport and repair U.S. ships that were struck by mines and the cost of the mines themselves.

Ship	Damage Cost	Mine Cost
USS Samuel B. Roberts	$52.1 M	< $1,500
USS Princeton	$24 M	$3,000
USS Tripoli	$3.5 M	$1,500

Table IV-4 Cost of Mine Damage Compared to Cost of Mine

(d) Future

Improvements in technology are further complicating the mine threat. Mines are being developed with active burial systems and non-metallic parts to reduce their target signature.

Mines are becoming more robust with hardened casings and resistant fuses. Mines are also becoming more resistant to mine countermeasures through the use of ship counters. Although advances in technology are improving mines, vintage mines from WW II still pose a threat to U.S. forces. Table IV-5 shows characteristics of mines the Sea Base assets may encounter in various water regions.

	MINE-1 SURF ZONE & CLZ (0 - 10 ft)	**MINE-2 VERY SHALLOW WATER (VSW) (10 - 40 ft)**	**MINE-3 SHALLOW WATER (SW) (40 - 200 ft)**	**MINE-4 DEEP WATER (DW) (200 ft)**
Type	Bottom	Bottom	Bottom / Moored	Moored
Actuation	Contact / Influence	Contact / Influence	Contact / Influence	Influence
Delivery	Personnel / Ship / Aircraft	Ship / Aircraft / Sub	Ship / Aircraft / Sub	Ship / Aircraft / Sub
Warhead (lbs)	700	1000	700	800
Dimensions (ft)	Length - 1.5 Diameter - 3.0	Length - 5.5 Diameter - 2.0	Length - 3.5 Diameter - 4.0	Length - 6.5 Diameter - 1.5
Active Sonar Assumptions* H_2O Temp = 25 C Salinity = 34 ppt Reflectivity = 0.1 Active Sonar @ 25 kHz				
Target Strength (dBsm)*	-22.82	-26.34	-20.32	-28.84

*See Sensor Analysis (Chapter V-B) for further details.

Table IV-5 Mine Threat Representative Characteristics

(2) Torpedoes

(a) Definition

This study defines a torpedo as a steerable, self-propelled, underwater projectile filled with an explosive charge used for destroying ships or submarines.

(b) Threat to Sea Base

The torpedo poses a threat to the Sea Base for numerous reasons. A single torpedo is capable of seriously damaging or destroying Sea Base ships and/or any escorts. Torpedoes can be employed from air, surface, or subsurface platforms. Torpedoes are difficult to locate visually and may be difficult to detect. Furthermore, they are highly maneuverable and travel at speeds faster than Sea Base shipping.

(c) History

The torpedo has evolved from a floating mine used in the Revolutionary War to the fast-moving, self-guided, homing torpedoes used today. WW I- and WW II-era torpedoes traveled in a straight line on a pre-set course. The homing torpedo is fired in the direction of the target and automatically changes its course to seek out the target.

(d) Future

Torpedo technology is proliferating and advancing throughout the world. There are more than 30 different torpedo models with varying capabilities that include: silent, wake-free propulsion; high speed capability; multiple, selectable attack geometries; long range; at least 12 different guidance, homing, or fusing techniques; decoy rejection; state of the art signal processing to improve the chance for target acquisition; multiple re-attack logic; use of a wide band of the acoustic spectrum (less than 10 kHz to nearly 100 kHz); adaptive, countermeasure-resistant homing (Braga, 1996).

Representative torpedo threats the Sea Base may encounter will likely have the characteristics listed in Table IV-6.

	TORP-1 (Sub Launched)	**TORP-2** (Sub Launched)	**TORP-3** (Air or Surface Launched)
Length (ft)	26	26	8
Diameter (in)	21	21	13
Warhead (lbs)	600	600	100
Speed (kts)	50	200	40
Range (nm)	25	4	4
Depth (ft)	700	700	1200
Guidance	passive / active acoustic wake homing	passive / active acoustic homing	passive / active acoustic homing
Passive Sonar Assumptions* Depth of Torp = 10 m Speed of Torp1 = 50 kts Speed of Torp2 = 200 kts Speed of Torp3 = 40 kts H_2O Temp = 25 C Salinity = 34 ppt Reflectivity = 0.1 Passive Sonar @ 25 kHz			
Source Level (dB)*	135	285	125
Active Sonar Assumptions* Depth of Torp = 10 m Speed of Torp1 = 50 kts Speed of Torp2 = 200 kts Speed of Torp3 = 40 kts Target Angle = 0^{o} H_2O Temp = 25 C Salinity = 34 ppt Reflectivity = 0.1 Active Sonar @ 25 kHz			
Target Strength (dBsm)*	-27.50	-27.50	-35.88

*See Sensor Analysis (Chapter V-B) for further details.

Table IV-6 Torpedo Threat Representative Characteristics

(3) Submarines

(a) Definition

This study defines a submarine as a warship that can operate on the surface or underwater. For purposes of the study, the submarine will be focused primarily on traditional submarine mission areas: anti-surface and anti-submarine.

(b) Threat to Sea Base

The submarine poses a versatile threat capable of both direct and indirect actions towards the Sea Base. Indirectly, the submarine can act as an intelligence platform intercepting valuable communications and/or providing targeting data to other assets. Conversely, a potential adversary could easily deny access to a region by advertising its presence. In a more direct sense, a submarine threatens the Sea Base by possessing the capability to seriously damage or sink Sea Base shipping through the use of torpedoes, mines, or ASCMs.

(c) History

Submarines have proven their destructive potential throughout history. During WW I, German U-boats exacted a huge toll on merchant shipping while practicing unrestricted submarine warfare. In order to mitigate this problem, a new warfare area was created, anti-submarine warfare (ASW). ASW included the use of depth charges and maneuvering surface assets in convoys. During WW II, U.S. submarines played an important role against Japan’s surface assets. By 1945, about one-third of all Japanese warships and over half of Japan’s merchant vessels were destroyed by U.S. submarines. During the Cold War, nuclear attack submarines were developed to protect carrier battle groups against Soviet submarines. After the end of the Cold War, the focus of the submarine threat moved to the littorals.

Although the overall number of submarines in the world has decreased, their quality and versatility have improved. Forty-five countries around the world have submarines in their inventory. Due to affordability, nations that are unable to produce their own submarines are able to purchase submarines from other countries. Nations are also obtaining the submarine’s threat capability by purchasing cheaper “midget” submarines. Midget submarines can deploy as diver vehicles to attack larger ships using mines or torpedoes (Hutchinson, 2001).

(d) Future

Research has indicated that foreign militaries are concentrating much of their naval efforts on costal defense and area denial capabilities in their own littorals. An intricate part of littoral defense is the employment of submarines. As indicated above, many foreign militaries have obtained submarines, or have increased the number of submarines in their inventories. It is quite probable that future expeditionary forces may be particularly vulnerable to submarine attacks while operating in the littorals. Sea Base assets may encounter three generic types of attack submarines listed in Table IV-7.

	SUB-1	**SUB-2**	**SUB-3**
Length (ft)	240	360	66
Beam (ft)	30	36	7
Displacement (tons) (surfaced/submerged)	2325 / 3076	6000 / 7000	90 / 110
Speed (kts) (surfaced/submerged)	10 / 19	15 / 30	8 / 11
Armament	6 – 21 in torpedo tubes (18 torpedoes) 24 – Mines (replaces torpedoes) 8 – SAMs	6 – 21 in torpedo tubes (18 torpedoes) 24 – Mines (replaces torpedoes) 8 – SAMs	2 - 21 in tubes (2 torpedoes)
Propulsion	Diesel electric (AIP)	Nuclear / Pressurized Water Reactors	Diesel electric
Endurance (days)	45	45	2
Diving depth (ft)	1000	1000	125
Passive Sonar Assumptions* Depth of Sub = 300 m Target Angle = 0 ° H_2O Temp = 20 C Salinity = 34 ppt Reflectivity = 0.1 Active Sonar @ 1 kHz			
Source Level (dB)*	100	100	90
Active Sonar Assumptions* Depth of Sub = 300 m Target Angle = 0 ° H_2O Temp = 20 C Salinity = 34 ppt Reflectivity = 0.1 Active Sonar @ 1 kHz			
Target Strength (dBsm)*	-2.82	-1.23	-15.46

*See Sensor Analysis (Chapter V-B) for further details.

Table IV-7 Submarine Threat Representative Characteristics

c. On the Water

(1) Small Boats

(a) Definition

This study defines small boats as an extensive range of craft designed to operate in shallow coastal water such as patrol boats, patrol gunboats, torpedo boats, missile boats, fast-attack craft, drones, suicide craft, and motorboats. The armament mounted or carried on small boats range from miscellaneous side- and shoulder-fired weapons to large caliber machine guns, cannons, mortars, rockets, and torpedoes. These small craft are inherently constrained in range, endurance, and capability due to their size, seaworthiness, and reliance on non-organic platforms for over-the-horizon targeting information and support.

(b) Threat to Sea Base

Small boats are a considerable challenge to Sea Base assets operating in the littoral environment. The small radar cross section of vessels in this class make them particularly difficult to detect and target. Their speed (up to 50 knots in some cases) and maneuverability complicate the difficulty of targeting them with current weapons systems. Furthermore, the current means of addressing the small boat threat are not cost effective. In mass, small boats could attrite the weapons inventory as Sea Base assets use costly means to defend themselves.

(c) History

“When John Paul Jones pleaded for a fast-sailing ship because he intended ‘to go in harm’s way,’ he set the tone for the first hundred years of American naval history (Hagan, 1991, XI).” The United States Navy was “built around fast ships skippered by bold captains, officered by ambitious lieutenants, and manned by individualistic seamen (Hagan, 1991, XI).” The Navy employed “hit and run” tactics in order to disrupt enemy merchant traffic and engage smaller enemy combatants. Though the Navy’s roots stemmed from using fast, small “boats” as an effective platform from which to conduct warfare at sea, it wasn’t until those same tactics were used against the U.S. Navy that small boats were viewed as a viable threat.

The Tanker War, from 1984-1987, would bring to light the large combatant’s inherent vulnerability when challenged by fast, small boats. The Iranians conducted 43 small boat attacks against merchant shipping during this conflict. Their swarming tactics proved to be quite successful and though they rarely sank a ship, they were effective at inflicting serious damage on the tankers and their crews. These small boats harassed U.S. ships as well, but luckily, the Iranians made no significant efforts to go toe-to-toe with the Americans. The U.S. Navy, whose assets were not designed or equipped to deal with the small boat threat, countered the Iranians with Special Operations Forces and helicopter gun-ships.

The Liberation Tigers of Tamil Elam (LTTE), a.k.a. the Tamil Tigers, an ethnic insurgent group fighting for independence in Sri Lanka, have notably been the most successful group to employ small boat swarm tactics against larger naval forces. This group generally employs 10-15 craft, armed with machineguns, and will overwhelm their enemy by attacking from many different directions. “Sri Lanka has lost at least a dozen naval vessels, both in harbor and at sea, as a result of LTTE attacks (Sakhuja, 2003).” The Tamil Tigers have also successfully employed “kamikaze” style attacks against their targets.

(d) Future

As foreign militaries concentrate on coastal defense because they cannot afford a blue water naval capability, small boats will likely play a larger role in future enemy strategies to deny access to, or disrupt, U.S. naval and amphibious operations in the littorals. Small boats require smaller crews to operate, thereby reducing manning, training, and operating costs. Furthermore, small boats are cheaper to acquire and replace, and are easier to hide or disguise. For terrorists, non-state actors, or rogue governments seeking high payoff targets, small boats are likely to become a viable asymmetric option to counter U.S. supremacy of the sea. The ExWar ships and the Sea Base transport assets may be particularly vulnerable to small boat attacks, while attempting to project power to an objective during the assault phase of the amphibious operation.

Sea Base assets may encounter small boat threats with the characteristics highlighted in Table IV-8.

		SB-1	SB-2	SB-3
Dimension (ft)	**Length**	10	82	190
	Beam	4	18	26
	Height	2	20	33
Displacement (lton)		0.34	46.5	280
Speed (kts)		40	50	40
Range (nm)		125	500	1500
Engine Type		1.2L Turbo	3 Diesel	4 Diesel
Engine Power (MW)		.12	1.54	7.94
Hull		Fiberglass	Steel / Aluminum	Steel / Aluminum
Armament Type		Machine gun / RPG / Explosives	Machine gun / Rocket / Torpedo / Missile	Machine gun / Rocket / Torpedo / Missile
Radar Cross Section (RCS) Assumptions* Target Angle = 0^o (Nose on) Radar Freq = 3 GHz Reflectivity = 0.1				
Total RCS (m^2)*		0.058	2630	5490
Passive Sonar Assumptions* Target Speed = 10 kts H_2O Temp = 25 C Salinity = 34 ppt Passive Sonar @ 1 kHz				
Source Level (dB)*		90.78	110.01	117.02
Active Sonar Assumptions* Target Speed = 10 kts Target Angle = 0^o H_2O Temp = 25 C Salinity = 34 ppt Reflectivity = 1.0 Active Sonar @ 1 kHz				
Target Strength (dBsm)*		-2.34	7.98	14.00

*See Sensor Analysis (Chapter V-B) for further details.

Table IV-8 Various Small Boat Characteristics

(2) Unconventional Vessels

(a) Definition

This study defines unconventional vessels as innocent craft such as, sailboats, junks, dhows, small merchants, large merchants, container ships, cargo vessels, Petroleum Oil Lubrication or natural gas container ships used with the intent of causing harm or providing targeting information against friendly forces. These vessels require an increased level of identification to discern their disposition. Unconventional vessels cover an extensive range of surface craft.

(b) Threat to Sea Base

Unconventional vessels are a potentially devastating threat to the Sea Base operating in the littoral environment for numerous reasons. These vessels can cause harm to the Sea Base both directly and indirectly. Direct action means gaining access to the Sea Base by closing distances due to an unsuspecting nature, and conducting direct action missions employing various types of conventional or unconventional weapons. Indirect attack includes actions such as: saturating the operating area to make maneuver difficult; laying mines; clandestine movement of enemy assets; intelligence gathering operations; or providing targeting information to fixed or mobile enemy weapons systems. If an organized effort was made, either directly and indirectly, to inhibit the movement of Sea Base assets, disrupt operations, or target friendly assets, the Sea Base may be unable to execute certain critical missions, thus making the overall mission a failure.

(c) History

Deception and military operations go hand in hand. The Greeks successfully conquered Troy after their "gift" to the Trojans was moved inside the city. Though not a sea-going vessel, the Trojan horse can easily be used as an example of the devastation that may befall friendly forces if an unconventional vessel is allowed within weapons range or successfully accomplishes its mission. The USS Cole (DDG 67) was severely damaged in October 2000, by an unsuspecting surface craft that was helping it moor to an offshore fuel point.

(d) Future

Foreign militaries, terrorists, non-state actors, and rogue nations will continue their efforts to counter the U.S. using asymmetric means. Unconventional vessels allow America's enemies a new platform from which to implement their weapons systems. A Sea Base attempting to conduct a forced-entry mission and sustainment of forces ashore would be extremely vulnerable to these types of vessels. For example, a large merchant vessel could transit close to the Sea Base using a standard shipping lane and quickly unleash a barrage of anti-ship cruise missiles from its containers.

d. Above the Water

(1) Anti-Ship Cruise Missile (ASCM)

(a) Definition

This study defines cruise missiles as unmanned, self-propelled vehicles that sustain flight through the use of aerodynamic lift. ASCMs are cruise missiles capable of engaging ships or other surface vessels. Because of the maneuverability inherent in ships and surface craft, ASCMs are typically guided by one or more means and possess flight controls that allow them to maneuver in order to hit their designated target(s).

(b) Threat to Sea Base

ASCMs present a significant threat to the Sea Base. ASCMs are widely proliferated and increasingly able to travel further and faster while enjoying greatly reduced signatures through the use of low observable technologies. They are capable of being employed on a variety of platforms including surface craft, aircraft, submarines, and coastal batteries. Due to an advantage in accuracy, ASCMs, in the littoral, are regarded as a far more dangerous threat than that posed by other threats such as ballistic missiles. Many ballistic missile systems use inherently inaccurate inertial guidance systems and do not possess a means of guiding onto maneuvering targets such as ships. The typical ASCM, however, is able to use many forms of guidance, both internally and externally. Modern ASCMs are capable of using inertial navigation augmented by inputs from the Global Positioning System (GPS) or other remote sensors, such as digital scene mapping and/or radar altimeters. Target designation and terminal guidance may be provided through a variety of means including infrared (IR), electro-optical (EO), and/or radar. These enhanced guidance packages greatly reduce the typical ASCM’s circular error probable (CEP) as compared to the CEP of a typical ballistic missile.

(c) History

For several decades, warfare at sea has concentrated on the threat posed by ASCMs. Indeed, many countermeasures and weapon systems have been developed specifically to address this ever-increasing threat. The growing trend in ASCM proliferation demands that modern navies develop and deploy effective means of dealing with ASCMs. Two notable examples in recent history demonstrate the effectiveness of modern ASCMs: during the 1983 Falkland Islands conflict, three Exocet ASCMs were used to sink or damage three British ships and killed 45 sailors; and in 1987, two Exocets severely damaged the USS Stark (FFG 31) killing 37 sailors.

(d) Future

Many students of the Revolution in Military Affairs (RMA) have pointed to the emergence of high-speed, long-distance, and highly accurate weapons as a key technological development for future warfare. Several countries have recognized these observations. Recently, the United States, Russia, China, Japan, India, and several European countries have shown great interest in hypersonic technology. Advances in ramjets and scramjets have produced vehicles with ranges greater than 700 km and sustained speeds in excess of Mach 5. These technologies will undoubtedly make their way into future ASCMs.

Two current threat representative ASCMs and one potential future ASCM, with corresponding characteristics and flight profiles, are presented as likely future threats. The information for these ASCMs was obtained or derived using open source material. The three phases of an ASCM's flight, generally referred to as boost, midcourse, and terminal, are assumed for the three missiles. The missile characteristics and associated flight profiles are listed in Table IV-9 and Figure IV-11.

	ASCM - 1	**ASCM - 2**	**ASCM - 3**
Length (ft)	12.3	29.2	38.1
Diameter (ft)	1.38	2.2	3.0
Speed (kts)	583	1602	3208
Max Range (nm)	81	162	540
Cruise Altitude (ft)	16	33	79000
Terminal Altitude (ft)	10	16	79000 (30^o dive)
Seeker Type	Radar / EO / IR	Radar / EO / IR	Radar / EO / IR
Radar Cross Section (RCS) Assumptions Target Angle = 0^o (Nose on) Radar Freq = 3 GHz Reflectivity = 0.1			
Total RCS (m^2)	0.014	0.035	0.066
Infrared (IR) Assumptions Target Angle = 0^o (Nose on) Emissivity = 0.9			
Radiant Exitance (W/m^2-μ) Wavelength (λ) = 3 - 5 μm	29.76	3357.22	125130.12
Radiant Exitance (W/m^2-μ) Wavelength (λ) = 8 - 12 μm	250.82	2117.78	13599.65

Table IV-9 ASCM Threat Representative Characteristics

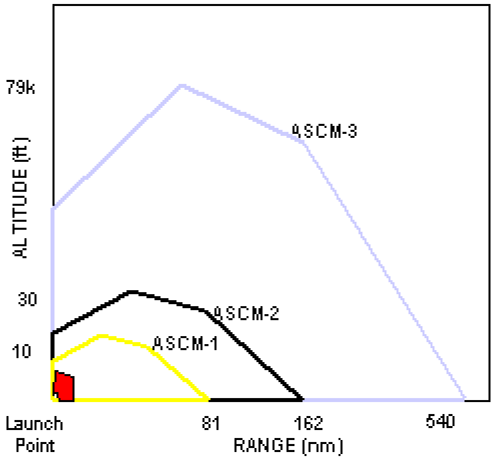


Figure IV-11 ASCM Threat Representative Flight Profiles

(2) Rotary Wing Aircraft/Fixed Wing Aircraft/Unmanned Aerial Vehicle (UAV)

(a) Definition

For this study's purpose, aircraft include both manned rotary wing and manned fixed wing platforms, although each will be treated separately. Rotary wing aircraft require the generation of lift, largely from overhead spinning rotors, and are regarded as manned helicopters. Fixed wing aircraft require the generation of lift by the rapid flow of air over a surface, or wing, that for the most part does not move, and is firmly attached to or is a part of the aircraft's main body. While the wings of a fixed wing aircraft may be variable geometry, the motion of the wings themselves does not contribute directly to the generation of airflow.

A UAV may either be fixed wing or rotary wing, but it differs from the term aircraft as used here in that it is unmanned and can fly autonomously or be piloted remotely. A UAV can be expendable or recoverable and can carry a lethal or nonlethal payload. Ballistic or semi-ballistic vehicles, cruise missiles, and artillery projectiles are not considered unmanned aerial vehicles.

(b) Threat to Sea Base

Rotary wing aircraft, fixed wing aircraft, and UAVs present a significant threat to the Sea Base and the associated delivery vehicles. Numerous varieties of attack aircraft are produced in many countries around the world. Many of these aircraft are widely proliferated and are increasingly able to travel large distances at relatively high speeds while carrying greater payloads and enjoying greatly reduced signatures through the use stealth and other low observable technologies. These aircraft are typically capable of conducting air superiority, surveillance, and reconnaissance in addition to their attack roles. Attack aircraft, in the littoral, are regarded as dangerous threats because of their versatility and ever-increasing capabilities.

(c) History

Since WW I, aircraft have played ever-increasing roles in warfare at sea, on land, and in the air. The military uses of aircraft have evolved from scouting to air defense, air superiority, and strike/attack. The means of conducting these missions have involved an increasing variety of both hard and soft kill armament.

The ability to achieve air superiority has proven decisive in many of the conflicts in modern history. The ability to strike an opponent's forces while denying him the ability to do the same is of great importance to military planners. While augmented by surface-to-air missiles, anti-aircraft artillery, cruise missiles, or ballistic missiles, these missions rest primarily with manned aircraft.

UAVs do not have as long a history as manned aircraft, yet several variants have enjoyed great success in recent conflicts. UAVs have proven invaluable because of their relatively long endurances, low observability features, and tactical flexibility. In Bosnia, Afghanistan, and Iraq, UAVs proved extremely reliable and capable in performing surveillance, reconnaissance, and attack missions.

(d) Future

Because of the significant investment in equipment and training required to obtain modern fighter-attack aircraft and the pilots to man them, many countries may turn instead to the relative affordability offered by UAVs. The development of UAVs, such as the Unmanned Combat Air Vehicle (UCAV), promise an affordable weapon system capable of performing a wide variety of tactical missions, either autonomously or remotely, as early as 2010.

The use of both rotary wing and fixed wing manned aircraft cannot be discounted for future warfare. The proliferation and continued development of manned aircraft ensure that these platforms will remain in the arsenals of many countries for the foreseeable future.

Two current threat representative manned aircraft, one potential future manned aircraft, and one potential future multi-role UAV with corresponding characteristics are determined to present likely future threats. The information for these aircraft and the UAV was obtained or derived using open source material. The aircraft and UAV characteristics are listed in Table IV-10.

	ACFT - 1 Rotary Wing)	**ACFT - 2 (Fixed Wing)**	**ACFT - 3 (Fixed Wing, Low Observable)**	**UAV / UCAV-1 (UAV, Low Observable)**
Fuselage Length (ft)	49.2	56.8	66.6	26.2
Fuselage Height (ft)	13.1	15.4	12.5	6.6
Rotor Diameter / Wingspan (ft)	47.6	36.1	43.6	33.8
Tail Height (ft)	N/A*	6.6	N/A*	N/A*
Tail Width (ft)	N/A*	6.6	N/A*	N/A*
Tail / Wing / Rotor Thickness (ft)	.16	.33	.16	.16
Max Speed (kts)	184	1602	583	551
Max Range (nm)	248	905	1080	999
Service Ceiling (ft)	18,045	60,368	61,024	39,370
Max Payload (lbs)	5512	8818	4409	2998
Sensors	EO, IR, FLIR, Laser, Radar, Visual	EO, IR, FLIR, Laser, Radar, Visual	EO, IR, FLIR, Laser, Radar, Visual	EO, IR, FLIR, Laser, Radar
Radar Cross Section (RCS) Assumptions** Target Angle = 0^o (Nose on) Radar Freq = 3 GHz Reflectivity ACFT 1/2 = 0.1 Reflectivity ACFT 3/UAV = 0.0001				
Total RCS (m^2)**	92.30	165	0.08	0.06
Infrared (IR) Assumptions** Target Angle = 0^o (Nose on) Emissivity ACFT 1/2 = 0.9 Emissivity ACFT 3/UAV = 0.9999				
Radiant Exitance (W/m^2-μ)** Wavelength (λ) = 3 - 5 μm	6.74	9.91	9.91	6.74
Radiant Exitance (W/m^2-μ)** Wavelength (λ) = 8 - 12 μm	128.48	152.84	152.84	128.48

*Not Applicable.

**See Sensor Analysis (Chapter V-B) for further details.

Note: Specific weapon types carried by these platforms are not addressed in this section. The types of weapons carried by these platforms will be similar to the weapons addressed in other sections of this document.

Table IV-10 Aircraft and UAV Threat Representative Characteristics

(3) Surface-to-Air Missiles (SAMs)

(a) Definition

For the purposes of this study, SAMs are defined as surface-launched missiles that are used against airborne targets.

(b) Threat to Sea Base

SAMs will present a significant threat to the Sea Base's airborne assets. SAMs are widely proliferated throughout the world in a variety of forms and are typically fast and very accurate. Many SAMs are capable of using a variety of both passive and active methods for guidance and homing. These methods include radar, laser, EO, IR, and ultraviolet (UV). Furthermore, many SAM systems are highly mobile and do not rely on fixed site emplacement. These SAMs are normally man-portable or are employed on tracked or wheeled vehicles or onboard surface craft. The ability of these systems to shoot and move greatly complicates counter-targeting by enemy forces.

(c) History

SAMs have enjoyed great success in several conflicts in recent history. They have been widely used in many areas and at various times with devastating results. While not able to gain air superiority themselves, SAMs have acted as effective barriers to the attainment of air superiority by opponents.

(d) Future

SAMs will continue to be used in future conflicts. Their affordability and lethality are attractive alternatives to the establishment of an expensive air defense composed of high-cost, air-defense fighters. Furthermore, SAMs provide an effective deterrent against many modern air forces.

SAMs will most likely continue to increase in speed, range, and accuracy. Many experts attribute the success of the U.S. in recent conflicts to the attainment of air superiority. Future enemies will most likely focus on the denial of air superiority through increases in the performance capabilities of their air defense systems.

Two current threat representative SAMs with corresponding characteristics are likely to present future threats. The information for these SAMs was obtained or derived using open source material. The SAMs' characteristics are listed in Table IV-11.

	SAM - 1	**SAM - 2**
Length (ft)	23	4.9
Diameter (ft)	1.5	.3
Max Speed (kts)	3600	1602
Max Range (nm)	108	5.4
Max Altitude (ft)	98,425	19,685
Launch Platform	Mobile / Semi-Mobile (TEL, ship)	MANPAD
Sensors	EO, IR, Radar	EO, IR, UV, Laser, Visual
Radar Cross Section (RCS) Assumptions* Target Angle = 0^o (Nose on) Radar Freq = 3 GHz Reflectivity = 0.1		
Total RCS (m^2)*	0.016	0.00078
Infrared (IR) Assumptions* Target Angle = 0^o (Nose on) Emissivity = 0.9		
Radiant Exitance (W/m^2-μ)* Wavelength (λ) = 3 - 5 μm	181943.69	2625.63
Radiant Exitance (W/m^2-μ)* Wavelength (λ) = 8 - 12 μm	17166.46	1890.59

*See Sensor Analysis (Chapter V-B) for further details.

Table IV-11 SAM Threat Representative Characteristics

(4) Unguided Weapons

(a) Definition

For the purposes of this study, unguided weapons are defined as projectiles that follow a ballistic trajectory with no in-flight control. Unguided weapons encompass small arms, artillery, and ballistic rocket systems.

(b) Threat to Sea Base

Unguided weapons present a significant threat to the Sea Base and its associated delivery assets. Unguided weapons are relatively cheap and widely proliferated throughout the world in a variety of forms.

(c) Threat to Sea Base

Unguided weapons present a significant threat to the Sea Base and its associated delivery assets. Unguided weapons are relatively cheap and widely proliferated throughout the world in a variety of forms.

(d) History

Unguided weapons have been used in almost every conflict since Man first picked up a rock. They have evolved from simple slings and spears to catapults and crossbows to modern day machine guns and long-range howitzers.

(e) Future

Unguided weapons will continue to be heavily used in future conflicts. Their affordability, lethality, and ease of use ensure their continued existence in every arsenal. Unguided weapons will most likely continue to increase in range, accuracy, and firepower.

The Sea Base may encounter three representative unguided weapons listed in Table IV-12. The information for these unguided weapons was obtained or derived using open source material.

	DW - 1 (MLRS-type)	**DW - 2 (Crew Served)**	**DW - 3 (Assault Rifle)**
Projectile	227mm	40mm	7.62mm
Effective Range	16 nm	1695 yds	328 yds
Max Rounds Per Minute (RPM)	6 rockets per launcher (644 submunitions per rocket)	60	600
Armor Penetration of Rolled Homogenous Armor (RHA)	4 in (per submunition)	2 in	N/A
Portability	Truck w / 13-ft bed	3 man	1 man
Radar Cross Section (RCS) Assumptions** Target Angle = 0^{o} (Nose on) Radar Freq = 3 GHz Reflectivity DW1 = 0.1 Reflectivity DW2/3 = 0.7			
Total RCS (m^2)**	0.0041	0.00088	0.000032
Infrared (IR) Assumptions** Target Angle = 0^{o} (Nose on) Emissivity DW1 = 0.9 Emissivity DW2/3 = 0.3			
Radiant Exitance (W/m^2-μ)** Wavelength (λ) = 3 - 5 μm	125130.12	27.22	3357.22
Radiant Exitance (W/m^2-μ)** Wavelength (λ) = 8 - 12 μm	13599.65	240.94	2117.78

*Not Applicable.

**See Sensor Analysis (Chapter V-B) for further details.

Table IV-12 Unguided Weapons Threat Representative Characteristics

e. Conclusion

In the complicated process of weapons development, very few innovations have arisen solely from original thinking, flown in the face of convention, or challenged the status quo. Many weapons are developed through a person or group of people who are able to bring unique points of view and sets of experience to known facts. Many other advances in weaponry can be traced ultimately to the steady march of technology. While scientific breakthroughs cannot be discounted and may have great impacts on the battlefields of the future, the threats or platforms examined by this study are currently in existence or are reasonably judged to be in existence by 2016. This study has matched the future threats with future platforms and has listed them in Table IV-13.

PHASE	PLATFORM	WEAPON
I	SUB-1/2	Mine-3/4, Torp-1/2, ASCM-1/2, SAM-2
	UnconVes	Mine-3/4, Torp-3, ASCM-1/2, SAM-2, DW-1/2/3
	Land	ASCM-2/3
	SB-3	Mine-3/4, Torp-3, ASCM-1/2, SAM-2, DW-1/2/3
	ACFT-2/3 & UAV	ASCM-1/2, TORP-3, MINE-3/4, DW-2/3
II	SUB-1/2	Mine-2/3, Torp-1/2, ASCM-1/2, SAM-2
	SUB-3	Mine-2/3, Torp-1/2
	UnconVes	Mine-1/2/3, Torp-3, ASCM-1/2, SAM-2, DW-1/2/3
	Land	ASCM-1/2/3, SAM-1/2, DW-1/2/3
	SB-1	DW-2/3, SAM-2
	SB-2	MINE-1/2/3, SAM-2, DW-2/3
	SB-3	Mine-2/3, Torp-3, ASCM-1/2, SAM-2, DW-1/2/3
	ACFT-1/2/3 & UAV	ASCM-1/2, TORP-3, MINE-1/2/3/DW-2/3
III	SUB-3	Mine-2/3, Torp-1/2
	UnconVes	Mine-1/2/3, Torp-3, ASCM-1/2, SAM-2, DW-1/2/3
	Land	ASCM-1/2/3, SAM-1/2, DW-1/2/3

Table IV-13 Phases and Associated Threat Platforms with Possible Future Weapons

The characteristics of weapons and platforms listed in Table IV-13 will be used as inputs for the modeling and simulation, and design of critical systems that will make up the conceptual architecture of this study's force protection recommendation.

E. EFFECTIVE NEED

The end product of the needs analysis is the effective need statement. After identifying and addressing force protection issues, defining the functions of the system, analyzing the system operating environment, and understanding the needs of the stakeholders; the SEA-4 Team was able to develop an effective need statement. The effective need was determined to be:

> "Conserve the force's fighting potential so it can be applied at the decisive time and place. Conserving the force's fighting potential is achieved through maximizing survivability by minimizing susceptibility and vulnerability."

This effective need statement was used to provide focus and used as the central theme in the continuation of the study.

F. VALUE SYSTEM DESIGN

Building from the effective need statement and functional analysis, survivability was determined to be the primary measure of effectiveness of force protection for the Sea Base and its transport assets. Survivability was further divided into the measures susceptibility and vulnerability. Using these critical functions as starting points, the value system design phase was started. Traditionally, the primary purpose of the value system design is to develop a value hierarchy that will be used to evaluate potential alternative solutions and ultimately select the best-proposed alternative. However, this study took a different approach to the value hierarchy concept. Instead of applying values to the critical functions (survivability, susceptibility, and vulnerability) with regards to stakeholder needs, wants, and desires, this study concluded that relative values should be applied with regards to the ability of the team to affect the design of the architecture. In other words, on what should the SEA-4 Team focus its efforts in order to attain the greatest affect on asset survivability? Review of the governing documents, brainstorming, and discussions with stakeholders allowed the SEA-4 Team to create the value hierarchy displayed in Figure IV-12.

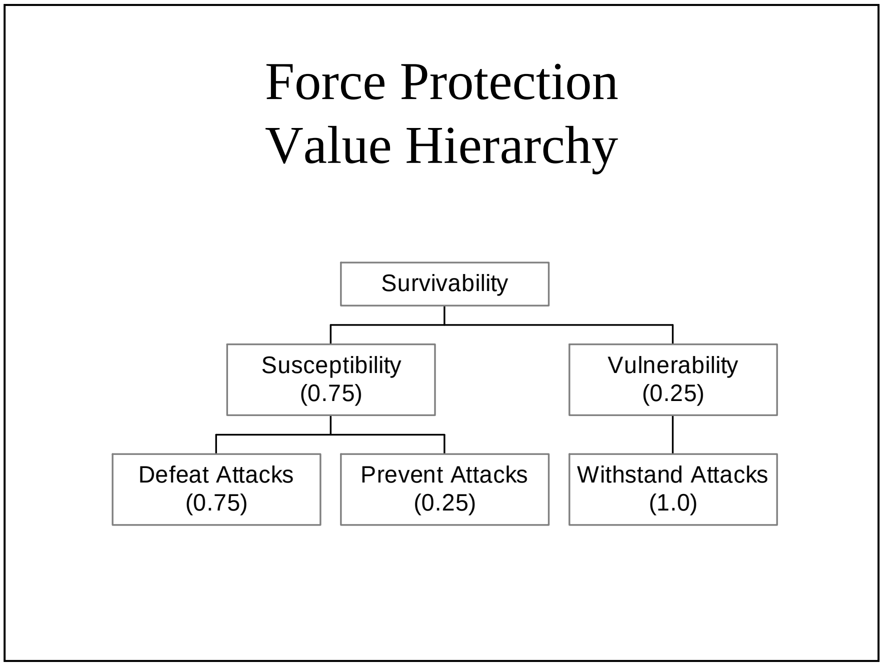


Figure IV-12 Force Protection Weighted Value Hierarchy

Vulnerability is the ability of the system to withstand enemy attacks or actions. Possible methods of withstanding enemy attacks might include adding armor to a system or component, damage control actions or training, implementing quality construction practices, or adding redundant elements to vital systems. Because many of the systems considered for possible inclusion into this study's conceptual solution were already designed, little could be done by the SEA-4 Team with regard to affecting this critical function. Therefore, a weighting of .25 was applied to vulnerability and thus minimal effort was expended on trying to decrease the level of system vulnerability in order to increase the overall measure of survivability. Vulnerability is addressed, however, in the modeling section of this study. Friendly assets were broken down into critical regions in order to determine how many enemy hits they could withstand prior to becoming a "mission kill."

Susceptibility is the ability of the system to prevent and defeat enemy attacks or actions. The SEA-4 Team's initial inclination into what a possible conceptual solution to the force protection problem might be lead the team to expend the majority of its efforts on attempting to increase the overall measure of survivability by defeating and preventing enemy attacks against the Sea Base. Potential methods of preventing enemy attacks might include the employment of electronic or IR countermeasures, executing evasive maneuvers, deploying chaff, flares or decoys, or designing systems with signature management as the primary goal. Once again, as in the example regarding vulnerability, this study could do little to affect many of these mitigation efforts as most of the systems were already designed. Therefore, a value of .25 was applied to the preventing attacks subfunction of susceptibility. The SEA-4 Team did address susceptibility, with the intent of reducing friendly asset susceptibility to enemy weapons systems, by placing certain friendly assets at greater distances from enemy forces.

The defeating attacks subfunction was considered something this study could affect with regards to a conceptual solution to the force protection problem. Methods of defeating enemy attacks might include employing kinetic or directed energy weapons against enemy threats. Various missile, gun, and directed energy weapons were considered as varying elements of the final force protection architecture proposal, and thus a weighting of .75 accompanied that subfunction.

Though not listed in Figure IV-12, this study considered the ability to detect enemy threats as the genesis of protecting the Sea Base and its transport assets. Methods for detecting enemy threats might include the employment of radar, lidar, IR, ultra-violet, sonar, or electro-optical sensors. The SEA-4 Team expended considerable effort on this subject as it ultimately served as the origin for possible alternative solutions to the force protection problem.

G. REQUIREMENTS GENERATION

1. Overview

The generation of requirements is not a formal part of the SEMP, but is necessary for any system. The key to success for any project is to have well defined and well understood requirements. A requirement is considered to be something that must be accomplished, transformed, produced, or provided. A requirement must accurately translate the client’s need to the supporting teams. Ideally, the Systems Engineers would complete the problem definition phase, and then develop detailed requirements for the supporting teams. In this study, the supporting teams had to begin work before the Systems Engineering Team was able to begin with the SEMP. Therefore, the supporting teams were only provided with a set of general overarching requirements. Detailed requirements were provided to the TSSE Team in the design of a LCS that would be specially designed to support force protection of the Sea Base.

2. Overarching Requirements

The systems engineering methodology described in Chapter III did not include a formal requirements generation phase. During the problem definition phase, the SEA-4 Team developed a set of overarching requirements using the SEI-3 study for guidance. Force protection was broken into specific mission areas as shown in the functional analysis. A set of overarching requirements was developed focusing on self-defense and the primary threats in each specific mission area. The initial overarching requirements for Sea Base force protection were:

- Self-defense for ExWar ships
    - Defense against ASCMs (AAW)
    - Defense against small-boat attack (ASUW)
    - Defense against submarine/UUV attack (ASW)
- Robust organic Mine Countermeasures (MCM) capability (MIW)
- Capability to identify and defend against unconventional attacks
- Highly survivable transport aircraft and landing craft
- Provide protection for logistic transports from the Sea Base to the objectives
- Chemical, Biological, Radiological, Nuclear and Enhanced Conventional Weapons (CBRNE) defense

These were validated using the results of this study's functional analysis and with functional flow block diagrams and functional analysis sheets completed by the SEI-3 Team as shown in the SEI-3 report.

3. LCS Requirements

The TSSE Team was tasked with the design of a Littoral Combat Ship specifically suited for force protection. This mandated the generation of detailed requirements by the SEA-4 Team. Detailed requirements were delivered to the TSSE Team in the form of a requirements document. The document contained a general description of the required operational capability that included the mission need statement, overall mission area, and a description of the proposed system. The document also described system states and associated threats along with specifics in each warfare area. Requirements for supportability and human systems integration were also included. The entire LCS requirements document is included in this report as Appendix A.

H. CONCLUSION

Defining the problem is considered the most difficult part of any systems engineering problem. The SEA-4 Team endeavored to scope and bound the problem using several techniques. An overall skeleton was erected by determining a realistic time schedule in which to study, analyze, and deliver a final product to the stakeholders. Assumptions were then made and associated critical issues were developed and discussed in order to further scope and bound the problem. The force protection function was broken down into subfunctions in order to better understand how measures of effectiveness might be evaluated. Studying the operating environment and projecting a plausible future in which the critical functions of force protection could be tested then set the stage for this study’s modeling efforts. Throughout this process, a solid understanding of stakeholder needs, wants, and desires served as the basis from which the effective need statement was developed. Developing the effective need allowed the SEA-4 Team to begin adding the muscle to the skeleton and essentially concluded the needs analysis phase of the Systems Engineering Management Process. Diverging from the practiced method of value system design, the SEA-4 Team was able to focus its efforts towards critical elements that could actually be affected by this study. The next step was to concentrate on those critical elements so that conceptual alternatives to the force protection problem could be developed.

V. DESIGN

A. ALTERNATIVES GENERATION

Alternatives generation is the means of bringing system alternatives into being while fulfilling the functions of the system that were developed during the problem definition phase. This process is also referred to as ideation, or the creative process of producing concepts and ideas in order to meet system requirements. Concepts serve as the map from functions to form and require scoping and bounding in order to compose a list of feasible solutions for Sea Base force protection.

This study analyzed the threats to the Sea Base and determined the key functions associated with the protection of the Sea Base. From functional analysis and requirements generation, survivability was determined to be the primary measure of effectiveness of force protection. Survivability was further divided into the measures of susceptibility and vulnerability. Susceptibility is the ability of the system to prevent and defeat enemy attacks or actions, while vulnerability is the ability of the system to withstand the enemy attacks or actions. This functional hierarchy was applied to the three primary mission areas of air warfare, surface warfare, and undersea warfare and their respective threats from the Threat Analysis.

In order for any system to be successful in minimizing force susceptibility, it must adequately detect and defeat threats. If the system cannot detect and defeat the threats, it must limit its vulnerability, or be able to withstand the attack. There are numerous methods to detect, defeat, and withstand the threats.

From a very top-level view, detection was determined to include human intelligence (HUMINT), signal intelligence (SIGINT), imagery, and field detection. SIGINT includes communication intelligence and electronic intelligence. Imagery includes electro-optical (EO), infrared (IR), ultraviolet (UV), radar, lidar, sonar, synthetic aperture radar (SAR), and inverse synthetic aperture radar (ISAR). Field detection includes magnetic anomaly detection (MAD) or quantum effects.

The force protection function of defeating the threat was divided into two categories: destruction of the threat and distraction of the threat. Destruction of the threat included any means that provided for the physical defeat (i.e., hard kill) of the threat and included both kinetic and directed energy weapons. Distraction was determined to be the prevention of a successful attack by the threat (i.e., soft kill) after the attack has commenced. Distraction could be accomplished through any number of means including decoys, chaff, flares, signature management, and countermeasures (electronic, infrared, acoustic).

If the system were unable to defeat or prevent the attack, it must be able to withstand the intended effect of the threat. The primary means of withstanding attacks consist of redundancy of vital systems, compartmentalization, armor (to include reactive and reflective), and inherent resiliency of systems (easily restored).

Finally, this study determined a myriad of platforms from which to deploy or operate the desired functionality. These platforms could include aircraft, aerostats, ships, shore-based facilities, submarines, unmanned underwater vehicles (UUV), unmanned aerial vehicles (UAV), unmanned surface vehicles (USV), and satellites.

Through subject matter expert brainstorming sessions and unclassified research, the study produced a number of means to accomplish the desired force protection functions. These methods, or means, are best displayed graphically, divided by function. Table V-1 illustrates some of the possible means of accomplishing the desired functions.

DETECT	**DEFEAT**	**PREVENT**	**WITHSTAND**	**DEPLOY**
Radar	Missile	Chaff	Armor	Ship
Lidar	Gun	Flare	Reactive Armor	Aircraft
IR	Laser	Decoys	Reflective Armor	UAV
EO	Microwave	Maneuver	Redundant Vital Systems	Aerostat
UV	Acoustic	Electronic Countermeasures	Quality Construction	Satellite
SAR/ISAR		IR Countermeasures		Submarine
Hyperspectral		Acoustic Countermeasures		UUV
Sonar		Signature Management		Shore
Seismic				

Table V-1 Function to Form

In order to continue the process of ideation, a morphological chart was developed to represent possible concepts to investigate further (see Table V-2). The morphological chart was used to scope and bound the concepts for further research and analysis. This iterative process of scoping and bounding is detailed in the following Sensor, Search, and Weapons Analysis sections.

DETECT	DEFEAT	PREVENT	WITHSTAND	DEPLOY
Radar	**Missile**	Chaff	**Armor**	**Ship**
Lidar	**Gun**	Flare	Reactive Armor	Aircraft
IR	**Laser**	Decoys	Reflective Armor	**UAV**
EO	Microwave	Maneuver	**Redundant Vital Systems**	**Aerostat**
UV	Acoustic	**Electronic Countermeasures**	Quality Construction	Satellite
SAR/ISAR		**IR Countermeasures**		Submarine
Hyperspectral		**Acoustic Countermeasures**		**UUV**
Sonar		Signature Management		Shore
Seismic				

Table V-2 Morphological Chart

Ultimately, the SEA-4 Team endeavored to construct a force protection architecture that would meet the needs, wants, desires, and requirements of this study's stakeholders. The transformation of force protection functions into various forms was accomplished through detailed deterministic modeling. The SEA-4 Team was able to screen the alternatives laid out in Table V-2 by establishing suitable threat-sensor pairs, sensor-platform pairs, and the appropriate weapons with which to accomplish the goal of increasing force survivability. Insights and enhancements to this architecture were made, or drawn from a myriad of supporting studies reviewed or coordinated by the SEA-4 Team. These supporting studies provided the means by which to fill resource gaps. The conclusion of this chapter combines the deterministic models and the supporting studies in order to propose and outline two overarching force protection architectures that a future Sea Base might employ while conducting forced entry amphibious operations.

B. SENSOR ANALYSIS

1. Introduction

The Threat Document identified certain "baseline" future representative threats that will pose considerable challenges to Sea Basing assets in the 2016 timeframe. The "Future" sections of the Threat Document displayed several capabilities and characteristics of each identified threat platform or threat weapon. An important part of effectively countering these threat platforms and weapons is the ability to detect them. For these reasons, this study assessed the ability of various sensors (radar, lidar, IR, and sonar) to detect threats as a critical first step in defending the Sea Base and its associated transport assets. A general approach, using first principle equations is used to ensure an unclassified discussion and an inclusive threat matrix. Where possible, the results obtained by this study were verified using open source documents. This chapter will outline the preliminary analysis completed regarding the sensors studied, the methodology employed, and equations used to derive the values displayed in the Sensor Analysis, as well as the Threat Document.

2. Preliminary Analysis

a. Conventional Radar

This study modeled conventional microwave radar, and focused on two frequencies (3 GHz and 20 GHz) in order to determine detection ranges and cross sections of the future representative threats. These two frequencies were chosen because they represent typical air search or surface search frequencies possessing relative extremes with respect to beam spread and resolution; furthermore, these two frequencies are not susceptible to significant atmospheric attenuation. It is readily apparent that viewing the target's broadside, (90° target angle) and using a higher frequency presents a much larger radar cross section for many targets and therefore allows for a greater detection range. It is also important to note that, in many cases, the radar is limited by its line of sight. These facts support the use of a greater height of eye for radar. A higher sensor can, in many circumstances, obtain a greater radar cross section through an increased look angle, while simultaneously extending the radar horizon.

However, if a greater height of eye is achieved through the use of an aircraft, UAV, aerostat, or satellite, two key attributes of the radar system—power and antenna size—will most likely change as well. By placing radar on an airborne asset, one could expect the radar to have a reduced capacity for power generation and a reduced antenna size, thus lowering the radar's capability to detect and range various targets. These trade-offs are considered in the Sensor and Search Analysis sections and were critical in determining this study's conceptual force protection architecture.

b. Lidar

This study's laser radar model concentrated on one wavelength (10 μm) in order to determine detection ranges and cross sections of the future representative threats. This wavelength was chosen based on the limited unclassified information available to this study. It is apparent that lidar does not provide very good detection ranges. Because of its small wavelength, various aspects of the target are largely irrelevant in determining the detection range. Furthermore, lidar is largely affected by target reflectivity and shows a much reduced detection range against targets with low reflectivity (i.e., low observable targets). The poor detection ranges can also be largely attributed to atmospheric attenuation. If lidar were to be used as an area detection sensor, it should be used as a part of an extensive distributed network in order to obtain reasonable detection probabilities (see Search Analysis). Though capable of measuring chemical concentrations and compositions of remote targets (i.e., target exhaust) at extended ranges, for the purposes of this unclassified study, that option was not explored, and therefore, lidar was considered better suited for target identification and tracking rather than search applications. Used in conjunction with another system to initially assist in directing it, lidar's capability to discriminate and track targets could prove quite useful to a cooperative sensor network.

c. IR

This study modeled the infrared search and track system by concentrating on two ranges of wavelengths (3-5 μm and 8-12 μm) in order to determine detection ranges and cross sections of the future representative threats. These wavelength bands were chosen because of the relatively low attenuation characteristics when compared to other IR frequencies. Initial results show that IR systems do not perform, as well as radar when considering detection range; however, IR is a passive sensor and therefore greatly reduces the chance of counter-detection by the enemy. Furthermore, IR systems can be used as a cueing sensor for active systems and can be used themselves to determine ranges and track targets through triangulation. Viewing the targets' broadside gives the IR system a much greater projected area and associated greater detection range. The height of eye limitations are not as great as those associated with the radar systems, but a slightly greater height of eye would prove beneficial against some of the threats.

For these reasons, once again, IR systems should be considered for use as part of an elevated and cooperative sensor network.

d. Sonar

The last sensor this study considered with regard to detecting the future representative threats identified in the Threat Document was sonar. Both active and passive sonar were modeled. This study concentrated on three frequencies, 1 kHz, 25 kHz, and 56 kHz, in order to determine detection ranges. These frequencies were based on the unclassified information available to this study. Initial active sonar findings indicate that lower frequencies tend to propagate with less attenuation at extended ranges and are therefore more effective at detecting larger targets at longer ranges. Because of many threats' small aspects when viewed from small target angles, higher sonar frequencies appear to be more effective at target detection at short ranges. Above 25 kHz, however, greater attenuation appears to overcome the benefits of the additional target strength associated with greater frequencies. Developing or employing a lower frequency distributed sonar system that can search the underwater battle space may prove beneficial to the force protection mission.

Initial passive sonar results demonstrate that passive sonar may not be a particularly effective detection sensor against several of the threats when used in an area of heavy shipping. Furthermore, passive sonar does not provide good detection results against submarines or slower moving vessels when used in an area of moderate shipping. Because it is a passive sensor, two or more should be used in conjunction to achieve reasonable detection probabilities (see Search Analysis), as well as determine the target's range. For these reasons, passive sonar may be used with greater results when distributed throughout the operating area.

3. Methodology

This study first considered what sensors the Sea Base in the 2016 timeframe would most likely employ against the stated future representative threats. Radar, lidar, IR, active, and passive sonar were all considered. Next, this study employed the Systems Engineering Process to determine what sensors could reasonably detect which threat platform or weapon. Brainstorming, functional decomposition, and expert opinion were some of the tools used to develop the following threat-sensor pairs displayed in Table V-3.

THREAT	ASSOCIATED SENSOR
Anti-Ship Cruise Missile (ASCM)	Radar, Lidar, IR
Surface-to-Air Missile (SAM)	Radar, Lidar, IR
Aircraft / Unmanned Aerial Vehicle (ACFT / UAV)	Radar, Lidar, IR
Unguided Weapon (DW)	Radar, Lidar, IR
Small Boat (SB)	Radar, Lidar, IR, Active Sonar, Passive Sonar
Submarine (SUB)	Active Sonar, Passive Sonar
Torpedo (TORP)	Active Sonar, Passive Sonar
Mine (MINE)	Active Sonar

Table V-3 Threats and Associated Sensors

From these initial pairings, and by making several assumptions with respect to the threats themselves and the environments in which they function, this study was able to begin the sensor-modeling phase of the analysis. Applying these assumptions, certain characteristics of the threat platforms or weapons such as radar cross section (RCS), radiant exitance, projected area, and sonar source level (SL) were then calculated, or in some cases, obtained from open source references. These results, as well as other sensor system characteristics, were then used as inputs into mathematical spreadsheet sensor models for each sensor.

Next, this study concentrated on the future representative threats and how their shapes should be represented and modeled within the mathematical spreadsheets. In order to simplify many of the calculations, the threats (MINE, TORP, SUB, SB, ASCM, ACFT, and DW) were assumed to have basic shapes in the forms of flat plates, cylinders, or spheres. These shapes were often used in conjunction with each other in order to “build” a threat. Of course, the threats' shape changes with the target look angle; therefore, this study looked at the two extreme angles a target might present itself to a sensor: 0^o (nose-on) and 90^o (broadside). Drawing from the threat-sensor pairs listed in Table V-3, this study then applied these shapes (specifically, the associated formulas used to calculate their surface areas) to the various mathematical models. In only two cases (SB 2 and 3) were different shapes used to represent the same threat to different sensors. SB 2 and 3 were modeled using flat plates in the radar, lidar, and IR models and were then modeled using a spherical bow and cylindrical body in the sonar model. (Note: In this case (SB and sonar), the SB shapes were assumed to be half of a sphere and cylinder because only part of the shape was below the waterline.)

Though these shapes are rather simplistic, RCS results from the mathematical models, when compared to other open source RCS figures, demonstrate that they are reasonable, conservative, and thus appropriate for use as a gross level look at the effects each future representative threat may have on various sensor suites. The assumptions were also briefed to, and approved by, this study's stakeholders. Figure V-1 shows the various shapes used to model the future representative threats for a specific sensor.

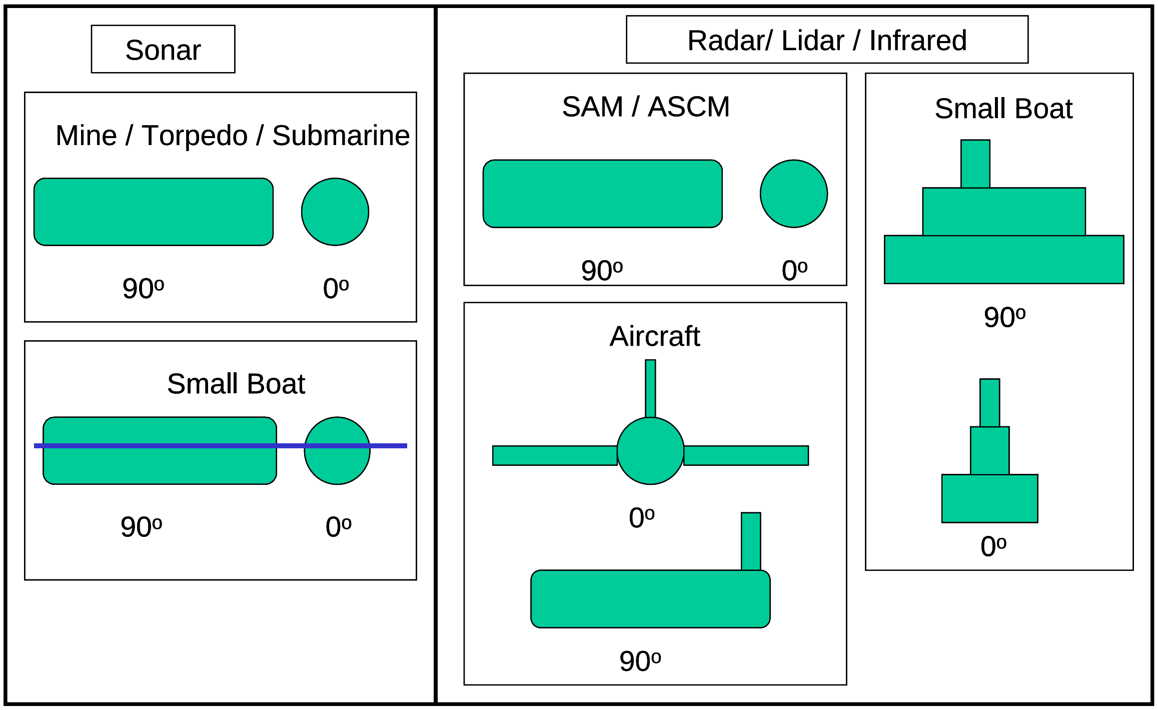


Figure V-1 Threat Shapes

Additional assumptions regarding threat characteristics were then made in order to continue with the modeling process; specifically, target reflectivity (π), emissivity (ε), and radiated noise levels (NL) (NL to be discussed later). These assumptions were determined from various open source materials such as online articles, Principles of Underwater Sound, and Combat Systems Vol. 2: Sensor Elements. The low reflectivity assumptions drive this study's mathematical sensor models to "perform" at higher levels in order to achieve the required probabilities of detection. This study, along with its stakeholders, views the assumptions and basic approach as reasonable, conservative, and appropriate. The extremely low reflectivity assumption for ACFT-3/4 relates to the "stealth" characteristics that a future adversary would be expected to possess by the 2016 timeframe. Table V-4 summarizes the assumed shapes, sensor modeled, and values of reflectivity and emissivity for each threat.

THREAT / PLATFORM	SENSOR MODELED	SHAPE	REFLECTIVITY	EMISSIVITY
MINE-1 / 2 / 3 / 4	Sonar	Spherical Nose Cylindrical Body	0.1	N/A*
TORP-1 / 2 / 3	Sonar	Spherical Nose Cylindrical Body	0.1	N/A*
SB-1	Radar, Lidar, IR	Spherical Bow Cylindrical Body	0.1	0.9
	Sonar		1.0	N/A*
SB-2 / 3	Radar, Lidar, IR	Flat Plates	0.1	0.9
	Sonar	Spherical Bow Cylindrical Body	1.0	N/A*
ASCM-1 / 2 / 3	Radar, Lidar, IR	Spherical Nose Cylindrical Body	0.1	0.9
ACFT-1 / 2	Radar, Lidar, IR	Spherical Nose Cylindrical Fuselage Flat Plate Wings / Tails / Rotors	0.1	0.9
ACFT-3 / 4	Radar, Lidar, IR	Spherical Nose Cylindrical Fuselage Flat Plate Wings / Tails / Rotors	0.0001	0.9999
SAM-1 / 2	Radar, Lidar, IR	Spherical Nose Cylindrical Body	0.1	0.9
DW-1	Radar, Lidar, IR	Spherical Nose Cylindrical Body	0.1	0.9
DW-2 / 3	Radar, Lidar, IR	Spherical Nose Cylindrical Body	0.7	0.3

*Not Applicable.

Table V-4 Threat Characteristic Assumptions Applied to Sensor Models

Finally, this study considered several other critical assumptions regarding such things as the environment, and additional sensor physical characteristics. This led to assumptions regarding attenuation coefficients, radiation propagation characteristics, sensor aperture diameter, power output, system frequency, physical location on larger platforms, and required carrier to noise ratios (CNR) a sensor would need in order to achieve reasonable probability of detection thresholds, etc. These assumptions will be covered in greater detail in the following section, as it describes the governing equations used to represent both the threats and the sensor, and results of those calculations.

4. Modeling Equations and Results

a. Radar

This study used the following radar range equation to model its microwave radar sensor:

Equation (1) $$R = \left[\frac{\pi P_T D^4 \sigma}{64\lambda^2 kTBF(CNR)}\right]^{1/4}$$ where:

R = Range (km)
P_T = Power (W)
D = Antenna Diameter (m)
σ = Target Cross Section (m^2)
λ = Radar Wavelength (m)
k = Boltzmann's Constant (J/K)
T = Ambient Temperature (K)
B = Radar Bandwidth (Hz)
F = Radar Noise Figure
CNR = Sensor Required Carrier-to-Noise Ratio (linear)

All of the variables within the radar range equation can be changed with the exception of Boltzmann's Constant. Through careful research, this study made the following assumptions with regards to the values for the variables associated with the radar range equation:

P_T = 3 MW
D = 2 m
σ = Varies based on target (explained in greater detail below)
λ = Varies based on frequency (3 GHz and 20 GHz frequencies studied)
$k = 1.38 \times 10^{-23}$ J/K
T = 300 K
B = 100 MHz
F = 1
CNR = 200 (23 dB)

Before calculating the range at which microwave radar might detect the various future representative threats, the RCS for each target had to be calculated. The RCS of the various threats is dependent on the target's shape, size, reflectivity, and for certain observed angles, the wavelength of the radar used against it. As mentioned earlier, two target angles (0^o (nose-on) and 90^o (broadside)) were considered for each threat input to the radar model, and the resulting target RCSs (listed in Table V-5) were calculated using Equations (1) through (6).

- ASCM-1/2/3, SAM-1/2, DW-1/2/3, SB-1

Equation (2) $$\sigma = (\pi r^2 \rho)(\cos\Theta) + \left[\frac{2\pi r l^2 \rho}{\lambda}\right](\sin\Theta) \text{ where:}$$

ρ = Target Reflectivity (See Table V-4)
Θ = Target Angle (radians) (0^o and 90^o)
r = Target Radius (m) (See Threat Document for Dimensions)
l = Target Length (m) (See Threat Document for Dimensions)
λ = Wavelength (μm) (Based on 3 GHz and 20 GHz radar frequencies)

- ACFT-1

Equation (3) $$\sigma = \left[\frac{4\pi A^2 \rho}{\lambda^2}\right] + (\pi r^2 \rho)(\cos\Theta) + \left[\frac{2\pi r l^2 \rho}{\lambda}\right](\sin\Theta) \text{ where:}$$

ρ = Target Reflectivity (See Table V-4)
Θ = Target Angle (radians) (0^o and 90^o)
r = Target Radius (m) (See Threat Document for Dimensions)
l = Target Length (m) (See Threat Document for Dimensions)
λ = Wavelength (μm) (Based on 3 GHz and 20 GHz radar frequencies)
A = Target Surface Area of Rotor Blades (m^2) (See Threat Document for Dimensions)

- ACFT-2

Equation (4) $$\sigma = \left[\frac{4\pi A_1^2 \rho}{\lambda^2} + \pi r^2 \rho\right](\cos\Theta) + \left[\frac{2\pi r l^2 \rho}{\lambda} + \frac{4\pi A_2^2 \rho}{\lambda^2}\right](\sin\Theta) \text{ where:}$$

ρ = Target Reflectivity (See Table V-4)
Θ = Target Angle (radians) (0^o and 90^o)
r = Target Radius (m) (See Threat Document for Dimensions)
l = Target Length (m) (See Threat Document for Dimensions)
λ = Wavelength (μm) (Based on 3 GHz and 20 GHz radar frequencies)
A_1 = Target Surface Area of Wings (m^2) (See Threat Document for Dimensions)
A_2 = Target Surface Area of Tail (m^2) (See Threat Document for Dimensions)

- ACFT-3, UAV/UCAV-1

Equation (5) $$\sigma = \left[\frac{4\pi A_1^2 \rho}{\lambda^2} + \pi r^2 \rho\right](\cos\Theta) + \left[\frac{2\pi r l^2 \rho}{\lambda}\right](\sin\Theta) \text{ where:}$$

ρ = Target Reflectivity (See Table V-4)
Θ = Target Angle (radians) (0^o and 90^o)
r = Target Radius (m) (See Threat Document for Dimensions)
l = Target Length (m) (See Threat Document for Dimensions)
λ = Wavelength (μm) (Based on 3 GHz and 20 GHz radar frequencies)
A_1 = Target Surface Area of Wings (m^2) (See Threat Document for Dimensions)

- SB-2, SB-3

Equation (6)

$$\sigma = \left[\frac{4\pi A_1{}^2\rho}{\lambda^2}+\frac{4\pi A_2{}^2\rho}{\lambda^2}+\frac{4\pi A_3{}^2\rho}{\lambda^2}\right](\cos\Theta)+\left[\frac{4\pi A_1{}^2\rho}{\lambda^2}+\frac{4\pi A_2{}^2\rho}{\lambda^2}+\frac{4\pi A_3{}^2\rho}{\lambda^2}\right](\sin\Theta)$$

where:

ρ = Target Reflectivity (See Table V-4)
Θ = Target Angle (radians) (0^o and 90^o)
λ = Wavelength (μm) (Based on 3 GHz and 20 GHz radar frequencies)
A_1 = Target Surface Area of Freeboard (m^2) (See Threat Document for Dimensions)
A_2 = Target Surface Area of Superstructure (m^2) (See Threat Document for Dimensions)
A_3 = Target Surface Area of Mast (m^2) (See Threat Document for Dimensions)

Threat	RCS (m^2) Tgt Angle: 0^o f = 3 GHz	RCS (m^2) Tgt Angle: 0^o f = 20 GHz	RCS (m^2) Tgt Angle: 90^o f = 3 GHz	RCS (m^2) Tgt Angle: 90^o f = 20 GHz
ASCM-1	.0138	.0138	18.5	124
ASCM-2	.0352	.0352	167	1110
ASCM-3	.0664	.0664	389	2590
SAM-1	.0159	.0159	69.2	462
SAM-2	.000785	.000785	.707	4.71
ACFT-1	92.3	4050	2920	22900
ACFT-2	165	7260	4920	51800
ACFT-3	.0847	3.71	4.92	32.8
UAV-1	.065	2.88	.402	2.68
DW-1	.00405	.00405	11.4	76
DW-2	.000879	.000879	.00141	.00938
DW-3	.0000319	.0000319	.000255	.0017
SB-1	.0583	.0583	17.8	119
SB-2	2630	117000	11100	494000
SB-3	5490	244000	40400	1790000

Table V-5 Calculated Threat Radar Cross Sections

Using the radar cross sections listed in Table V-5, maximum radar detection ranges were then calculated by using the radar range equation (Equation (1)). However, the performance based radar detection ranges calculated from the radar range equation are not the actual ranges that could always be expected. These ranges represent the maximum performance range of the radar and does not account for horizon limitations. Therefore, in order to obtain more realistic radar detection ranges, this study determined the horizon limit for each target based on target height or assumed target altitude, with an assumed radar sensor height of 10 meters. The set of equations used to determine the radar horizon are as follows:

Equation (7) $L_{Obs} = 4.122(\sqrt{H})$ where:

L_{Obs} = Radar Line of Sight (km)
H = Sensor Height of Eye (m)

Equation (8) $L_{Total} = L_{Tgt} + L_{Obs}$ where:

L_{Total} = Total Line of Sight (km)
L_{Tgt} = Target Line of Sight (km)
L_{Obs} = Radar Line of Sight (km)

These ranges were then compared to the maximum performance ranges calculated using the radar range equation for a 3 GHz and 20 GHz microwave radar system, and are displayed in Table V-6.

Threat (Altitude)	Range (km) Tgt Angle: 0^{o} f = 3 GHz	Range (km) Tgt Angle: 0^{o} f = 20 GHz	Range (km) Tgt Angle: 90^{o} f = 3 GHz	Range (km) Tgt Angle: 90^{o} f = 20 GHz	Horizon Limit (km) 10 m height
ASCM-1 (3 m)	14.1	36.4	85.3	353.8	20.2
ASCM-2 (5 m)	17.8	45.6	147.6	612.5	22.3
ASCM-3 (24 km)	20.9	53.9	182.5	757	651.6
SAM-1 5000 m	14.6	37.7	118.5	491.8	304.5
SAM-2 (5000 m)	6.9	17.8	37.7	156.3	304.5
ACFT-1 (10 m)	127.4	846.3	302	1305	26.1
ACFT-2 (5000 m)	147.3	979.3	344.1	1600	304.5
ACFT-3 (10 m)	22.2	147.3	61.2	253.9	26.1
UAV-1 (10 m)	20.7	138.2	32.7	135.8	26.1
DW-1 (2000 m)	10.4	26.8	75.5	313.3	197.4
DW-2 (1 m)	7.1	18.3	7.9	33	17.2
DW-3 (1 m)	3.1	7.9	5.2	21.5	17.2
SB-1 (0 m)	20.2	52.1	84.4	350	13
SB-2 (0 m)	294.4	1962.5	421.9	2812.9	13
SB-3 (0 m)	353.7	2357.9	582.5	3883.4	13

Table V-6 Radar Detection Ranges

It can be seen that broadside target angles and higher frequency radars present a much larger radar cross section for many targets and therefore allow for greater detection ranges. However, it is also important to note that, in many cases, the radar will be limited by its line of sight to the target. By elevating the radar, in many circumstances larger radar cross-sections, and thus longer detection ranges, can be obtained. By elevating the radar, it now has the ability to see (in most cases) more of the target due to the change in geometry. Figure V-2 displays this basic concept. Increased elevation of the radar increases the look angle, the radar horizon, and in many cases, the targets' RCS.

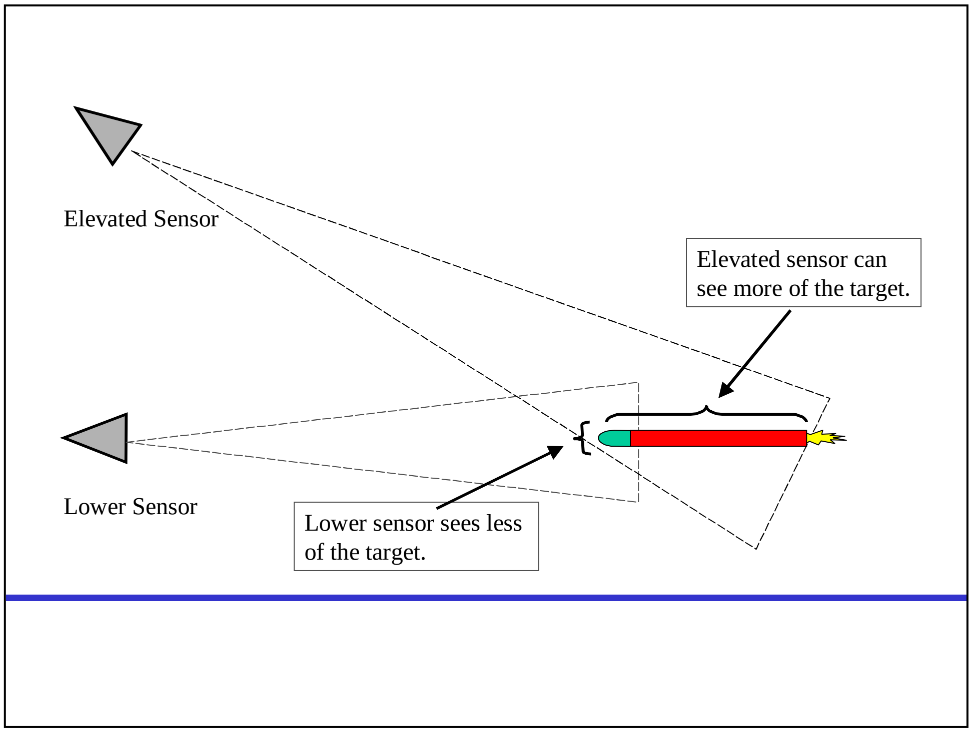


Figure V-2 Sensor Change in Elevation and Resulting Difference in Target Aspect

However, if the greater height of eye is achieved through the use of an aircraft, aerostat, or satellite, two key attributes—power and antenna size—of a conceptual radar system will most likely change as well. An airborne radar will most likely have a reduced capacity for power generation and a reduced antenna size. Taking this into account, the following assumptions were made with respect to the power output and antenna diameter of a conceptual airborne sensor:

$P_T = 500$ kW
$D = 1$ m

Substituting these values for the original assumed values and recalculating radar detection ranges and radar horizon limits based on the same target RCSs, and a sensor height of eye of 5000 meters, new detection ranges and horizon limits were derived and listed in Table V-7.

Threat (Altitude)	Range (km) Tgt Angle: 0 º f = 3 GHz	Range (km) Tgt Angle: 0 º f = 20 GHz	Range (km) Tgt Angle: 90 º f = 3 GHz	Range (km) Tgt Angle: 90 º f = 20 GHz	Horizon Limit (km) 5000 m height
ASCM-1 (3 m)	4.5	11.6	27.2	113	298.6
ASCM-2 (5 m)	5.7	14.7	47.2	195.7	300.7
ASCM-3 (24 km)	6.7	17.2	58.3	241.8	930
SAM-1 (5000 m)	4.7	12	37.9	157.1	582.9
SAM-2 (5000 m)	2.2	5.7	12	49.9	582.9
ACFT-1 (10 m)	40.7	270.4	96.5	416.9	304.5
ACFT-2 (5000 m)	47	312.9	109.9	511.3	582.9
ACFT-3 (10 m)	7.1	47.1	19.5	81.1	304.5
UAV-1 (10 m)	6.6	44.1	10.5	43.4	304.5
DW-1 (2000 m)	3.3	8.5	24.1	100.1	475.8
DW-2 (1 m)	2.3	5.8	2.5	10.6	295.6
DW-3 (1 m)	1	2.5	1.7	6.9	295.6
SB-1 (0 m)	6.5	16.7	27	111.8	291.5
SB-2 (0 m)	94	627	134.8	898.7	291.5
SB-3 (0 m)	113	753.3	186.1	1240.6	291.5

Table V-7 Airborne Radar Detection Ranges

b. Lidar

This study determined the range at which a lidar sensor could detect a threat through an assumed CNR requirement. A 10 dB CNR was assumed to be the required level a typical lidar sensor would need in order to achieve reasonable probability of detection levels. The lidar system modeled for this study was based on a heterodyne system and not a direct detection system. (Note: Probability of detection levels will be discussed further in the Search Analysis.) The lidar CNR equation used by this study is as follows:

Equation (9)

$$\text{CNR} = \frac{\eta m \varepsilon_T \varepsilon_R P e^{-2\alpha R^{\beta}}}{h\nu B}\left[\frac{\rho D^2}{MR^2}\right]\left[1 - e^{\frac{-\pi D^2 \sigma}{M\rho\lambda^2 R^2}}\right]$$

where:

CNR = Required Carrier to Noise Ratio
η = Quantum Efficiency
m = Heterodyne Mixing Efficiency
ε_T = Transmit Optical Efficiency
ε_R = Receive Optical Efficiency
P = Transmitter Laser Power (W)
λ = Laser Wavelength (m)
h = Planck's Constant (J-s)
v = Laser Frequency (Hz)
B = Noise Bandwidth (Hz)
w_0 = Laser Beam Waist (m)
M = Aperture-Beam Waist Matching Factor
D = Transceiver Aperture Diameter (m)
α = Atmospheric Extinction Coefficient (km^{-1})
r_T = Effective Target Radius (m) (See Threat Document)
ρ = Target Diffuse Reflectivity (See Table V-4)
σ = Target Cross Section (m^2) (Explained in greater detail below)
R = Target Detection Range (km)
β = Correction Factor

All of the variables within the lidar CNR equation can be changed, with the exception of Planck's Constant. The atmospheric extinction coefficient (α) and the associated correction factor (β) were obtained using the R384 meteorological database and are representative of the 95th percentile. Basically, the lidar sensor modeled by this study should be capable of operating at least 95% of the time anywhere in the world's maritime environment (Harney, 2002, Vol. I, Part I, 93). These figures were deemed conservative, reasonable, and appropriate for use by this study and its stakeholders. Through careful research, this study made the following assumptions with regards to the values for the variables associated with the lidar CNR equation:

CNR = 10 (10 dB)
η = .7
m = .9
ε_T = .8
ε_R = .4
P = 3 MW
λ = 10 μm
h = 6.62607876^{-34} J-s
v = 3x10^{13} Hz
B = 100,000 Hz
w_0 = .894 m
M = 5
D = 2 m
α = .72255 (km^{-1})
r_T = Varies based on target (m) (See Threat Document for Dimensions)
ρ = Target Diffuse Reflectivity (See Table V-4, same as used in radar section)
σ = Target Cross Section (m^2) (Calculated using the same target cross section formulas used in the radar section.)
β = .92409

As with radar, this study first had to determine target cross sectional areas prior to determining the ranges at which a lidar might detect the various future representative threats. Again, target angles of 0^o (nose-on) and 90^o (broadside) were considered. Using the above assumptions, and the same equations (Equations (2-6)) used to determine RCS in the radar section, target cross sections were determined for the lidar system and are listed in Table V-8.

Threat	**Cross Section (m^2) Tgt Angle: 0° f = 30 THz**	**Cross Section (m^2) Tgt Angle: 90° f = 30 THz**
ASCM-1	.0138	$1.85\text{x}10^5$
ASCM-2	.0352	$1.67\text{x}10^6$
ASCM-3	.0664	$3.89\text{x}10^6$
SAM-1	.0159	$6.92\text{x}10^5$
SAM-2	.00785	7060
ACFT-1	$9.11\text{x}10^9$	$9.13\text{x}10^9$
ACFT-2	$1.63\text{x}10^{10}$	$5.03\text{x}10^{10}$
ACFT-3	$8.35\text{x}10^6$	55,800
UAV-1	$6.47\text{x}10^6$	9170
DW-1	.00405	$1.14\text{x}10^5$
DW-2	.000879	14.1
DW-3	.0000319	2.55
SB-1	.0583	$1.78\text{x}10^5$
SB-2	$2.63\text{x}10^{11}$	$1.11\text{x}10^{12}$
SB-3	$5.49\text{x}10^{11}$	$4.04\text{x}10^{12}$

Table V-8 Lidar Threat Cross Sections

Using the calculated lidar threat cross sections listed in Table V-8, maximum lidar detection ranges were then calculated by using the lidar CNR equation (Equation (9)). Again, as in radar, lidar detection ranges calculated from Equation (9) indicate lidar's maximum performance range, and do not take into account horizon effects on the system. In order to obtain more realistic lidar detection ranges, the horizon limit was determined for each target based on target height or assumed target altitude, with an assumed radar sensor height of 10 meters, and used the following set of equations to determine the lidar horizon:

Equation (10) $L_{Obs} = 3.839(\sqrt{H})$ where:

L_{Obs} = Radar Line of Sight (km)
H = Sensor Height of Eye (m)

Equation (11) $L_{Total} = L_{Tgt} + L_{Obs}$ where:

L_{Total} = Total Radar Line of Sight (km)
L_{Tgt} = Target Line of Sight (km)
L_{Obs} = L = Radar Line of Sight (km)

These ranges were then compared to the maximum performance ranges calculated using the lidar CNR equation for a 30 THz lidar system, and are displayed in Table V-9.

Threat (Altitude)	Range (km) Tgt Angle: 0° f = 30 THz	Range (km) Tgt Angle: 90° f = 30 THz	Horizon Limit (km) 10 m height
ASCM-1 3 m	9.8	9.8	18.8
ASCM-2 5 m	9.8	9.8	20.7
ASCM-3 24 km	9.8	9.8	606.9
SAM-1 5000 m	9.8	9.8	283.6
SAM-2 5000 m	9.7	9.8	283.6
ACFT-1 10 m	9.8	9.8	24.3
ACFT-2 5000 m	9.8	9.8	283.6
ACFT-3 10 m	4.9	4.9	24.3
UAV-1 10 m	4.9	4.9	24.3
DW-1 2000 m	9.8	9.8	183.8
DW-2 1 m	10.2	11.2	16
DW-3 1 m	8.2	11.2	16
SB-1 0 m	9.8	9.8	12.1
SB-2 0 m	9.8	9.8	12.1
SB-3 0 m	9.8	9.8	12.1

Table V-9 Lidar Detection Ranges

The results demonstrate that lidar does not provide very good detection ranges. Because of its small wavelength, even larger target aspects are fundamentally irrelevant in determining the detection range. Furthermore, lidar is largely affected by target reflectivity and shows a much reduced detection range capability against targets with low reflectivity (i.e., low observable targets). The poor detection ranges can also be largely attributed to atmospheric attenuation. Lidar, however, has proven effective in determining the chemical composition or concentration of remote targets (i.e., target exhaust) at extended ranges, but because of the unclassified nature of this study this option was not explored. Therefore, it was reasoned if lidar were to be used as an area detection sensor, it should be employed as a part of an extensive cooperative sensor network.

c. IR

An infrared sensor is passive, and detects and locates targets through the collection and processing of thermal radiation. Because it is a passive sensor, IR uses a target's emissive properties, rather than a target's reflective properties, to determine detection ranges. Therefore, a target's projected area (analogous to RCS in radar and target cross section in lidar) is not dependent on system wavelength. However, as in the radar and lidar cases, the projected area is affected by target angle. Once again, target angles of 0° (nose-on) and 90° (broadside) were used. The future representative threat's projected areas were calculated using the following equations and are listed in Table V-10.

- ASCM-1/2/3, SAM-1/2, DW-1/2/3, SB-1

Equation (12) $A_{Proj} = (\pi r^2 \varepsilon)(\cos\Theta) + (\pi r l \varepsilon)(\sin\Theta)$ where:

A_{Proj} = IR Projected Area (m^2)
ε = Target Emissivity (See Table V-4)
Θ = Target Angle (radians) (0^o and 90^o)
r = Target Radius (m) (See Threat Document for Dimensions)
l = Target Length (m) (See Threat Document for Dimensions)

- ACFT-1

Equation (13) $A_{Proj} = (A\varepsilon) + (\pi r^2 \varepsilon)(\cos\Theta) + (\pi r l \varepsilon)(\sin\Theta)$ where:

A_{Proj} = IR Projected Area (m^2)
ε = Target Emissivity (See Table V-4)
Θ = Target Angle (radians) (0^o and 90^o)
r = Target Radius (m) (See Threat Document for Dimensions)
l = Target Length (m) (See Threat Document for Dimensions)
A = Target Surface Area of Rotor Blades (m^2) (See Threat Document for Dimensions)

- ACFT-2

Equation (14) $A_{Proj} = (A_1\varepsilon + \pi r^2\varepsilon)(\cos\Theta) + (\pi rl\varepsilon + A_2\varepsilon)(\sin\Theta)$ where:

A_{Proj} = IR Projected Area (m^2)
ε = Target Emissivity (See Table V-4)
Θ = Target Angle (radians) (0^o and 90^o)
r = Target Radius (m) (See Threat Document for Dimensions)
l = Target Length (m) (See Threat Document for Dimensions)
A_1 = Target Surface Area of Wings (m^2) (See Threat Document for Dimensions)
A_2 = Target Surface Area of Tail (m^2) (See Threat Document for Dimensions)

- ACFT-3, UAV/UCAV-1

Equation (15) $A_{Proj} = (A_1\varepsilon + \pi r^2\varepsilon)(\cos\Theta) + (\pi rl\varepsilon)(\sin\Theta)$ where:

A_{Proj} = IR Projected Area (m^2)
ε = Target Emissivity (See Table V-4)
Θ = Target Angle (radians) (0^o and 90^o)
r = Target Radius (m) (See Threat Document for Dimensions)
l = Target Length (m) (See Threat Document for Dimensions)
A_1 = Target Surface Area of Wings (m^2) (See Threat Document for Dimensions)

- SB-2, SB-3

Equation (16) $A_{Proj} = (A_1\varepsilon + A_2\varepsilon + A_3\varepsilon)(\cos\Theta) + (A_1\varepsilon + A_2\varepsilon + A_3\varepsilon)(\sin\Theta)$ where:

A_{Proj} = IR Projected Area (m^2)
ε = Target Reflectivity (See Table V-4)
Θ = Target Angle (radians) (0^o and 90^o)
A_1 = Target Surface Area of Freeboard (m^2) (See Threat Document for Dimensions)
A_2 = Target Surface Area of Superstructure (m^2) (See Threat Document for Dimensions)
A_3 = Target Surface Area of Mast (m^2) (See Threat Document for Dimensions)

Threat	IR Projected Area (m^2) Tgt Angle: 0^o	IR Projected Area (m^2) Tgt Angle: 90^o
ASCM-1	.1246	2.2256
ASCM-2	.3171	8.426
ASCM-3	.598	15.08
SAM-1	.1431	4.4511
SAM-2	.0071	.212
ACFT-1	11.9565	85.4415
ACFT-2	16.5966	118.5042
ACFT-3	11.9992	121.1072
UAV-1	3.6546	25.1204
DW-1	.0364	1.283
DW-2	.0004	.0008
DW-3	.00001	.0001
SB-1	.6689	5.2514
SB-2	18.8755	79.665
SB-3	39.3293	289.3956

Table V-10 Threat IR Projected Areas

Using the IR projected areas listed in Table V-10; detection ranges were determined by calculating target incidance (M), target exitance (E), and noise equivalent power (NEP). The following equations to determine these variables:

Equation (17) $$M = \left(\frac{2\pi c^2 h}{\lambda^5}\right)\left(\frac{1}{e^{hc/\lambda kT} - 1}\right)$$ and

Equation (18) $$T = T_{ambient}(1 + 0.2(MachNumber)^2)$$ where:

M = Target Exitance (W/m^2-μm)
c = Speed of Light (m/s)
λ = Wavelength (μm)
h = Planck's Constant (J-s)
k = Boltzmann's Constant (J/K)
T = Target Body Temperature (K)
$T_{ambient}$ = Ambient Temperature (K)
$MachNumber$ = Threat Mach Number Derived from Maximum Velocity

Equation (19) $$E = \frac{A_{Proj} M \left(e^{-\alpha R^{\beta}}\right)}{\pi R^{2}}$$ where:

E = Target Incidance (W/m^2)
A_{Proj} = IR Projected Area (m^2)
M = Target Exitance (W/m^2- μm)
R = Target Range (m)
α = Atmospheric Extinction Coefficient (km^{-1})
β = Correction Factor

Equation (20) $$NEP = \frac{\sqrt{A_D B}}{D_{\lambda}^{*}}$$ where:

NEP = Noise Equivalent Power (W)
A_D = Sensor Element Size (μm)
B = Sensor Bandwidth (Hz)
$D*_{\lambda}$ = Specific Detectivity $(cm\sqrt{Hz}/W)$

All of the variables in the above equations can be changed, with the exception of Planck's Constant and Boltzmann's Constant. Through careful research, this study made the following assumptions with regards to the values for the variables associated with the target exitance, target incidance, and noise equivalent power equations:

c = 3 x 10^8 m/s
λ = 3-5 μm, 8-12 μm
h = 6.62607876^{-34} J-s
k = 1.380650x10-23 J/K
$T_{ambient}$ = 300 K
A_{Proj} = Varies with the threat (m^2) (See Table V-10)
M = Varies with the threat and wavelengths studied (W/m^2- μm)
(See below for further explanation)
α = .98757 km^{-1} (for 3-5 μm band) and
.72255 km^{-1} (for 8-12 μm band)
β = .69721 km^{-1} (for 3-5 μm band) and

.92409 km^{-1} (for 8-12 μm band)
$D*_\lambda$ = 9x10^{10} $cm\sqrt{Hz}/W$ (for 3-5 μm band) and
2.5x10^{10} $cm\sqrt{Hz}/W$ (for 8-12 μm band)
B = 10,000 Hz
A_D = 20 μm (for 3-5 μm band) and
30 μm (for 8-12 μm band)

Wavelength bands of 3-5 μm and 8-12 μm were chosen because the IR sensor data available is largely limited to these two major atmospheric windows. The atmospheric extinction coefficient (α) and the associated correction factor (β) were obtained through R384 meteorological data and are representative of the 95th percentile. Mercury cadmium telluride (HgCdTe(PV)) cooled to 77 K was chosen as the infrared detector material to be used in this IR sensor due to its higher specific detectivity qualities when compared to other detection materials such as Lead Sulfide (PbS), Lead Selenium (PbSe), or Indium Antimonide (InSb). The specific detectivity ($D*_\lambda$) values were obtained from the HgCdTe(PV) detectivity curves displayed in Professor Harney's text.

The NEP values were calculated to be: 2.222 x 10^{-12} W for the 3-5 μm band, and 1.2 x 10^{-11} W for the 8-12 μm band. The required target flux in order to obtain reasonable probabilities of detection was assumed to be 10 times greater than the calculated NEP. Next, the required target flux was compared with the total target exitance in order to determine the range at which the future representative threats could be detected. The target exitance was determined for each wavelength based on assumed target speeds or nominal operating temperatures of certain targets. Through the use of trapezoidal integration, the total target exitance was determined over the studied wavelength bands (3-5 μm and 8-12 μm). Just as in the radar and lidar cases, IR is also limited by the visual horizon. The set of equations used for determining the IR horizon are the same as those used to determine the lidar visual horizon (Equation (10) and Equation (11)). In order to obtain more realistic IR detection ranges, the horizon limit for each target was determined based on target height or assumed target altitude, with an assumed IR sensor height of 10 meters. The horizon limits for each target were then compared to the maximum performance range of the IR sensor and are listed in Table V-11.

Threat (Altitude)	**Range (km) Tgt Angle: 0°** λ **= 3-5μm**	**Range (km) Tgt Angle: 0°** λ **= 8-12μm**	**Range (km) Tgt Angle: 90°** λ **= 3-5μm**	**Range (km) Tgt Angle: 90°** λ **= 8-12μm**	**Horizon Limit (km) 10 m height**
ASCM-1 (3 m)	8	7.6	13.4	11.4	18.8
ASCM-2 (5 m)	20.1	11.6	29.7	16.4	20.7
ASCM-3 (24 km)	32.9	15.2	44.4	20.1	606.9
SAM-1 (5000 m)	29.5	13.4	41.3	18.6	283.6
SAM-2 (5000 m)	10.8	6.6	18.4	10.9	283.6
ACFT-1 (10 m)	13.9	12.8	18.5	15.6	24.3
ACFT-2 (5000 m)	15.5	13.5	20.4	16.4	283.6
ACFT-3 (10 m)	14.7	13	20.5	16.4	24.3
UAV-1 (10 m)	11.4	11.1	15.5	13.8	24.3
DW-1 (2000 m)	24.1	11.2	35.5	16.3	183.8
DW-2 (1 m)	1.7	2.1	2.1	2.6	16
DW-3 (1 m)	2.7	1.5	5	3	16
SB-1 (0 m)	8.2	8.9	12	11.6	12.1
SB-2 (0 m)	14.9	13.4	18.4	15.5	12.1
SB-3 (0 m)	16.6	14.5	21.8	17.5	12.1

Table V-11 IR Detection Ranges

These results indicate that IR systems do not perform, as well as radar when considering target detection range; however, IR is a passive sensor and therefore greatly reduces the chance of counter-detection by the enemy. IR systems might be used as a cueing sensor for active systems and can themselves be used for ranging and tracking applications through triangulation. Viewing the targets from broadside, as in the radar and lidar cases, gives the IR system a much greater projected area and associated greater detection range. The height of eye limitations are not as great as those associated with the radar systems, but a slightly greater height of eye would prove beneficial against some of the threats. For these reasons, IR systems should be considered for use as part of a distributed sensor network.

d. Active Sonar

This study used the following active sonar CNR equation, and associated equations to determine target detection ranges:

Equation (21) $DT = SL - 2TL + TS - (NL - DI)$ where:

DT = Detection Threshold (dB)
SL = Source Level (dB)
TL = Transmission Loss (dB)
TS = Target Strength (dBsm)
NL = Noise Level (dB)
DI = Directivity Index (dB)

Equation (22) $SL = 171.5 + 10 \log P$ where:

P = Source Power (W)

Equation (23) $TL = 20 \log R + \alpha R \times 10^{-3}$ where:

α = Total Absorption Coefficient (dB/kyd)
R = Range (yds)

Equation (24) $TS = 10 \log \sigma$ where:

σ = Effective Target Size (m^2)

Equation (25) Directivity Index (DI) = $10 \log N$

N = Number of Sonar elements

Before calculating sonar detection ranges, assumptions regarding seawater temperature (T), salinity (S), and noise levels at the various sonar frequencies were made. This study assumed the following values for each:

T = 25 C
S = 34 ppt
$NL_{1kHz} = 80$ dB
$NL_{25kHz} = 50$ dB
$NL_{56kHz} = 30$ dB

Using these assumed values, along with varying sonar frequencies (three were studied, 1 kHz, 25 kHz, and 56 kHz), and the depth (d) at which the threats operate (see Threat Document), the speed of sound in water was calculated using the following equation:

Equation (26) $$V_{Sound} = 1402.06 + 1.34\,(S) - 0.01025\,(S)(T) + 4.95\,(T) - 0.05304\,(T^2) + 2.374 \times 10^{-4}\,(T^3) + 0.0163\,(d) + 1.675 \times 10^{-7}\,(d^2) - 7.139 \times 10^{-13}\,(T)(d^3)$$

Next, the effective target size was calculated using the following equation:

Equation (27) $$\sigma = \rho\left[\frac{r^2}{4}(\cos\Theta) + \frac{2\pi r l^2}{\lambda 4\pi}(\sin\Theta)\right]$$ where:

σ = Effective Target Size (m^2)
ρ = Target Reflectivity (See Table V-4)
r = Target Radius (m) (See Threat Document)
l = Target Length (m) (See Threat Document)
Θ = Target Angle (radians) (0^o and 90^o)
λ = Sonar Wavelength (m)

Sonar TS of the various threats were then calculated using Equation (24) and the previously calculated effective target size, and are listed in Table V-12.

Threat	**TS* (dBsm)** **Tgt Angle: 0°**	**TS (dBsm)** **Tgt Angle: 90°** **f = 1 kHz**	**TS (dBsm)** **Tgt Angle: 90°** **f = 25 kHz**	**TS (dBsm)** **Tgt Angle: 90°** **f = 56 kHz**
SUB-1	-2.82	29.04	43.02	46.52
SUB-2	-1.24	33.36	47.35	50.84
SUB-3	-15.46	11.51	25.49	28.99
SB-1	-2.34	10.64	24.62	28.13
SB-2	7.98	34.08	48.06	51.56
SB-3	14	44.39	58.37	61.87
Mine-1	-22.82	-25.06	-11.08	-7.58
Mine-2	-26.34	-15.54	-1.56	1.94
Mine-3	-20.32	-16.46	-2.48	1.02
Mine-4	-28.84	-15.35	-1.37	2.14
Torp-1	-27.5	-2.63	11.35	14.86
Torp-2	-27.5	-2.63	11.35	14.86
Torp-3	-35.88	-12.84	1.14	4.64

*TS values for nose-on aspect are not sensor wavelength dependent.

Table V-12 Threat Target Strengths

In order to determine the TL, the total absorption coefficient (α) was then calculated using the following formulas:

Equation (28) $f_T = 21.9 \times 10^{6\left(\frac{-1520}{T+273}\right)}$ where:

f_T = Temperature Dependent Relaxation Frequency (kHz)
T = Seawater Temperature (C)

Equation (29) $\alpha_0 = 1.86\times10^{-2}\left[\frac{Sf_T f^2}{f_T + f^2}\right] + 2.68\times10^{-2}\left[\frac{f^2}{f_T}\right]$ where:

α_0 = Environmental Absorption Coefficient (dB/kyd)
S = Salinity (ppt)
f = Sonar Frequency (kHz)
f_T = Temperature Dependent Relaxation Frequency (kHz)

Equation (30) $\alpha = \alpha_0 (1 - 1.93 \text{ x } 10^{-5} \text{ d})$ where:

α = Total Absorption Coefficient (dB/kyd)
α_0 = Environmental Absorption Coefficient (dB/kyd)
d = Target Depth (ft)

This study then used the 14 dB sonar receiver operating characteristics curve to determine the desired detection threshold (DT) for active sonar (see Equation (31)). A 10-second integration time was assumed to be reasonable if the sonar system employed a matched filter receiver and with a known transmitted signal.

Equation (31) $\text{DT} = 10\log\left[\frac{25.11886}{2(t)}\right]$ where:

t = Sensor Integration Time (s)

The following assumptions regarding the remaining variables pertaining to the active sonar CNR equation, source power (P) and number of sonar elements (N), were made:

P = 1000 W
N = 256

All of the variables associated with the active sonar CNR equation can be changed. Utilizing the results from the above equations, future representative threat detection ranges were calculated and are listed in Table V-13.

Threat	Range (yds) Tgt Angle: 0 º f = 1 kHz	Range (yds) Tgt Angle: 0 º f = 25 kHz	Range (yds) Tgt Angle: 0 º f = 56 kHz	Range (yds) Tgt Angle: 90 º f = 1 kHz	Range (yds) Tgt Angle: 90 º f = 25 kHz	Range (yds) Tgt Angle: 90 º f = 56 kHz
SUB-1	3496	4585	2304	21674	10330	3918
SUB-2	3829	4756	2353	27695	10932	4066
SUB-3	1690	3316	1922	7956	7970	3327
SB-1	3595	5128	2577	7577	8876	3695
SB-2	6502	6475	2946	28931	12604	4602
SB-3	9185	7315	3166	51845	14339	5009
Mine-1	1107	2880	1884	973	4092	2395
Mine-2	904	2562	1771	1683	5228	2731
Mine-3	1278	3122	1967	1596	5117	2700
Mine-4	783	2352	1696	1702	5262	2744
Torp-1	846	2461	1734	3536	6942	3199
Torp-2	846	2462	1734	3536	6944	3200
Torp-3	522	1810	1478	1965	5575	2830

Table V-13 Active Sonar Detection Ranges

Lower frequencies tend to propagate with less attenuation at extended ranges and are therefore more effective at detecting larger targets at longer ranges. Because of the small effective target sizes of many future representative threats, coupled with small target angles, higher sonar frequencies appear to be more effective at target detection at short ranges. Above 25 kHz, however, greater attenuation appears to overcome the benefits of the increased target strength associated with greater frequencies. Because lower frequency systems obtain greater detection ranges due to the wider beam spread of the active signal (see Search Analysis), it can reasonably be assumed that if low frequency active sonar systems could be employed in a distributed fashion, the likelihood of greater detection ranges would increase.

e. Passive Sonar

This study used the following passive sonar CNR equation, and associated equations to determine target detection ranges:

Equation (32) $DT = SL - TL - (NL - DI)$ where:

DT = Detection Threshold (dB)
SL = Source Level (dB)
TL = Transmission Loss (dB)
NL = Noise Level (dB)
DI = Directivity Index (dB)

Equation (33) $SL^*_{\text{Small Boat}} = 60 \log K + 9 \log T - 20 \log F - 20 \log D + 35$ where:

K = Boat Speed (kts) (See Threat Document)
T = Boat Displacement (ltons) (See Threat Document)
F = Frequency (kHz)
D = Distance (yds)
*SL for Small Boat assumed at 1 kHz.

Equation (34) $TL = 20 \log R + \alpha R \times 10^{-3}$ where:

α = Total Absorption Coefficient (dB/kyd)
R = Range (yds)

Equation (35) Directivity Index (DI) = 10 log N where:

N = Number of Sonar elements

Similar to the active sonar case, before passive sonar detection ranges could be calculated, assumptions regarding seawater temperature (T), salinity (S), NL, and various threats' SL were made. This study assumed the following values for each:

T = 25 C
S = 34 ppt
$NL_{\text{Light Shipping Area}} = 30$ dB
$NL_{\text{Medium Shipping Area}} = 50$ dB
$NL_{\text{Heavy Shipping Area}} = 80$ dB
$SL_{\text{SUB-1/2}} = 100$ dB (Assumed at 1 kHz)
$SL_{\text{SUB-3}} = 90$ dB (Assumed at 1 kHz)
$SL_{\text{Torp-1}} = 135$ dB (Assumed at 25 kHz)
$SL_{\text{Torp-2}} = 285$ dB (Assumed at 25 kHz)
$SL_{\text{Torp-3}} = 125$ dB (Assumed at 25 kHz)

The speed of sound in water calculations, as well as the TL calculations, was developed in the same manner as described above in the active sonar section. This study again relied on the 14 dB sonar receiver operating characteristics curve to determine the desired detection threshold (DT). The equation used to determine that level is slightly different though due to the nature of passive sonar (see Equation (36)). A 10-second integration time was assumed to be reasonable if the passive sonar system employed a broadband (1000 Hz) receiver and was prosecuting an unknown threat signal. The passive sonar was also assumed to possess the same number of sonar elements as in the active sonar case (N = 256).

Equation (36) $$\mathrm{DT} = 5\log\left[\frac{1000(25.11886)}{t}\right]$$ where:

t = Sensor Integration Time (s)

As in the active sonar case, all variables within the passive sonar CNR equation can be changed as well. To reiterate, SUB-1/2/3 and SB-1/2/3 were modeled at 1 kHz frequency and TORP-1/2/3 were modeled at 25 kHz. Utilizing the results from the above equations, future representative threat detection ranges were calculated and are listed in Table V-14.

Threat	**SL (dB)**	**Range (yds) NL = 80 dB**	**Range (yds) NL = 50 dB**	**Range (yds) NL = 30 dB**
SUB-1	100	23	714	7119
SUB-2	100	23	714	7119
SUB-3	90	7	226	2257
SB-1 (40 kts)	127	500	15721	148358
SB-2 (50 kts)	152	8906	253133	1480579
SB-3 (10 kts)	117	160	5063	49650
Torp-1 (50 kts)	135	1271	40144	397352
Torp-2 (200 kts)	285	187449730	292526296	365186081
Torp-3 (40 kts)	125	402	12705	126632

Table V-14 Threat Source Levels and Detection Ranges

The results show that passive sonar may not be a particularly effective detection sensor against several of the threats when used in an area of heavy shipping. Furthermore, passive sonar does not provide good detection results against submarines or slower moving vessels when used in an area of moderate shipping. Because it is a passive sensor, two or more must be used in conjunction and achieve detection in order to determine the target's range. For these reasons, passive sonar may be used with greater results when distributed throughout the operating area.

5. Conclusion

Detecting threats is the critical first step in defending the Sea Base and its transport assets. If the force cannot "see" the enemy, it cannot defend against it. This study attempted to bound the force protection problem at hand by taking a realistic look at threat-sensor pairings. Though not all encompassing, with regards to the number or type of sensors available, or the tactics and techniques in which the ones mentioned above might be employed, several basic initial insights from the mathematical models developed can be drawn. First, in all cases, a sensor can detect threats at greater ranges if it is relatively positioned so the threat presents a 90^{o} (broadside) target angle. Second, the visual horizon, the environment, or both may limit many of the sensors' performance levels. Third, some sensors, such as lidar, are better suited for certain applications over others after considering the first two insights mentioned. Finally, if sensors were to be employed with varying tactics, friendly forces might be better served with regards to force protection. The distribution of sensors offers greater detection ranges by extending the sensors' horizons and by achieving greater target aspects. The benefits of a distributed sensor network throughout the battle space are readily apparent from the results, as the potential for a favorable target angle on a future representative threats increases. The next step is to take the results obtained in this document and apply them to a search detection model based on area or volume covered, and beam spread or field of view for each sensor to determine probabilities of detection for each threat-sensor pair.

C. SEARCH ANALYSIS

1. Introduction

The Sensor Analysis addressed the capability of various sensors (radar, lidar, IR, and sonar) to detect future representative threats as the critical first step in defending the Sea Base and its transport assets. Various threat-sensor pairs were developed, studied, and analyzed in order to determine potential detection ranges of the various threats by an associated sensor. From the initial sensor analyses, lidar and passive sonar were discounted as options for further study because of their relatively poor detection ranges. For the remaining sensors, detection ranges alone, though useful, do not tell a complete story with regard to system performance. For this reason, first principle probability-of-detection equations were applied to facilitate developing an unclassified discussion and to garner further insight into what type of sensor architecture might best protect the Sea Base. This chapter will outline the preliminary analysis completed regarding the probabilities of detection and associated reaction times that were derived from the threat-sensor pairings, the methodology employed, and the equations used to derive the values displayed in the Search Analysis.

2. Preliminary Analysis

a. Overview

Preliminary analysis of the search models demonstrates that several threats are able to approach very close to the defended assets if a point sensor is utilized. The maximum weapons release range for several of the threat platforms is 300 km (maximum effective range of ASCM-2). Therefore, a future sensor should be able to detect the threat platform well before the maximum weapons release range and allow time for defensive weapons to prevent the release of the enemy's weapons. This capability gap drives the need for a sensor that is able to detect threat platforms at longer ranges and with ample time to counter them before they can reach their weapons' maximum effective ranges. These requirements drive the need for a distributed sensor network.

b. Conventional Radar

Following the Sensor Analysis, this study again focused on two frequencies (3 GHz and 20 GHz) when modeling the conventional microwave radar. Both radar variations were then modeled as either a point or distributed sensor. Additionally, each radar variation was employed on one of three platforms, a ship (10 m height of eye), a UAV (10 km height of eye), or an aerostat (50 km height of eye) in order to determine the effects on sensor probability of detection. It is readily apparent that the use of the shipboard 3 GHz Radar with the cylinder search is the best of the search designs considered for the point system. While this design may not provide the best reaction times when compared to some of the threats using the 20 GHz system, it is able to detect every threat with a 0.95 probability of detection prior to weapons impact. The reason for this is the 3 GHz system's reduced search frame time, which may be attributed to its greater beam spread. This factor, together with the severe limitations to the point sensor's line of sight, makes the 3 GHz system superior to the 20 GHz system for a full volume search.

When the 20 GHz radar is mounted on the aerostat, it is superior to that of the 3 GHz radar. While the 20 GHz system has a much longer search frame time, it has a much greater detection range when compared to the 3 GHz system and does not face the line of sight limitations that impaired its performance in the point sensor platform. As a result, not all, but many of the threat platforms are detected before their maximum weapons release ranges. The use of a UAV with the 20 GHz system onboard provides a nice complement to the aerostat and point sensor systems as it “bridges the gap” between fixed overhead and point sensor systems by increasing detection ranges, and thus reaction times, against threats that were not readily detected by either the point or overhead systems.

c. IR

This study’s model of the IR sensor system followed the same methodology as the radar system. It was determined that an IR system observing the 3-5 μm spectrum typically provides enhanced detection ranges and reaction times when compared to the 8-12 μm system. When compared to the optimal point radar system (3 GHz Cylinder), the 3-5 μm IR system provides better detection ranges against three of five high-speed future representative threats. The relatively large radar cross sections presented to the point sensor seem to overcome the emissivity of the two threats not detected by the IR system allowing radar for these cases to attain greater detection ranges and more reaction time. Likewise, the minimal cross sections presented to the point sensor by the high-speed, low-reflective threats makes IR the better of the two for detecting the remaining three threats. An aerostat operating at 50 km altitude does not appear to be a good choice as a platform for the IR sensor. The 3-5 μm system is capable of providing an extra two seconds of reaction time against one threat; however, it is not capable of detecting any of the other remaining threats. The IR UAV system using the 3-5 μm spectrum, much like the 20 GHz UAV radar system, seems to “bridge the gap” between the point and overhead sensor systems.

d. Active Sonar

The last sensor modeled by this study was active sonar. The only difference between the approach taken with sonar and the one taken with radar and IR was the platform on which the sensor was mounted. This study chose either a ship, a USV, or a UUV with a maximum depth of 300 m. Based on results from the radar section, the more efficient search geometry, cylindrical, was also applied for sonar. By modeling an active sonar system searching equal volumes using 1 kHz and 25 kHz frequencies it was determined that the 25 kHz option is impractical due to the long search time required to achieve a 0.95 probability of detection. Furthermore, the use of the

25 kHz frequency does not give detection ranges as long as the 1 kHz system. This shows that the higher frequency sonar systems (25 kHz and 56 kHz) will require more narrowly defined search volumes in order to be used effectively. For these reasons, the higher frequency sonar is better suited for searching very slow or non-moving objects such as mines in a restricted volume. Also of note, many of the future representative threats are able to approach very close to the defended assets if the defenders use the point sonar system. Just as in the radar and IR cases, by distributing a sonar sensor network onboard USVs or UUVs, an effective tripwire can be established against every surface or subsurface threat to the Sea Base. The distributed sensors, when compared to the point system, achieve improved detection ranges and reaction times.

3. Methodology

In order to begin examination of sensor probability of detection, this study first had to determine what detection law should govern how each sensor is analyzed. Three detection laws were considered: coverage factor, inverse cube, and random search. A variation of the random search model was chosen to model a sensor system's probabilities of detection because it is generally considered a conservative estimate and is often used to represent the lower bound of the detection probability in a well-conducted search. This concept is illustrated in Figure V-3. As with any analytical model, certain assumptions apply. The following assumptions were made with regards to the random search model:

- The search volume is fixed
- The possible location of the target is uniformly distributed at all times during the search within a fixed volume
- The target is moving
- The sensor platform or sensor itself is moving and searching randomly

The model and its assumptions that followed were considered reasonable, conservative, and appropriate.

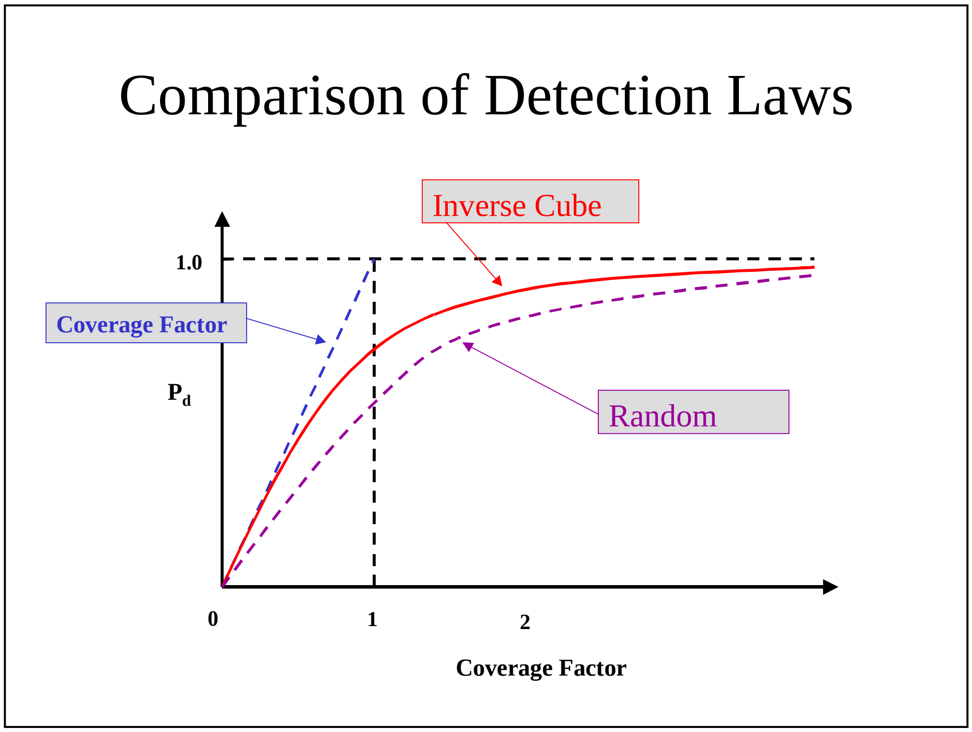


Figure V-3 Comparison of Detection Laws

Once the detection model was selected, this study was then able to incorporate and build upon previous conclusions derived in the Threat and Sensor Analysis in order to focus its efforts even further. Three variables, sensor elevation (or depth), sensor search geometry, and sensor configuration, were studied with the purpose of determining how changes in those variables might affect a sensor system's ability to achieve a 0.95 probability of detection of a given future representative threat. As concluded in the Sensor Analysis, an elevated (or off-axis) sensor could, in many circumstances, obtain a greater aspect angle against the target while simultaneously extending the sensor horizon. This study continued with this line of thought and focused on placing a conventional microwave radar, IR, or sonar system on differing platforms at varying elevations (or depths) to determine how an increased height of eye might affect the sensor's probability of detecting a given target. Radar, IR, and active sonar were modeled on various platforms including ships, UAVs, USVs, UUVs, and aerostats. For shipboard sensors, a 10 m height of eye was chosen for radar and IR. The operating altitudes or depths of the "off board" platforms were chosen based on various threat characteristics obtained from the Threat Document. For example, the highest operating altitude of the future representative threats above the water was 24 km, while the deepest operating threat below the water was 300 m.

Various sensor platforms and their respective operating altitudes or depths were then researched and analyzed in an effort to achieve sufficient off-axis angles and produce higher probabilities of detection against the threats.

Through open source research, this study determined that the creation and subsequent use of high altitude aerostats and aerodynes have been recognized as critical future capabilities by several governments including China, the U.S., and many in Europe. Systematic studies in many of these countries have the goal of placing high altitude platform stations at altitudes of 20-50 km above a fixed point relative to the earth. For these platforms, the higher altitudes offer a greater coverage area and long free-space signal propagation paths with reduced latency, attenuation, and multi-path distortions. These operating altitudes may furthermore minimize an airborne platforms' susceptibility to enemy weapons. As a result of this research and with respect to the threats' operating altitudes/depths, an aerostat operating at 50 km, UAVs operating at 10 km, and USV/UUVs operating from 0-300 m were chosen to provide the necessary off-axis angles to achieve the desired 0.95 probability of detection.

Delving deeper into the random search model, this study then had to decide on what area or volume of space should be considered when trying to detect a future representative threat. It readily became apparent that an area search did not provide sufficient results when compared to a volume search. The volume search also presented a more realistic representation of how a sensor would operate in a three-dimensional threat environment. Three search geometries were chosen to represent a sensor's three-dimensional battle space: cylinder, hemisphere, and cone. Figure V-4 illustrates these geometries.

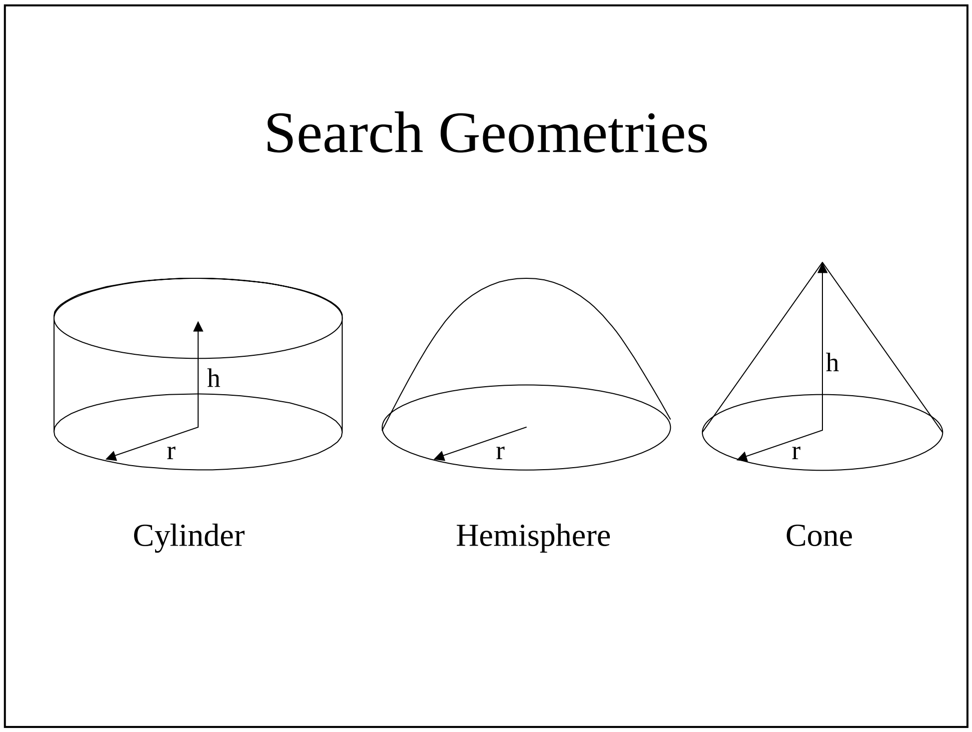


Figure V-4 Search Geometries

Next, two sensor configurations, point and distributed, were developed in order to further bolster previous conclusions drawn in the Sensor Analysis that postulated that a distributed sensor network may provide enhanced detection capabilities to a future expeditionary warfare force. Figure V-5 illustrates how a point sensor configuration was modeled. R represents the radius of the area concerned (R = 370 km); r represents the sensor distance from the “center” of the force being protected; and r′ represents the radius of the sensor coverage. A point sensor occurs when $r << R$. From the height of eye limitations addressed in the Sensor Analysis, it is apparent that a point sensor alone cannot provide the necessary coverage for an extended search volume. Figure V-6 illustrates how a distributed sensor configuration was modeled. In this case, R represents the radius of the area concerned; r represents the sensor distance from the “center” of the force being protected; and r′ represents the radius of the sensor coverage. A distributed sensor occurs when $r \approx R$. Basically, a network of sensors can provide the necessary coverage of the desired search volume.

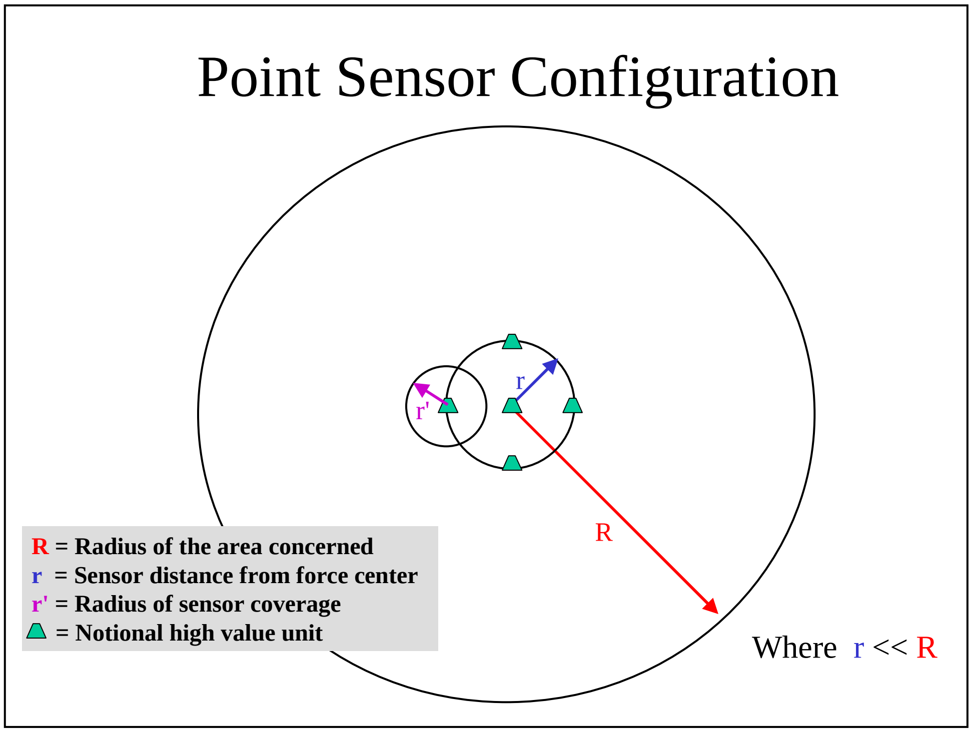


Figure V-5 Point Sensor Configuration

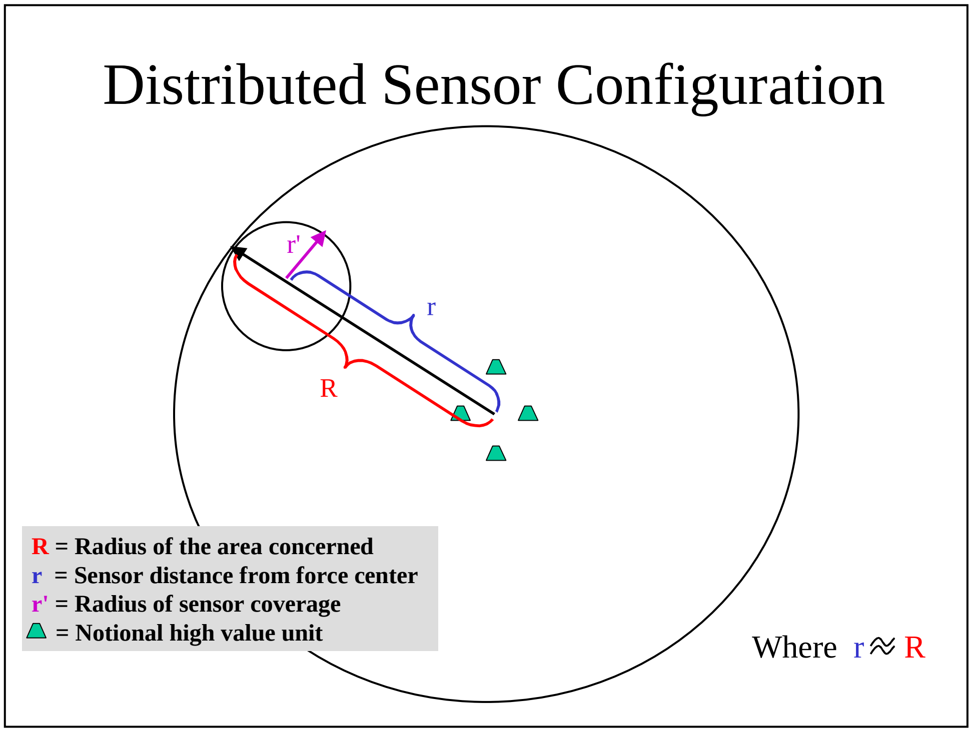


Figure V-6 Distributed Sensor Configuration

Table V-15 and Table V-16 highlight the assumptions made with regard to the point and distributed sensor configurations.

SENSOR	RADAR	IR (DIRECT DETECTION)	SONAR
Target Aspect	Nose-on (0^{o})*	Nose-on (0^{o})*	Nose-on (0^{o})
Target Disposition	Inbound	Inbound	Inbound
Sensor Characteristics	Ship-based	Ship-based	Ship-based
Height of Eye	10 m	10 m	0 m
Power	3 MW	N/A**	1 kW
Aperture Diameter	2 m	.1 m	5 m (1 kHz)
			2.5 m (25 kHz)
Threat Area	360^{o}	360^{o}	360^{o}
Search Geometry	Hemisphere Cylinder	Hemisphere	Cylinder
Desired Search Radius	370 km (Hemisphere) 370 km x 24 km (Cylinder)	N/A**	48 km x 300 m (1 kHz Cylinder) 1 km x 100 m (25 kHz Cylinder)
Miscellaneous	N/A**	ACFT-1 Velocity Mach .25 UAV-1 Velocity Mach .25 ACFT-2 Velocity Mach .5 ACFT-3 Velocity Mach .5 360^{o} Scan takes 1 second	Speed of Sound in H_2O = 1525 m/s

*Except for SAM: Broadside (90^{o}).
**Not applicable.

Table V-15 Point Sensor Assumptions

SENSOR	RADAR	IR (DIRECT DETECTION)	SONAR
Target Aspect	Broadside (90^{o})	Broadside (90^{o})	Broadside (90^{o})
Target Disposition	Inbound	Inbound	Inbound
Sensor Characteristics	Aerostat or UAV	Aerostat or UAV	USV or UUV
Height of Eye	50 km (Aerostat) 10 km (UAV)	50 km (Aerostat) 10 km (UAV)	0 m (USV) 300 m (UUV)
Power	500 kW (Aerostat) 2.5 kW (UAV)	N/A*	1 kW
Aperture Diameter	1 m	.1 m	5 m (1 kHz)
Threat Area	360^{o}	360^{o}	360^{o}
Search Geometry	Cone	Hemisphere	Cylinder
Desired Search Radius	370 km (Aerostat) 18 km (UAV)	N/A*	370 km x 300 m (1 kHz Cylinder)
Miscellaneous	N/A*	ACFT-1 Velocity Mach .25 UAV-1 Velocity Mach .25 ACFT-2 Velocity Mach .5 ACFT-3 Velocity Mach .5 360^{o} Scan takes 1 second	Speed of Sound in H_2O = 1525 m/s

*Not applicable.

Table V-16 Distributed Sensor Assumptions

Finally, a review was conducted to determine how the detection ranges were calculated for the various threat-sensor pairs in the Sensor Analysis. It was assumed that certain CNRs had to be achieved in order to detect a given future representative threat by an associated sensor.

While the CNR chosen from the Receiver Operating Characteristics curve for these particular sensors carried with them associated probabilities of detection, these probabilities of detection represent single glimpses at the target; furthermore, they assume that a target is present. For each CNR chosen, the associated single-pulse probability of detection was 0.9. This CNR probability of detection was assumed to hold true for all ranges. The probability of detection increases with an increase in search time. For radar, the various detection ranges and CNR single-pulse probabilities of detection were then applied to the random search theory model chosen by this study in order to determine the volume search frame times and cumulative probabilities of detection for each threat-sensor pair. For IR sensors, the pulse-dependent probability of detection was used to determine search frame times as well. Active Sonar is very similar to radar from the search detection standpoint, and this study used the same model to calculate probabilities of detection and their associated search frame times.

Analysis showed that radar was the best of the sensors considered for the detection of threats operating above or on the surface of the water. It is highly resistant to the environment in comparison to either IR or lidar and is not as sensitive to easily controlled target properties (i.e., target speed) for detection. While the addition of lidar to any conceptual network will most likely enhance the overall probability of detection against many targets, the limited resources and time available made only an in-depth study of radar and IR practical for the search detection study of threats operating on or above the surface of the water. Active sonar, while highly dependent on the environment, is not as sensitive to controllable target properties when compared to passive sonar. From the Sensor Analysis, passive sonar demonstrated poor detection performance against many threats in noisy environments (areas of medium to heavy shipping). For these reasons, and the fact that each of these sensors had relatively poor detection ranges, passive sonar and lidar were eliminated as options for further study in this document.

The following sections will describe the governing equations used to calculate the cumulative probabilities of detection and search frame times, and the results of those calculations.

4. Modeling Equations and Results

a. Random Search Model

The variation of the random search model chosen by this study is represented by:

Equation (37) $P_D = 1 - e^{\left(\frac{-nwvt}{A}\right)}$ where:

P_D = Probability of Detection
n = Number of Sensors
w = Sweep Volume (m^3)
v = Search Speed (Hz)
t = Search Time (s)
A = Volume to be Searched (m^3)

In this random search model, *w* is the volume covered by one dwell or one pulse due to beam spread. The formula for calculating beam spread is:

Equation (38) $A_D = \frac{\pi R^2 \lambda^2}{4D^2}$ where:

A_D = Dwell Area (m^2)
R = Range to be Searched (m)
λ = Wavelength (m)
D = Antenna Diameter (m)

The volume covered by one dwell (*w*) is thus calculated:

Equation (39) $w = A_D$ (1/3) (R) where:

w = Sweep Volume (m^3)
A_D = Dwell Area (m^2)
R = Range to be Searched (m)

The search speed, *v*, in this model, is analogous to the pulse repetition frequency (PRF) of the sensor for a given range. The formula for PRF is:

Equation (40) PRF = c/2R where:

PRF = Pulse Repetition Frequency (Hz)
c = Speed of Light in Air or Speed of Sound in Water Depending on Sensor (m/s)
R = Range to be Searched (m)

As mentioned earlier, the search volume is assumed to take one of three forms based on the sensor platform, the sensor characteristics, and the search requirements of the expeditionary force. The three shapes used to approximate the volumes searched are a hemisphere, a cylinder, and a cone. The formulas for calculating each volume are:

Equation (41) $V_{\text{Hemisphere}} = \frac{2}{3}\pi R^3$

Equation (42) $V_{\text{Cylinder}} = \pi R^2 h_{cylinder}$

Equation (43) $V_{\text{Cone}} = \frac{1}{3}\pi R^2 h_{cone}$ where:

$V_{\text{Hemisphere}}$ = Volume of a Hemisphere (m^3)
V_{Cylinder} = Volume of a Cylinder (m^3)
V_{Cone} = Volume of a Cone (m^3)
R = Desired Search Range (m)
$h_{cylinder}$ = Search Altitude or Depth Depending on Sensor (m)
h_{cone} = Sensor Altitude

From the results of the random search model, the calculated probability of detection was applied to the pulse-dependent probability of detection to determine the total probability of detection. The formula for calculating pulse-dependent probability of detection is:

Equation (44) $P_D(N) = 1-(1- P_D(1))^N$ where:

$P_D(N)$ = Pulse-Dependent Probability of Detection
N = Number of Pulses as a Ratio of the Volume Searched to Desired Search Volume
$P_D(1)$ = Single-Pulse Probability of Detection = .9

N is represented by the ratio of the volume searched to the desired search volume. If a single-pulse model is used, this ratio is simply represented by the exponent from the random search model (*nwvt*/*A*) from Equation (37).

Equation (37) and Equation (44), taken together, allow for the calculation of the total probability of detection for a given target by a given sensor. The total probability of detection is thus:

Equation (45) $$P_D(\text{Total}) = (1-e^{(-nwvt/A)})(1-(1-P_D(1))^N)$$

For each sensor, this study, with stakeholder concurrence, assumed that a .95 total probability of detection should serve as the desired threshold for valid target detection. Based on this assumption and the number of sensors conducting the search, search times were calculated. Associated Time To Go until Impact (TTGI), and Distance To Go until Impact (DTGI) figures were calculated as well. TTGI and DTGI are based on the assumption that the impact point of a given threat is the central point of the expeditionary warfare force (see Figure V-7).

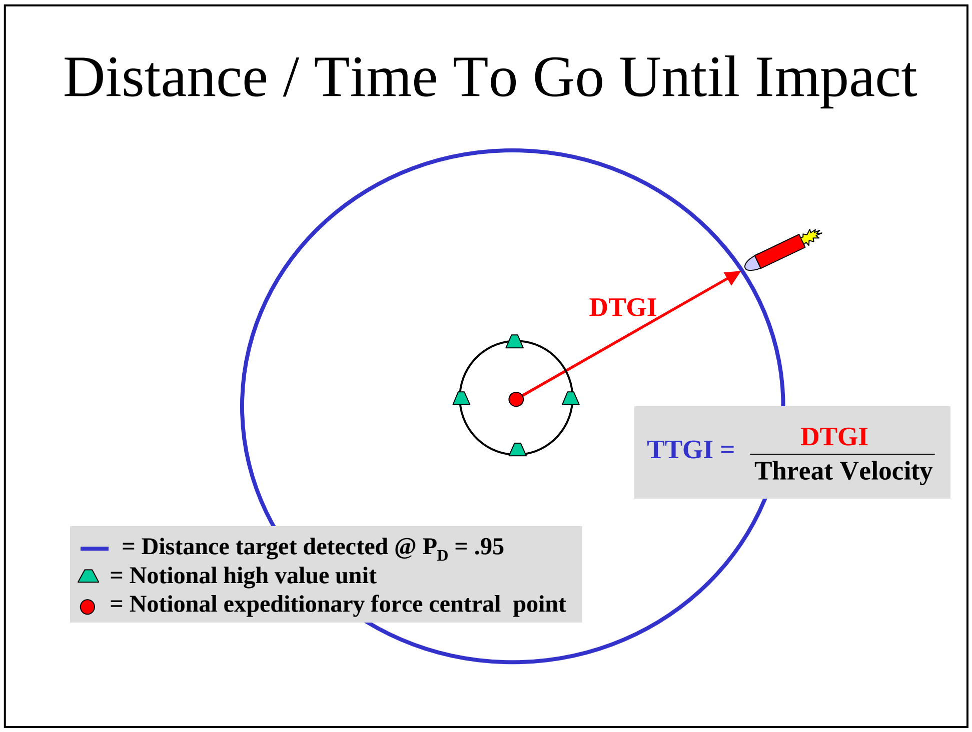


Figure V-7 DTGI / TTGI Pictorial

The DTGI represents the distance at which a given threat was detected, with a 0.95 probability of detection, from the expeditionary force center. The TTGI figure is calculated by dividing the DTGI figure by the threat's velocity. Threat velocities and threat performance limitations (i.e., maximum effective range) were drawn from the Threat Document. The Sensor Analysis provided sensor performance limitations and height of eye limitations. These threat and sensor characteristics were used to calculate and analyze the DTGI and TTGI figures. The following sections will display the DTGI and TTGI results and will provide additional insights into what those numbers mean with regard to protecting the Sea Base and its assets.

b. Radar — Point Sensor Configuration

Threat (Altitude)	Range (km) f = 3 GHz	Threat Speed (m / s)	Search Time (s) n = 1	Search Time (s) n = 6	DTGI (km)	TTGI (s)
ASCM-1 (3 m)	14.1	300	24	4	12.9	43
ASCM-2 (5 m)	17.8	825	24	4	14.5	17.6
ASCM-3 (24 km)	20.9*	1650	24	4	14.3	8.7
SAM-1 (5000 m)	118.5	1852	24	4	111.1	60
SAM-2 (5000 m)	10	825	24	4	6.7	8.1
ACFT-1 (10 m)	26.1	95	24	4	25.7	270.7
ACFT-2 (5000 m)	147.3	825	24	4	144	174.5
ACFT-3 (10 m)	22.2	300	24	4	21	70
UAV-1 (10 m)	20.7	284	24	4	19.6	68.9
DW-1 (2000 m)	10.4	1650	24	4	3.8	2.3
DW-2 (1 m)	3	240	24	4	2	8.5
DW-3 (1 m)	1.1	800	24	4	0**	0**
SB-1 (0 m)	13	20.6	24	4	12.9	627.1
SB-2 (0 m)	13	25.6	24	4	12.9	503.8
SB-3 (0 m)	13	15.4	24	4	12.9	840.2

*ASCM-3 has begun its 30^o dive and is at an altitude of 10.5 km.
**Zero indicates that these threats could only be detected at a .95 probability of detection after they passed or impacted the central point of the expeditionary force.

Table V-17 Ship-Based 3 GHz Radar — Hemisphere Search Geometry

Threat (Altitude)	**Range (km) f = 20 GHz**	**Threat Speed (m / s)**	**Search Time (s) n = 1**	**Search Time (s) n = 6**	**DTGI (km)**	**TTGI (s)**
ASCM-1 (3 m)	20.2	300	1057.5	176.3	0*	0*
ASCM-2 (5 m)	22.3	825	1057.5	176.3	0*	0*
ASCM-3 (24 km)	53.9	1650	1057.5	176.3	0*	0*
SAM-1 (5000 m)	200	1852	1057.5	176.3	0*	0*
SAM-2 (5000 m)	10	825	1057.5	176.3	0*	0*
ACFT-1 (10 m)	26.1	95	1057.5	176.3	9.4	98.4
ACFT-2 (5000 m)	304.5	825	1057.5	176.3	159.1	192.8
ACFT-3 (10 m)	26.1	300	1057.5	176.3	0*	0*
UAV-1 (10 m)	26.1	284	1057.5	176.3	0*	0*
DW-1 (2000 m)	26.8	1650	1057.5	176.3	0*	0*
DW-2 (1 m)	3	240	1057.5	176.3	0*	0*
DW-3 (1 m)	1.1	800	1057.5	176.3	0*	0*
SB-1 (0 m)	13	20.6	1057.5	176.3	9.4	454.8
SB-2 (0 m)	13	25.6	1057.5	176.3	8.5	331.5
SB-3 (0 m)	13	15.4	1057.5	176.3	10.3	667.9

*Zero indicates that these threats could only be detected at a .95 probability of detection after they passed or impacted the central point of the expeditionary force.

Table V-18 Ship-Based 20 GHz Radar — Hemisphere Search Geometry

Threat (Altitude)	Range (km) f =3 GHz	Threat Speed (m / s)	Search Time (s) n = 1	Search Time (s) n = 6	DTGI (km)	TTGI (s)
ASCM-1 (3 m)	14.1	300	2.31	.39	14	46.6
ASCM-2 (5 m)	17.8	825	2.31	.39	17.5	21.2
ASCM-3 (24 km)	20.9*	1650	2.31	.39	20.3	12.3
SAM-1 (5000 m)	118.5	1852	2.31	.39	117.8	63.6
SAM-2 (5000 m)	10	825	2.31	.39	9.7	11.7
ACFT-1 (10 m)	26.1	95	2.31	.39	26	274.3
ACFT-2 (5000 m)	147.3	825	2.31	.39	147	178.2
ACFT-3 (10 m)	22.2	300	2.31	.39	22.1	73.6
UAV-1 (10 m)	20.7	284	2.31	.39	20.6	72.5
DW-1 (2000 m)	10.4	1650	2.31	.39	9.8	5.9
DW-2 (1 m)	3	240	2.31	.39	2.9	12.1
DW-3 (1 m)	1.1	800	2.31	.39	.8	1
SB-1 (0 m)	13	20.6	2.31	.39	12.99	630.7
SB-2 (0 m)	13	25.6	2.31	.39	12.99	507.4
SB-3 (0 m)	13	15.4	2.31	.39	12.99	843.8

*ASCM-3 has begun its 30^o dive and is at an altitude of 10.5 km.

Table V-19 Ship-Based 3 GHz Radar — Cylinder Search Geometry

Threat (Altitude)	**Range (km) f = 20 GHz**	**Threat Speed (m / s)**	**Search Time (s) n = 1**	**Search Time (s) n = 6**	**DTGI (km)**	**TTGI (s)**
ASCM-1 (3 m)	20.2	300	102.6	17.1	15.1	50.3
ASCM-2 (5 m)	22.3	825	102.6	17.1	8.2	10
ASCM-3 (24 km)	53.9	1650	102.6	17.1	25.7	15.6
SAM-1 (5000 m)	200	1852	102.6	17.1	168.4	91
SAM-2 (5000 m)	10	825	102.6	17.1	0*	0*
ACFT-1 (10 m)	26.1	95	102.6	17.1	24.5	257.7
ACFT-2 (5000 m)	304.5	825	102.6	17.1	290.4	352
ACFT-3 (10 m)	26.1	300	102.6	17.1	21	69.9
UAV-1 (10 m)	26.1	284	102.6	17.1	21.2	74.8
DW-1 (2000 m)	26.8	1650	102.6	17.1	0*	0*
DW-2 (1 m)	3	240	102.6	17.1	0*	0*
DW-3 (1 m)	1.1	800	102.6	17.1	0*	0*
SB-1 (0 m)	13	20.6	102.6	17.1	12.6	614
SB-2 (0 m)	13	25.6	102.6	17.1	12.6	490.7
SB-3 (0 m)	13	15.4	102.6	17.1	12.7	827.1

*Zero indicates that these threats could only be detected at a .95 probability of detection after they passed or impacted the central point of the expeditionary force.

Table V-20 Ship-Based 20 GHz Radar — Cylinder Search Geometry

The ship-based 3 GHz radar with cylinder search is the best of the search designs considered for the point system. While this design may not provide the best reaction times when compared to some of the threats using the 20 GHz system, it is able to detect every threat with a .95 probability of detection prior to impact. The reason for this is the 3 GHz system's reduced search frame time, which can be attributed to its greater beam spread (as calculated using Equation (38)). This factor, together with the severe limitations to the point sensor's line of sight, makes the 3 GHz system superior to the 20 GHz system for a full volume search. A major disadvantage of the point system however, largely due to its limited line of sight, is its inability to detect several threat platforms prior to their maximum weapons release ranges. The maximum weapons release range for many of the threat platforms is 300 km (maximum effective range of ASCM-2). Therefore, a future sensor should be able to detect the threat platform well before the maximum weapons release range and allow time for defensive weapons to prevent the release of the enemy's weapons. This capability gap drives the need for a sensor that is able to detect threat platforms at longer ranges and with ample time to counter them before they can reach their weapons' maximum effective ranges. These requirements drive the need for a distributed sensor network.

c. Radar — Distributed Sensor Configuration

Threat (Altitude)	**Range (km) f = 20 GHz**	**Threat Speed (m / s)**	**Search Time (s)**	**DTGI (km)**	**TTGI (s)**
ASCM-1 (3 m)	113	300	131	62	206.8
ASCM-2 (5 m)	195.7	825	131	81.1	98.3
ASCM-3 (24 km)	241.8	1650	131	34.1	20.7
SAM-1 (5000 m)	157.1	1852	131	0*	0*
SAM-2 (5000 m)	49.9	825	131	0*	0*
ACFT-1 (10 m)	373.4	95	131	357.6	3763.8
ACFT-2 (5000 m)	335.9	825	131	224.8	272.5
ACFT-3 (10 m)	81.1	300	131	24.6	81.9
UAV-1 (10 m)	43.4	284	131	No detect**	No detect**
DW-1 (2000 m)	100.1	1650	131	0*	0*
DW-2 (1 m)	10.6	240	131	No detect**	No detect**
DW-3 (1 m)	6.9	800	131	No detect**	No detect**
SB-1 (0 m)	111.8	20.6	131	97.3	4723.2
SB-2 (0 m)	373.4	25.6	131	366.6	14322
SB-3 (0 m)	373.4	15.4	131	368	23895

*Zero indicates that these threats could only be detected at a .95 probability of detection after they passed or impacted the central point of the expeditionary force.

**No detect indicates that the sensor operating at the given altitude is incapable of detecting the given threat.

Table V-21 Aerostat 20 GHz Radar — Cone Search Geometry

Threat (Altitude)	Range (km) F = 3 GHz	Threat Speed (m / s)	Search Time (s)	DTGI (km)	TTGI (s)
ASCM-1 (3 m)	27.2	300	2.95	No detect*	No detect*
ASCM-2 (5 m)	47.2	825	2.95	No detect*	No detect*
ASCM-3 (24 km)	58.3	1650	2.95	53	32.2
SAM-1 (5000 m)	37.9	1852	2.95	No detect*	No detect*
SAM-2 (5000 m)	12	825	2.95	No detect*	No detect*
ACFT-1 (10 m)	96.5	95	2.95	82.3	866
ACFT-2 (5000 m)	109.9	825	2.95	98	118.7
ACFT-3 (10 m)	19.5	300	2.95	No detect*	No detect*
UAV-1 (10 m)	10.5	284	2.95	No detect*	No detect*
DW-1 (2000 m)	24.1	1650	2.95	No detect*	No detect*
DW-2 (1 m)	2.5	240	2.95	No detect*	No detect*
DW-3 (1 m)	1.7	800	2.95	No detect*	No detect*
SB-1 (0 m)	27	20.6	2.95	No detect*	No detect*
SB-2 (0 m)	134.8	25.6	2.95	125.7	4887
SB-3 (0 m)	186.1	15.4	2.95	179.2	11637

*No detect indicates that the sensor operating at the given altitude is incapable of detecting the given threat.

Table V-22 Aerostat 3 GHz Radar — Cone Search Geometry

The aerostat 20 GHz radar, for an overhead sensor, is superior to that of the 3 GHz radar. While the 20 GHz system has a much higher search frame time, it has a much greater detection range when compared to the 3 GHz system and does not face the line of sight limitations that impaired its performance from the point sensor platform. As a result, some threat platforms (ACFT-1, SB-1, SB-2, and SB-3) are detected before their maximum weapons release ranges. However, several key problems exist with using the overhead sensor only. Several threats (SAM-1, SAM-2, ACFT-2, ACFT-3, DW-1, and UAV-1) are not detected or are detected late (i.e. after entering potential weapons release range or after intercept). Two options for achieving detections before the maximum weapons release range for many of the threat platforms are: one, increase the power output of the sensor system; or two, place the sensor system further away from the force center of the protected assets. However, with regard to option one, the power for sensor platforms has been assumed to remain constant as future power generation capabilities may not be able to provide sufficient power to make the desired detection ranges possible. Therefore, the option to distribute a network of sensors around the expeditionary warfare force at sufficient ranges to detect and counter future threats could allow the force to detect many of the threats farther away, while giving it more time to react to the incoming threat.

This study assumed that the expeditionary force would desire 360^{o} sensor coverage out to a range of 370 km. In order to provide the necessary 360^{o} coverage and cover a desired radius of 370 km around the expeditionary warfare force, a UAV sensor network should be distributed according to the following formula:

Equation (46) $N = \frac{\pi R}{r}$ where:

N = Number of UAV
R = Radius of Deployment Around the Expeditionary Warfare Force (m)
r = Radius of Each Sensor's Coverage (m)

The shortest detection range of the threat platform drives the radius of each sensor's coverage for this formula. For example, 20.5 km is the shortest detection range against UAV-1. Using simple geometry, this translates to a horizontal detection distance of 18 km. The radius of deployment (R) is simply the horizontal detection distance subtracted from the desired search radius (370 km) or 352 km. Using these inputs, N equals 61.4 UAV. This means that 62 UAV must be used for the conceptual UAV network. This excessively large number of required sensors is the drawback to using the distributed network of smaller sensors over a large area. Smaller numbers, however, are possible if a smaller radius of deployment is desired or if larger and inherently more capable platforms are used. The first of these two alternative courses of action, however, would result in reduced distances to the protected assets and corresponding reduced reaction times.

Threat (Altitude)	**Range (km) f = 20 GHz**	**Threat Speed (m / s)**	**Search Time (s)**	**DTGI (km)**	**TTGI (s)**
ASCM-1 (3 m)	20.6	300	5.63	368.3	1227.8
ASCM-2 (5 m)	20.6	825	5.63	365.4	442.9
ASCM-3 (24 km)	No detect*	No detect*	No detect*	No detect*	No detect*
SAM-1 (5000 m)	10.3	1852	5.63	350.6	189.3
SAM-2 (5000 m)	10.3	825	5.63	356.4	432
ACFT-1 (10 m)	20.6	95	5.63	369.5	3889.2
ACFT-2 (5000 m)	10.3	825	5.63	356.4	432
ACFT-3 (10 m)	20.6	300	5.63	368.3	1227.7
UAV-1 (10 m)	20.5	284	5.63	368.3	1296.8
DW-1 (2000 m)	16.5	1650	5.63	357.1	216.4
DW-2 (1 m)	5	240	5.63	No detect*	No detect*
DW-3 (1 m)	3.3	800	5.63	No detect*	No detect*
SB-1 (0 m)	20.6	20.6	5.63	369.9	17955.5
SB-2 (0 m)	20.6	25.6	5.63	369.9	14447.5
SB-3 (0 m)	20.6	15.4	5.63	369.9	24020

*No detect indicates that the sensor operating at the given altitude is incapable of detecting the given threat.

Table V-23 UAV 20 GHz — Cone Search Geometry

Threat (Altitude)	**Range (km) f = 3 GHz**	**Threat Speed (m / s)**	**Search Time (s)**	**DTGI (km)**	**TTGI (s)**
ASCM-1 (3 m)	12.9	300	.13	360.1	1200.4
ASCM-2 (5 m)	20.6	825	.13	369.9	448.4
ASCM-3 (24 km)	No detect*	No detect*	No detect*	No detect*	No detect*
SAM-1 (5000 m)	10.3	1852	.13	360.8	194.8
SAM-2 (5000 m)	5.7	825	.13	354.7	429.9
ACFT-1 (10 m)	20.6	95	.13	369.9	3894.7
ACFT-2 (5000 m)	10.3	825	.13	360.9	437.5
ACFT-3 (10 m)	9.2	300	.13	No detect*	No detect*
UAV-1 (10 m)	4.9	284	.13	No detect*	No detect*
DW-1 (2000 m)	11.4	1650	.13	359.9	218.1
DW-2 (1 m)	1.2	240	.13	No detect*	No detect*
DW-3 (1 m)	.8	800	.13	No detect*	No detect*
SB-1 (0 m)	20.6	20.6	.13	369.9	17961
SB-2 (0 m)	20.6	25.6	.13	369.9	14453
SB-3 (0 m)	20.6	15.4	.13	369.9	24025

*No detect indicates that the sensor operating at the given altitude is incapable of detecting the given threat.

Table V-24 UAV 3 GHz — Cone Search Geometry

The UAV with the 20 GHz system provides a nice complement to the overhead and point sensor systems. With the exception of ASCM-3, the UAV sensor network would be able to act as an effective tripwire against every threat to the Sea Base. It provides particularly good detection ranges and reaction times against the stealth threats (ACFT-3 and UAV-1). If cued acquisition is used from another sensor platform, an uninterrupted track of these threats is possible throughout the battle space. Without the use of cued acquisition, the distributed network is still able to reduce the uncertainty of threat positions and narrow the scope of subsequent reacquisition searches.

d. IR — Point Sensor Configuration

Threat (Altitude)	**Range (km) Tgt Angle: 0°** **λ = 3-5 μm**	**Threat Speed (m / s)**	**Search Time (s)**	**DTGI (km)**	**TTGI (s)**
ASCM-1 (3 m)	8	300	1.31	7.6	25.4
ASCM-2 (5 m)	20.1	825	1.31	19	23.1
ASCM-3 (24 km)	32.9*	1650	1.31	30.7	18.6
SAM-1 (5000 m)	41.3	1852	1.31	38.6	20.8
SAM-2 (5000 m)	10.8	825	1.31	7.6	9.2
ACFT-1 (10 m)	13.9	95	1.31	13.8	145
ACFT-2 (10 m)	15.5	825	1.31	14.4	17.5
ACFT-3 (10 m)	14.7	300	1.31	14.3	47.7
UAV-1 (10 m)	11.4	284	1.31	11	38.8
DW-1 (2000 m)	24.1	1650	1.31	21.9	13.3
DW-2 (1 m)	1.7	240	1.31	1.4	5.8
DW-3 (1 m)	2.7	800	1.31	.05	.06
SB-1 (0 m)	8.2	20.6	1.31	8.2	396.7
SB-2 (0 m)	12.1	25.6	1.31	12.1	471.3
SB-3 (0 m)	12.1	15.4	1.31	12.1	784.4

*ASCM-3 has begun its 30° dive and is at an altitude of 16.5 km.

Table V-25 Ship-Based 3-5 μm IR Sensor — Hemisphere Search Geometry

Threat (Altitude)	Range (km) Tgt Angle: 0^o λ = 8-12 μm	Threat Speed (m / s)	Search Time (s)	DTGI (km)	TTGI (s)
ASCM-1 (3 m)	7.6	300	1.31	7.2	24
ASCM-2 (5 m)	11.6	825	1.31	10.5	12.8
ASCM-3 (24 km)	15.2*	1650	1.31	13	7.9
SAM-1 (5000 m)	18.6	1852	1.31	15.5	8.4
SAM-2 (5000 m)	10	825	1.31	7.6	9.2
ACFT-1 (10 m)	12.8	95	1.31	12.7	133.4
ACFT-2 (10 m)	13.5	825	1.31	12.4	15.1
ACFT-3 (10 m)	13	300	1.31	12.6	42
UAV-1 (10 m)	11.1	284	1.31	10.7	37.8
DW-1 (2000 m)	11.2	1650	1.31	9	5.5
DW-2 (1 m)	2.1	240	1.31	1.8	7.4
DW-3 (1 m)	1.1	800	1.31	.05	.06
SB-1 (0 m)	8.9	20.6	1.31	8.9	430.7
SB-2 (0 m)	12.1	25.6	1.31	12.1	471.3
SB-3 (0 m)	12.1	15.4	1.31	12.1	784.4

*ASCM-3 has begun its 30° dive and is at an altitude of 7.6 km.

Table V-26 Ship-Based 8-12 μm IR Sensor — Hemisphere Search Geometry

The IR system using the 3-5 μm spectrum provides better detection ranges and reaction times when compared to the 8-12 μm system. The only exception to this comparison is DW-2, which has a maximum effective range of 3 km. When compared to the optimal point radar system (3 GHz-Cylinder), the 3-5 μm IR system provides better detection ranges against several of the high-speed threats including ASCM-2, ASCM-3, and DW-1. Notable exceptions to this list of high-speed threats are SAM-1 and SAM-2. The relatively large radar cross sections presented to the point sensor seem to overcome the emissivity of the SAMs, allowing radar for these cases to attain greater detection ranges and more reaction time. Likewise, the minimal cross sections presented to the point sensor by the high-speed, low-reflective threats make IR the better of the two for detecting ASCM-2, ASCM-3, and DW-1.

e. IR — Distributed Sensor Configuration

Threat (Altitude)	**Range (km) Tgt Angle: 0^o λ = 3-5 μm**	**Threat Speed (m / s)**	**Search Time (s)**	**DTGI (km)**	**TTGI (s)**
ASCM-1 (3 m)	13.4	300	1.31	No detect*	No detect*
ASCM-2 (5 m)	29.7	825	1.31	No detect*	No detect*
ASCM-3 (24 km)	44.4	1650	1.31	33.8	20.5
SAM-1 (5000 m)	41.3	1852	1.31	No detect*	No detect*
SAM-2 (5000 m)	18.4	825	1.31	No detect*	No detect*
ACFT-1 (10 m)	18.5	95	1.31	No detect*	No detect*
ACFT-2 (10 m)	20.4	825	1.31	No detect*	No detect*
ACFT-3 (10 m)	20.5	300	1.31	No detect*	No detect*
UAV-1 (10 m)	15.5	284	1.31	No detect*	No detect*
DW-1 (2000 m)	35.5	1650	1.31	No detect*	No detect*
DW-2 (1 m)	2.1	240	1.31	No detect*	No detect*
DW-3 (1 m)	5	800	1.31	No detect*	No detect*
SB-1 (0 m)	12	20.6	1.31	No detect*	No detect*
SB-2 (0 m)	18.4	25.6	1.31	No detect*	No detect*
SB-3 (0 m)	21.8	15.4	1.31	No detect*	No detect*

*No detect indicates that the sensor operating at the given altitude is incapable of detecting the given threat.

Table V-27 Aerostat 3-5 μm IR Sensor — Hemisphere Search Geometry

Threat (Altitude)	**Range (km) Tgt Angle: 0^o λ = 8-12 μm**	**Threat Speed (m / s)**	**Search Time (s)**	**DTGI (km)**	**TTGI (s)**
ASCM-1 (3 m)	11.4	300	1.31	No detect*	No detect*
ASCM-2 (5 m)	16.4	825	1.31	No detect*	No detect*
ASCM-3 (24 km)	20.1	1650	1.31	No detect*	No detect*
SAM-1 (5000 m)	18.6	1852	1.31	No detect*	No detect*
SAM-2 (5000 m)	10.9	825	1.31	No detect*	No detect*
ACFT-1 (10 m)	15.6	95	1.31	No detect*	No detect*
ACFT-2 (10 m)	16.4	825	1.31	No detect*	No detect*
ACFT-3 (10 m)	16.4	300	1.31	No detect*	No detect*
UAV-1 (10 m)	13.8	284	1.31	No detect*	No detect*
DW-1 (2000 m)	16.3	1650	1.31	No detect*	No detect*
DW-2 (1 m)	2.6	240	1.31	No detect*	No detect*
DW-3 (1 m)	3	800	1.31	No detect*	No detect*
SB-1 (0 m)	11.6	20.6	1.31	No detect*	No detect*
SB-2 (0 m)	15.5	25.6	1.31	No detect*	No detect*
SB-3 (0 m)	17.5	15.4	1.31	No detect*	No detect*

*No detect indicates that the sensor operating at the given altitude is incapable of detecting the given threat.

Table V-28 Aerostat 8-12 μm IR Sensor — Hemisphere Search Geometry

An aerostat operating at 50 km altitude is not a good choice as a platform for the IR sensor. The 3-5 μm system is capable of providing an extra two seconds of reaction time against ASCM-3; however, it is not capable of detecting any of the other threats examined.

Threat (Altitude)	**Range (km) Tgt Angle: 0°** **λ = 3-5 μm**	**Threat Speed (m / s)**	**Search Time (s)**	**DTGI (km)**	**TTGI (s)**
ASCM-1 (3 m)	13.4	300	1.31	360.5	1201.8
ASCM-2 (5 m)	29.7	825	1.31	378.9	459.3
ASCM-3 (24 km)	44.4	1650	1.31	No detect*	No detect*
SAM-1 (5000 m)	41.3	1852	1.31	390.6	210.9
SAM-2 (5000 m)	18.4	825	1.31	368.6	446.8
ACFT-1 (10 m)	18.5	95	1.31	367.4	3867.9
ACFT-2 (10 m)	20.4	825	1.31	368.7	446.9
ACFT-3 (10 m)	20.5	300	1.31	369.5	1231.7
UAV-1 (10 m)	15.5	284	1.31	363.5	1279.9
DW-1 (2000 m)	35.5	1650	1.31	384.4	233
DW-2 (1 m)	2.1	240	1.31	No detect*	No detect*
DW-3 (1 m)	5	800	1.31	No detect*	No detect*
SB-1 (0 m)	12	20.6	1.31	358.6	17408
SB-2 (0 m)	18.4	25.6	1.31	367.4	14352
SB-3 (0 m)	21.8	15.4	1.31	371.4	24113.7

*No detect indicates that the sensor operating at the given altitude is incapable of detecting the given threat.

Table V-29 UAV 3-5 μm IR Sensor — Hemisphere Search Geometry

Threat (Altitude)	**Range (km) Tgt Angle: 0°** **λ = 8-12 μm**	**Threat Speed (m / s)**	**Search Time (s)**	**DTGI (km)**	**TTGI (s)**
ASCM-1 (3 m)	11.4	300	1.31	357.1	1190.3
ASCM-2 (5 m)	16.4	825	1.31	363.9	441.1
ASCM-3 (24 km)	20.1	1650	1.31	No detect*	No detect*
SAM-1 (5000 m)	18.6	1852	1.31	367.5	198.4
SAM-2 (5000 m)	10.9	825	1.31	360.6	437.1
ACFT-1 (10 m)	15.6	95	1.31	363.9	3830
ACFT-2 (10 m)	16.4	825	1.31	363.9	441.1
ACFT-3 (10 m)	16.4	300	1.31	364.6	1215.4
UAV-1 (10 m)	13.8	284	1.31	361.1	1271.7
DW-1 (2000 m)	16.3	1650	1.31	364	220.6
DW-2 (1 m)	2.6	240	1.31	No detect*	No detect*
DW-3 (1 m)	3	800	1.31	No detect*	No detect*
SB-1 (0 m)	11.6	20.6	1.31	357.9	17371.5
SB-2 (0 m)	15.5	25.6	1.31	363.8	14211.3
SB-3 (0 m)	17.5	15.4	1.31	366.3	23788.4

*No detect indicates that the sensor operating at the given altitude is incapable of detecting the given threat.

Table V-30 UAV 8-12 μm IR Sensor — Hemisphere Search Geometry

The IR UAV system observing the 3-5 μm spectrum provides better detection ranges and reaction times when compared to the 8-12 μm system. Furthermore, the IR UAV system provides better detection ranges and reaction times against ASCM-2, SAM-1, SAM-2, ACFT-3, DW-1, and SB-3 when compared to the UAV 20 GHz radar system.

f. SONAR — Point Sensor Configuration

Threat	Range (km) f = 1 kHz	Threat Speed (m / s)	Search Time (s) n = 1	Search Time (s) n = 6	DTGI (km)	TTGI (s)
SUB-1	3.2	5.1	152.92	25.49	3.1	601.3
SUB-2	3.5	5.1	152.92	25.49	3.4	661
SUB-3	1.5	5.1	152.92	25.49	1.4	277.5
SB-1	3.3	20.6	152.92	25.49	2.8	134.1
SB-2	5.9	25.6	152.92	25.49	5.3	206.8
SB-3	8.4	15.4	152.92	25.49	8	519.9
Mine-1	1	0	152.92	25.49	1	N/A*
Mine-2	.8	0	152.92	25.49	.8	N/A*
Mine-3	1.2	0	152.92	25.49	1.2	N/A*
Mine-4	.7	0	152.92	25.49	.7	N/A*
Torp-1	.8	25.6	152.92	25.49	.1	4.7
Torp-2	.8	102.9	152.92	25.49	0**	0**
Torp-3	.5	20.6	152.92	25.49	0**	0**

*Not applicable because the threat is not moving.

**Zero indicates that these threats could only be detected at a .95 probability of detection after they passed or impacted the central point of the expeditionary force.

Table V-31 1 kHz — Cylinder Search Geometry (.95 P_D)

These results show that several threats are able to approach very close to the defended assets if a point system is utilized. The maximum weapons release range for several of the threat platforms is 300 km (maximum effective range of ASCM-2). Therefore, a future sensor should be able to detect the threat platform well before the maximum weapons release range and allow time for defensive weapons to prevent the release of the enemy's weapons. This capability gap drives the need for a sensor that is able to detect threat platforms at longer ranges and with ample time to counter them before they can reach their weapons' maximum effective ranges. These requirements drive the need for a distributed sensor network.

The results of searching the same volume with the 25 kHz active sonar demonstrated its impracticality. The search time was 15,929 seconds, or 4 hours 26 minutes. Furthermore, the use of this frequency does not give sufficient detection ranges to search out as far as the 1 kHz system. This shows that the higher frequency sonar (25 kHz and 56 kHz) will require more narrowly defined search volumes in order to be used effectively. For these reasons, the higher frequency sonar is better suited for searching very slow or non-moving objects such as mines in a restricted volume. The volume chosen to model the 25 kHz sonar is a 1 km x 100 m cylinder. The results of searching for mines with the 25 kHz sonar in that volume are listed in Table V-32.

Threat	**Range (km) f = 25 kHz**	**Search Time (s) n = 1**	**Search Time (s) n = 6**
Mine-1	1	7890	1315
Mine-2	1	7890	1315
Mine-3	1	7890	1315
Mine-4	1	7890	1315

Table V-32 25 kHz — Cylinder Search Geometry (.95 P_D)

To put this table into perspective, with six point searchers, it would take approximately 22 minutes to search the volume to a 95 % probability. With one searcher, the search would take 2 hours and 12 minutes. In some cases, the time required to search to this probability may be excessive, therefore, Table V-33 shows the trade-off for an 80 % probability of detection.

Threat	**Range (km) f = 25 kHz**	**Search time (s) n = 1**	**Search time (s) n = 6**
Mine-1	1	4440	740
Mine-2	1	4440	740
Mine-3	1	4440	740
Mine-4	1	4440	740

Table V-33 25 kHz — Cylinder Search Geometry (.80 P_D)

With an 80 % probability of detection, six searchers would require approximately 12 minutes to sweep the volume. One searcher would require approximately 72 minutes to search the same volume. These tables show that deepwater mine hunting will be very time-consuming or platform intensive work with respect to other threat sensor pairings.

g. Sonar — Distributed Sensor Configuration

Threat	Range (km) f = 1 kHz	Threat Speed (m / s)	Search Time (s)	DTGI (km)	TTGI (s)
SUB-1	7	5.1	153	369.2	72396
SUB-2	7	5.1	153	369.2	72396
SUB-3	7	5.1	153	369.2	72396
SB-1	6.9	20.6	153	366.8	17803
SB-2	7	25.6	153	366.1	14300
SB-3	7	15.4	153	367.6	23873
Mine-1	.9	0	153	363.9	N/A*
Mine-2	1.5	0	153	364.5	N/A*
Mine-3	1.5	0	153	364.5	N/A*
Mine-4	1.6	0	153	364.6	N/A*
Torp-1	3.2	25.6	153	362.3	14152
Torp-2	3.2	102.9	153	350.5	3406
Torp-3	1.8	20.6	153	361.6	17556

*Not applicable because the threat is not moving.

Table V-34 1 kHz — Cylinder Search Geometry (.95 P_D)

Just as described in the radar distributed sensor configuration section, in order to provide the necessary 360^o coverage and cover a desired search radius of 370 km around the expeditionary warfare force, the number of USV or UUV required to populate a distributed sensor network could be calculated using Equation (46). In the sonar example, the shortest detection range occurs at 7 km against SUB-3. The resulting radius of deployment around the expeditionary warfare force (R) is 363 km. Using these inputs, the number of USV or UUV required to fill the sensor network (N) is 163. Once again, this excessively large number demonstrates the drawbacks of a distributed network that employs smaller sensors over a large area.

The conceptual USV/UUV sensor network, however, would be able to act as an effective tripwire against every surface or subsurface threat to the Sea Base. It provides particularly good detection ranges and reaction times against the submarines when compared to the point system. Once again, if cued acquisition is used from another sensor platform, an uninterrupted track of these threats is possible throughout the battle space. Without the use of cued acquisition, the distributed network is still able to reduce the uncertainty of threat positions and narrow the scope of subsequent reacquisition searches.

5. Conclusions

An interesting sensor system relationship (see Figure V-8) emerged from the search detection study. Each search system for a given sensor type is a trade-off of the number of search platforms, the search time, and the probability of detection in a defined volume. The goals of the system are to minimize the search time, minimize the number of search platforms required, and maximize the probability of detection. Any two of these goals may be satisfied to the detriment of the third. The relationship between these variables follows the probability of detection formulas identified for each sensor.

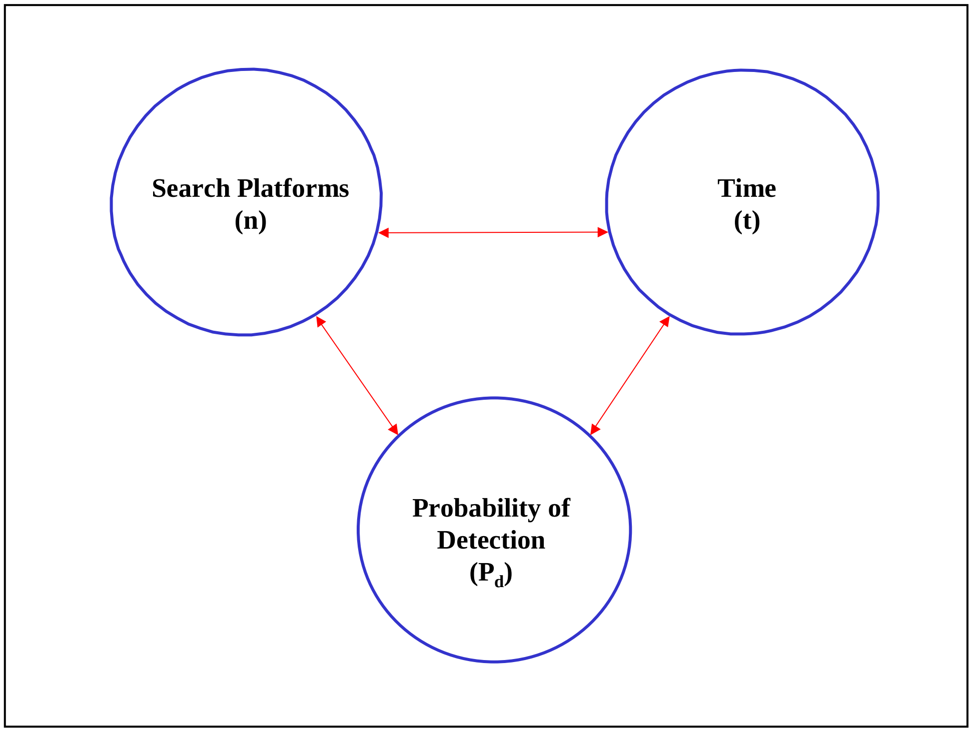


Figure V-8 Sensor System Relationship

The benefits of a distributed sensor network throughout the battle space are readily apparent from the results obtained. The point and distributed sensor configurations compliment each other very well. By employing a mix of point and distributed sensor systems, an effective tripwire against every threat to the Sea Base could be achieved. Furthermore, a distributed sensor network offers the benefits of greater detection ranges and more reaction time by extending the sensors' horizons and by achieving greater target cross sections against a variety of the threats. For example, the point sensor, assumed to be a ship, provides an early warning capability for the airborne assets in its vicinity against inbound SAMs. Likewise, the distributed sensors, assumed to be on UAV or UUV/USV, provide early warning for the point assets against many of the other threats. Cued acquisition from various sensor platforms might be able to provide uninterrupted track data throughout the battle-space. Even without the use of cued acquisition, a distributed sensor network could reduce the uncertainty of threat positions and narrow the scope of subsequent reacquisition searches, thus providing a more robust force protection capability to the expeditionary force. Point-only sensor systems (radar, IR, or sonar), or overhead-only sensor systems (radar or IR), display weaknesses in their inability to achieve a 0.95 probability of detection for several threat platforms prior to maximum weapons release ranges. This capability gap drives the need for a sensor system that is able to detect threat platforms at longer ranges and with ample time to counter them before they can reach their weapons' maximum effective ranges. The use of the IR and radar systems further allows the expeditionary warfare force to exploit attempted enemy trade-offs in reflectivity and emissivity. For these reasons, a mixed distributed and point sensor network system composed of IR, radar, and active sonar systems are recommended for implementation in future force structures.

A necessary next step in defeating the threat platforms is to develop weapons systems capable of destroying the targets prior to their weapons release points.

D. ENGAGEMENT ANALYSIS

1. Introduction

The Threat Analysis identified certain "baseline" future representative threats that the Sea Base might encounter in the 2016 timeframe. The Sensor Analysis identified the capability of various sensors (radar, lidar, IR, and sonar) to detect those threats by analyzing various threat-sensor pairings. The Search Analysis then addressed how differing sensor architectures might best detect those threats by calculating and analyzing the search time required to obtain a 0.95 probability of detection. Sensors were placed on various platforms in order to determine what mix of sensor-platform pairings would provide the most robust threat detection capability to the Sea Base. Given that the future representative threats were detected, a necessary next step in defending the Sea Base is a means of countering them. The method of defending the Sea Base analyzed in this chapter is through the employment of weapons capable of destroying the postulated threats identified in the Threat Analysis. The defensive weapons chosen by this study reflect current capabilities or capabilities that are thought to be attainable and deployable by 2016. All weapons information was obtained through the use of unclassified, and open-source material.

This chapter will outline the preliminary analysis completed regarding the effects and interactions of sensor range, weapon range, and weapon speed by analyzing various weapons and force protection architectures and those systems' associated probabilities of kill. Furthermore, the effects of reaction time on force survivability will be analyzed in order to illuminate certain advantages that differing weapon system architectures may have on the overall survivability of the expeditionary force.

2. Preliminary Analysis

a. Point Weapons

The greatest factor for attaining higher probabilities of kill against high-speed short notice threats is the ability to detect the threats at a greater range. For all of the point weapons analyzed, the ability to detect the threats at greater ranges resulted in more available reaction time, which generated more engagement opportunities. The increased engagement opportunities lead to increases in the probabilities of kill. For high-speed, short-notice threats, the weapons' minimum engagement ranges and speeds were also important secondary factors. The weapons' maximum engagement ranges however, were largely irrelevant. For these reasons, primary consideration for achieving higher probabilities of kill should be given to the sensor system's detection range and search speed. This leads to the conclusion that a distributed sensor network similar in design to that discussed in the Search Analysis should be used with a point weapon system. Furthermore, the weapons themselves should possess greater speeds and reduced minimum intercept ranges.

b. Distributed Weapons

For the distributed weapons, maximum range and speed were the primary factors for attaining greater reaction times and corresponding probabilities of kill. Because the sensor architecture for the distributed weapons is held constant and because the number of shots available to a distributed platform is limited in comparison to the number available from a point weapons platform, the ability of the weapon to generate more reaction time was the primary consideration. For these reasons, interceptors with higher speeds and longer ranges should be used with distributed platforms.

3. Methodology

This study first considered how a Sea Base in the 2016 timeframe would most likely mitigate future representative threats. Upon initial analysis, only physical defensive weapons were considered in mitigating those threats (e.g., missiles, guns, torpedoes, and lasers). However, further analysis revealed that other methods, such as electronic warfare could also effectively mitigate enemy threats. The SEA-4 Team employed the Systems Engineering Process to break down defensive weapons into two categories, hard kill and soft kill, as seen in Figure V-9.

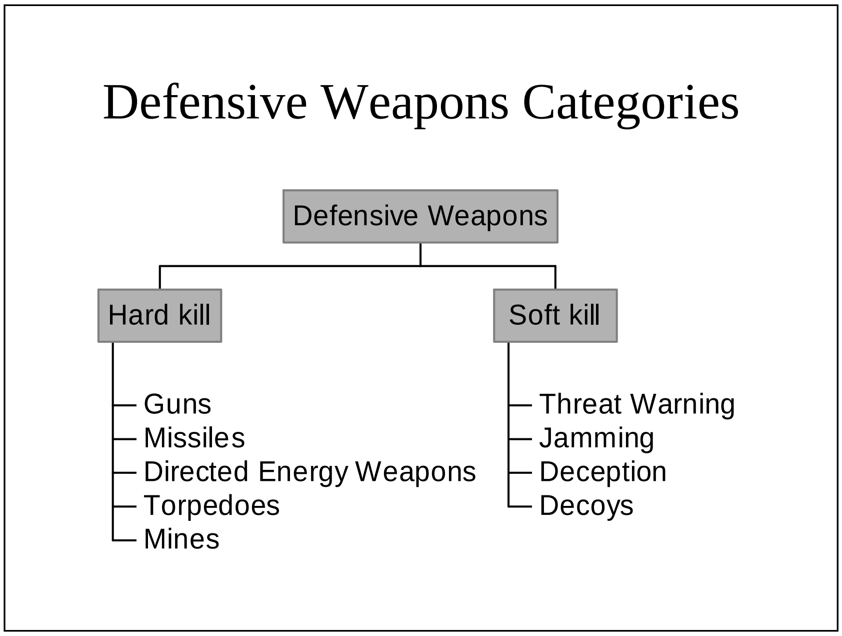


Figure V-9 Defensive Weapons

Building from these two methods, the next step was to determine what defensive weapons could reasonably intercept, or mitigate, each threat platform or weapon. For specific weapons considerations, each Sea Base platform and associated threat was evaluated and a list of possible defensive weapons was determined. Brainstorming, functional decomposition, and expert opinion were some of the tools used to develop the following threat-weapon pairings displayed in Table V-35.

PLATFORM	THREAT	DEFENSIVE WEAPON*
ExWar Ship	Anti-Ship Cruise Missile	HK- Missile, Gun, Directed Energy Weapon SK- Threat Warning, Jamming, Deception, Decoys
	Aircraft / Unmanned Aerial Vehicle	HK – Missile, Gun, Directed Energy Weapon SK – Threat Warning, Deception, Decoy
	Small Boat	HK – Missile, Gun, Directed Energy Weapon, Torpedo SK – Deception
	Torpedo	HK – Torpedo SK – Deception, Decoy
	Mine	HK – Gun, Directed Energy Weapon SK – Deception, Decoy
AAAV	Small Boat	HK – Gun SK – None
	Torpedo	HK – None SK – None
	Mine	HK – None SK – None
	Unguided Weapon	HK – None SK – None
HLCAC	Small Boat	HK – Gun SK – None
	Torpedo	HK – None SK – None
	Mine	HK – None SK – None
	Unguided Weapon	HK – None SK – None
LCU(R)	Small Boat	HK – Gun SK – None
	Torpedo	HK – None SK – None
	Mine	HK – None SK – None
	Unguided Weapon	HK – None SK – None
MV-22	Surface-to-Air Missile	HK – None SK – Threat Warning, Jamming, Deception, Decoy
	Aircraft / Unmanned Aerial Vehicle	HK – None SK – None
	Unguided Weapon	HK – None SK – None
HLAC	Surface-to-Air Missile	HK – None SK – Threat Warning, Jamming, Deception, Decoy
	Aircraft / Unmanned Aerial Vehicle	HK – None SK – None
	Unguided Weapon	HK – None SK – None
AH-1Z	Surface-to-Air Missile	HK – Missile SK – Threat Warning, Jamming, Deception, Decoy
	Aircraft / Unmanned Aerial Vehicle	HK – Missile SK – None
	Unguided Weapon	HK – None SK – None
UH-1Y	Surface-to-Air Missile	HK – None SK – Threat Warning, Jamming, Deception, Decoy
	Aircraft/Unmanned Aerial Vehicle	HK – None SK – None
	Unguided Weapon	HK – None SK – None

*Hard and Soft Kill are abbreviated as HK and SK, respectively.

Table V-35 Platforms, Threats, and Defensive Weapons Pairings

For purposes of clarity, as in the threat analysis, the defensive weapons terms are defined below. The following definitions for hard kill defense weapons were adapted from the threat analysis and used in this section to facilitate an understanding of all weapons considerations.

- **Gun** – A system capable of firing an unguided projectile that follows a ballistic trajectory with no in-flight control.
- **Missile** – An unmanned, self-propelled vehicle that sustains flight through the use of aerodynamic lift.
- **Directed Energy Weapon** – Uses the energy carried by radiation (electromagnetic, acoustic, or nuclear particle) collimated into directional beams to damage or destroy targets.
- **Torpedo** – A steerable, self-propelled, underwater projectile filled with an explosive charge used for destroying ships or submarines.
- **Mine** – An explosive device laid in the water with the intention of damaging or sinking ships or surface transport assets.

Electronic warfare is defined as military action using electromagnetic energy to control the electromagnetic spectrum or to attack the enemy. Electronic warfare is composed of three components: electronic attack, electronic protection, and electronic warfare support. Electronic warfare support is the act of searching, intercepting, identifying, and locating sources of radiated electromagnetic energy for the purpose of immediate threat recognition or exploiting the enemy's use of the electromagnetic spectrum. Electronic attack is the use of electromagnetic or directed energy to attack the enemy (personnel, facilities, and equipment) with the intent of degrading, neutralizing, or destroying their combat capability. The intent of electronic attack is to degrade or deny the enemy's use of the electromagnetic spectrum. Electronic protection is action taken to protect friendly forces from enemy employment of electronic warfare that would degrade or destroy combat capability. The following definitions for soft kill defensive weapons were adapted from electronic warfare principles and used in this section to summarize soft kill weapons capabilities.

- **Threat Warning** – Electronic warfare support system that provides the platform with unambiguous, real time, threat information that can be analyzed and used in developing an appropriate response to the given threat.
- **Jamming** – Electronic attack system that introduces noise into a sensor system as interference so that desired signals cannot be reliably detected.

- **Deception –** Electronic attack system that introduces signals into a sensor system that the sensor system will mistake for the desired signals and initiate incorrect actions.
- **Decoys –** Electronic protection system that is designed to imitate the signature characteristics of the intended target to draw a threat away from that target or to otherwise deceive the enemy as to the true status of the intended target.

Analysis of platform/weapon pairings enabled the team to determine the most effective weapon to use in the defense of Sea Base platforms. These conclusions were used to assign attributes to these particular platforms in the modeling process. In each case where there was no associated weapon to use for defense against a particular threat, it was determined that tactics (avoidance, evasion, etc.) and/or escorts would be used to provide a means of defense for that platform. Additionally, it was determined that most air assets would have to rely primarily on soft kill weapons for self-defense. This also reinforces the fact that these platforms should be designed and built with survivability as the paramount feature.

As described in the value system design section of Chapter IV, this study focused its efforts on the “defeat attacks” subfunction of susceptibility due to the limited resources and time available. By concentrating on the hard kill aspect of susceptibility, the SEA-4 Team felt it could better affect the overall survivability of the expeditionary force. The “preventing attacks” subfunction and the soft kill aspect of susceptibility was not addressed in this section, but was considered in the final proposed architecture through the use of the supporting studies section.

From these initial hard kill pairings, and by incorporating the results and conclusions from the Sensor and Search Analysis, this study was able to begin the weapons-modeling phase. Certain characteristics of the weapon systems, to include various system delay times, such as detect-to-track, track-to-launch, and mechanical delays, were then considered and used as inputs into mathematical spreadsheet models for each weapon. By adding these characteristics and making further assumptions regarding tactics, such as shoot-shoot-look-shoot-shoot (SS-L-SS) or shoot-shoot-look (SS-L), and future capabilities, such as common operational picture (COP), or cooperative engagement strategy (CES), these models were able to provide a more detailed look at the function of engagement. A COP will provide shared detection and track data from any sensor to all friendly platforms, essentially allowing all platforms to see the same battle space at the same time. CES will allow any platform to engage enemy threats based on the track data provided by any sensor. Table V-36 summarizes the assumptions made for the engagement analysis model.

ASSUMPTION	POINT WEAPON CONFIGURATION	DISTRIBUTED WEAPON CONFIGURATION
System detect-to-track delay (s)	1	1
System track-to-launch delay (s)	2	2
System engagement analysis delay after intercept (s)	2	N/A*
Delay between any two shots from same platform (s)	2	2
Common operational picture capability	Yes	Yes
Cooperative engagement strategy capability	Yes	Yes
Probability of track given a detection	1	1
Interceptor probability of kill	0.8	0.8
Firing doctrine	SS-L-SS	SS-L

*Not applicable—distributed platform employs only two weapons.

Table V-36 Engagement Analysis Model Assumptions

In order to study these tactics and capabilities, differing weapons configurations were established to determine their respective effects on force protection of the Sea Base.

The first weapon configuration modeled assumed that the defensive weapon analyzed originated from an asset located near the high-value force center. This architecture is referred to as the point weapons system and is similar in design to the point sensor system. In this case, r represents the weapon’s distance from force center, r′ represents the weapon’s range, and R is the radius of the area concerned. A point weapon configuration occurs when r << R. Figure V-10 graphically represents the point weapon architecture.

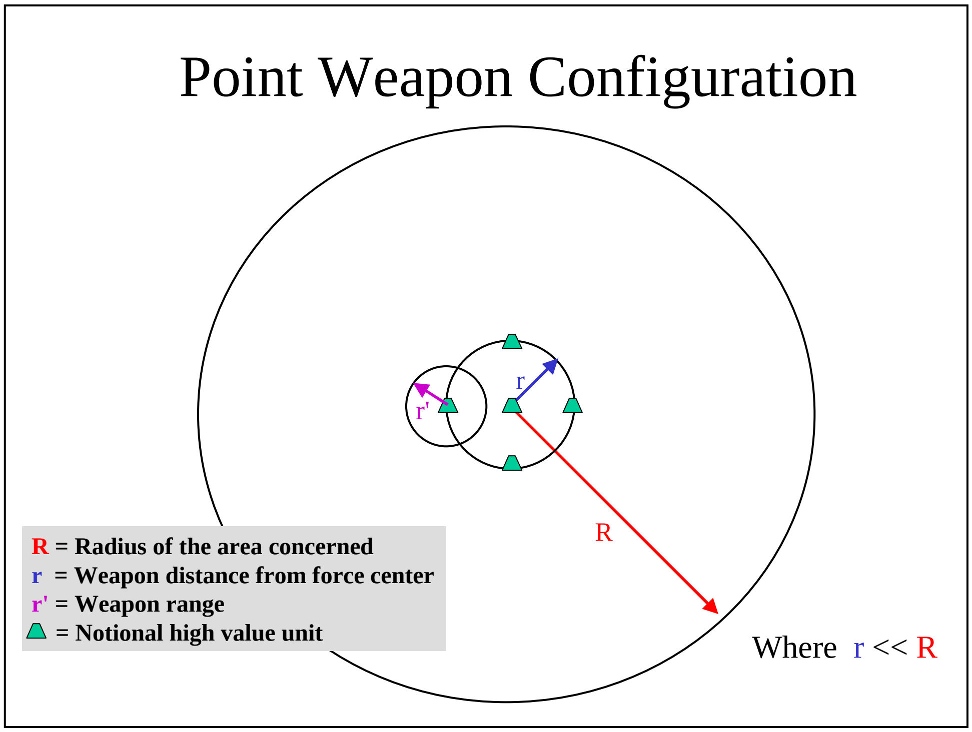


Figure V-10 Point Weapons Architecture

The second weapon configuration modeled assumed that the weapons were deployed from the force center and placed onboard various assets (UAV, UUV, or USV) in a manner consistent with the distributed sensor architecture. This architecture is referred to as the distributed weapons system. In this system, the defensive weapon analyzed originates from a distributed asset not located near the force center. Again, R represents the radius of the area of concern, r′ represents the weapon's range, and r represents the weapon's distance from the force center. The distributed weapon architecture occurs when $r \approx R$. Figure V-11 graphically represents the distributed weapon architecture.

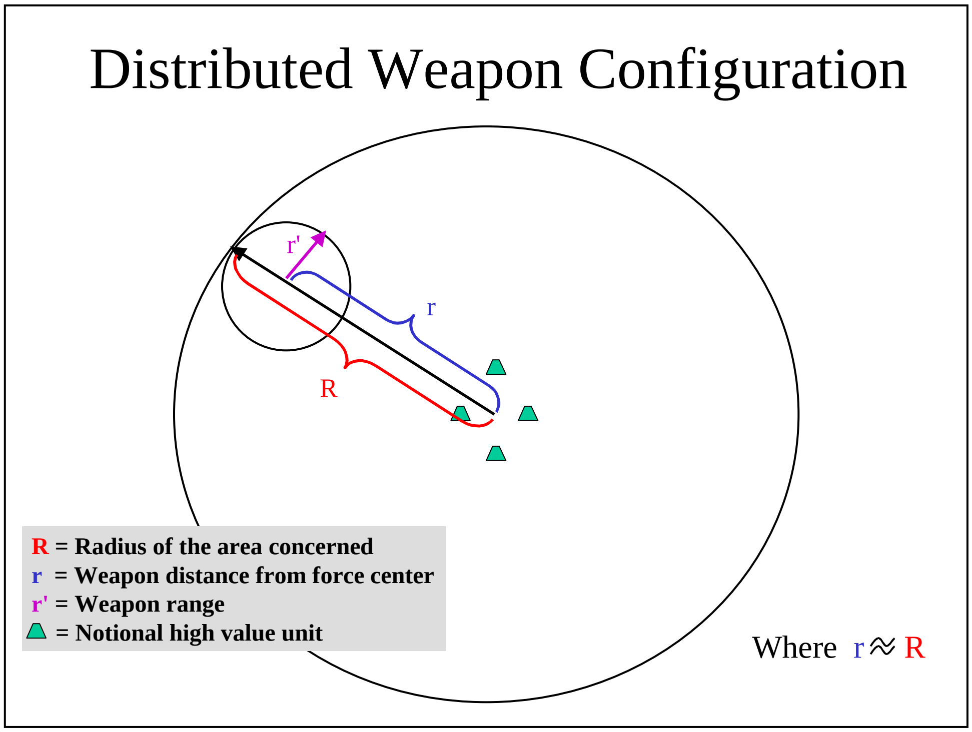


Figure V-11 Distributed Weapons Architecture

The next appropriate step is to employ some sort of weapon from these differing architectures in order to mitigate the various future representative threats. As mentioned earlier, missiles, torpedoes, and lasers were considered as possible weapons to be employed from point and distributed assets. Current and conceptual weapons were developed from open source information in order to provide a generic capability that exits either now, or could reasonably assumed to be available in the 2016 timeframe. Table V-37 shows the various characteristics of the current and conceptual weapons that were modeled in the engagement analysis.

WEAPON	TYPE	SPEED (m / s)	MAXIMUM RANGE (km)	MINIMUM RANGE (km)
Interceptor 1 (INT-1) (Current)	Surface-to-air missile	825	130	5
Interceptor 2 (INT-2) (Conceptual)	Surface-to-air missile	1650	370	5
Interceptor 3 (INT-3) (Current)	Air-to-air missile	1320	56	2
Interceptor 4 (INT-4) (Conceptual)	Air-to-air missile	1980	93	2
Free Electron Laser (FEL)	Directed energy	$3\text{x}10^8$	10	1
Torpedo 1 (T-1) (Current)	Surface- or subsurface-launched torpedo	20.6	7.3	.1
Torpedo 2 (T-2) (Conceptual)	Surface- or subsurface-launched torpedo	25.7	11	.1

Table V-37 Modeled Current and Conceptual Weapon Characteristics

Reverting back to the Sensor Analysis, the detection ranges calculated in that section were transformed into DTGI values in the Search Analysis by applying first principle probability of detection equations, and by introducing the concept of the time required to detect those threats with a 0.95 probability of detection. The DTGI values were then converted into TTGI values based on threat speed. These numbers (DTGI and TTGI) served as the starting point for the Engagement Analysis. An engagement model was then developed in order to determine the maximum number of engagements that could be made against any threat. This model was based on the assumptions and weapons listed in Table V-36 and Table V-37, respectively, the architectures illustrated in Figure V-10 and Figure V-11, and the DTGI and TTGI values calculated in the Search Analysis. An example of this model is demonstrated in Figure V-12. The x-axis represents the TTGI. Time zero begins when the threat is detected by the sensor architecture at its DTGI range from the Search Analysis. The y-axis represents the DTGI. The maximum intercept range is set by the defensive weapon's maximum effective range, conversely the minimum range at which the defensive weapon can effectively engage the threat sets the minimum intercept range. The time delays mentioned in the assumptions (Table V-36) are visibly represented along the x-axis. As an increase in time occurs, a corresponding decrease in distance between the threat and the defensive asset occurs.

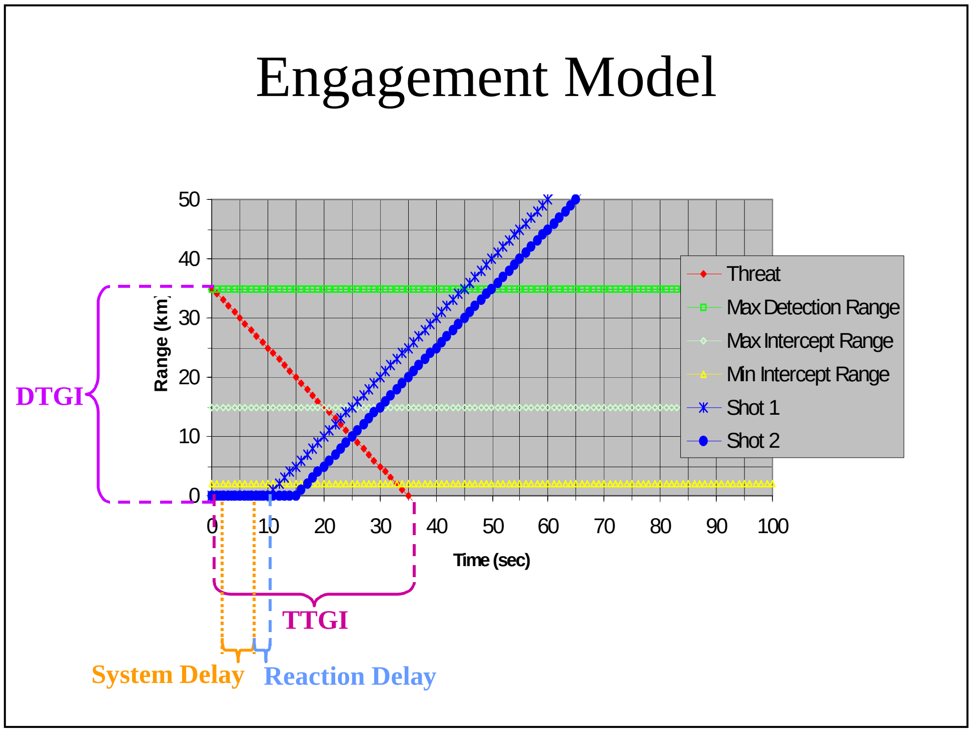


Figure V-12 Engagement Analysis Model Example

As seen in this example, one engagement with two shots was made on the single incoming threat. The speed of the incoming threat, coupled with the system delays and engagement analysis delay, prevented the system from conducting a second engagement prior to the threat reaching the minimum intercept range.

This model was then applied to each sensor-weapon pairing and tested against each future representative threat. The following sections outline those results.

4. Modeling Equations and Results

a. Point Weapons System

From the Search Analysis, ASCM-3 presented the lowest TTGI values for the point and distributed sensor systems and therefore was chosen as the "baseline" threat analyzed for the point weapons engagement analysis models. From the assumed system delay times, the available reaction delays and subsequent number of engagements can be computed for each of the threat-sensor-weapons groups. Figure V-13, Figure V-14, and Figure V-15 demonstrate the

Engagement Analysis models for the Interceptor-1 weapon system using point sensors against ASCM-3.

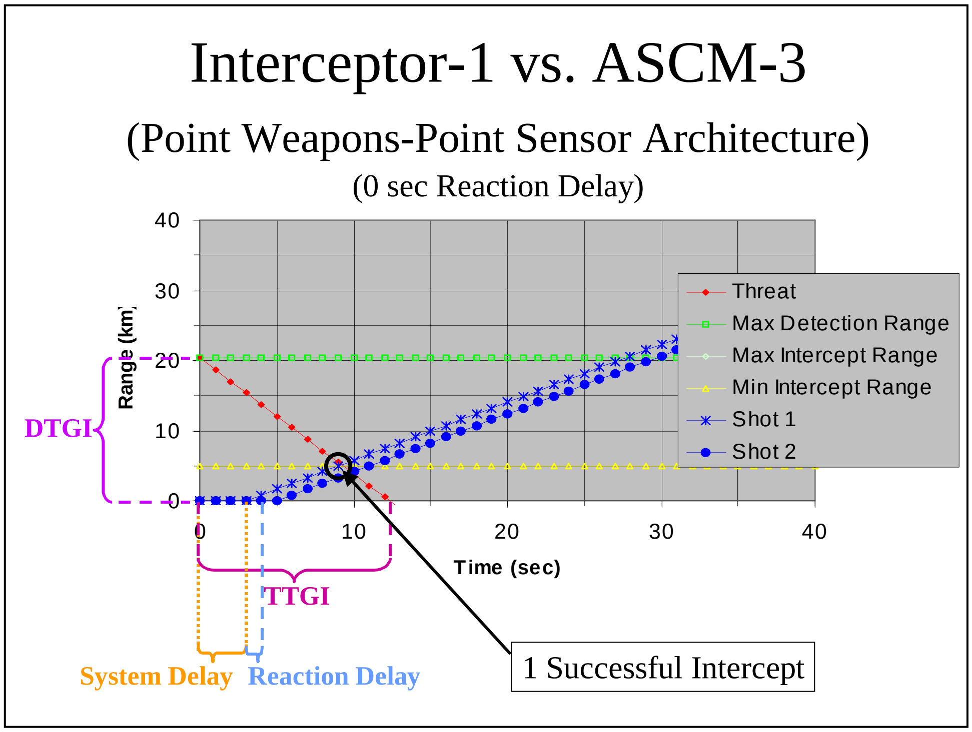


Figure V-13 INT-1 vs. ASCM-3 (0 sec delay)

In order for the given system to achieve an intercept, the reaction delay available to the operator cannot be more than one second beyond the system delay time. If the operator's reaction delay is more than one second, the second shot in the salvo will not achieve an intercept before the minimum intercept range, and therefore will not intercept the threat. The next two figures demonstrate a one-second reaction delay and a two-second reaction delay, respectively.

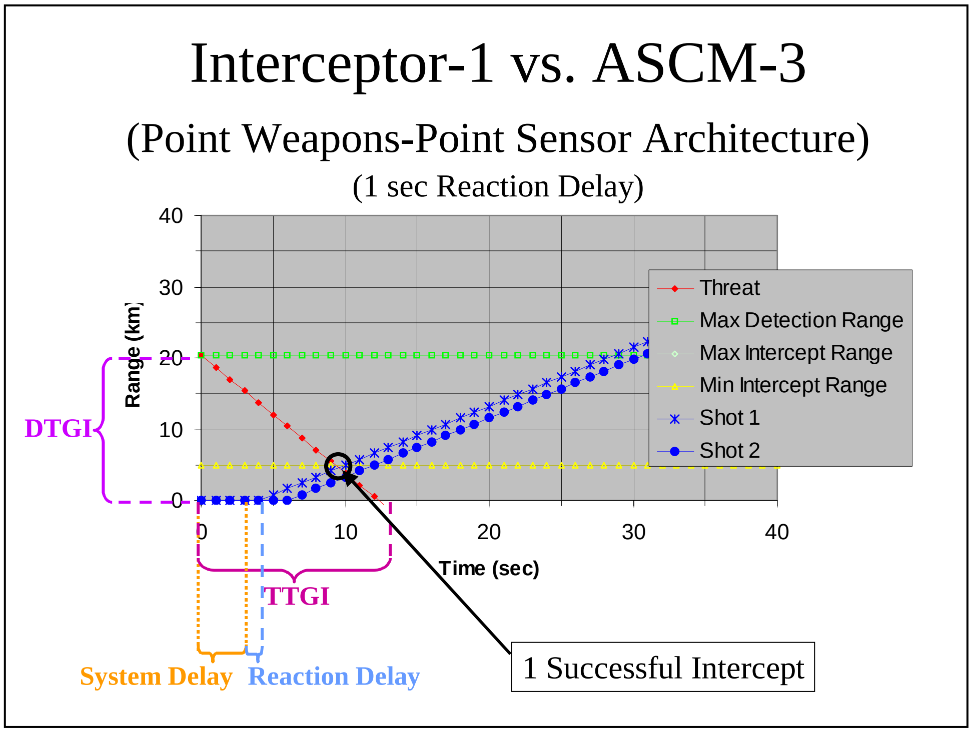


Figure V-14 INT-1 vs. ASCM-3 (1-sec delay)

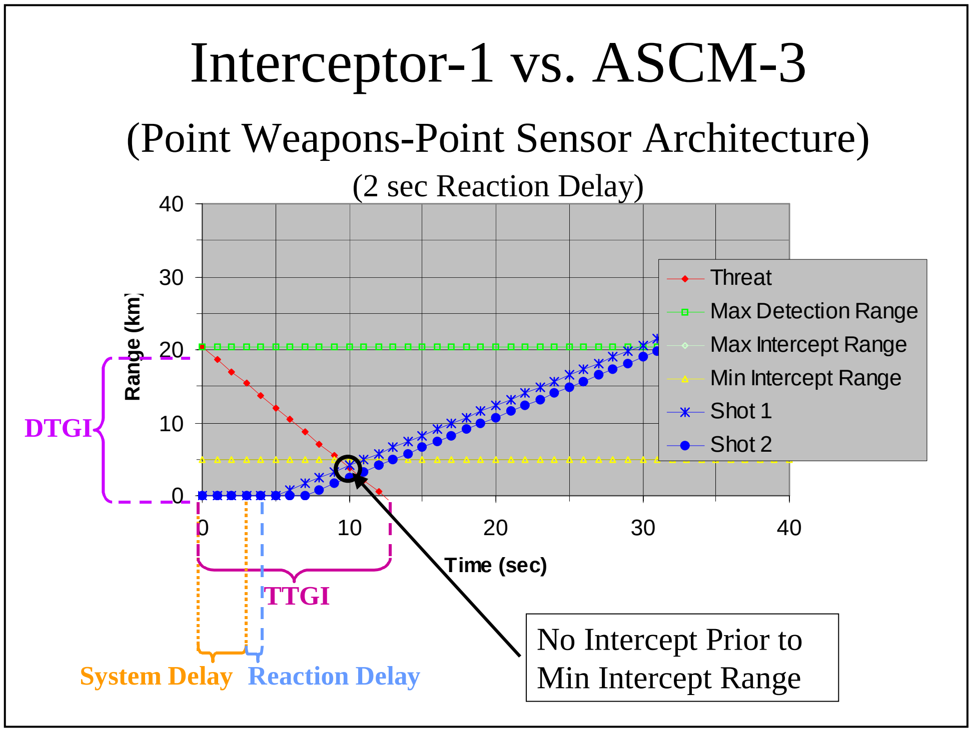


Figure V-15 INT-1 vs. ASCM-3 (2-sec delay)

The Engagement Analysis models were applied to each point weapon with both point and distributed sensor systems against ASCM-3. Using these models and the calculated reaction delay times, the number of interceptions that are possible can be calculated for each point weapons system. The results of the total number of possible interceptions, or shots, for each system versus reaction delays for the point weapons-point sensor architecture and the point weapons-distributed sensor architecture are displayed in Figure V-16 and Figure V-17, respectively.

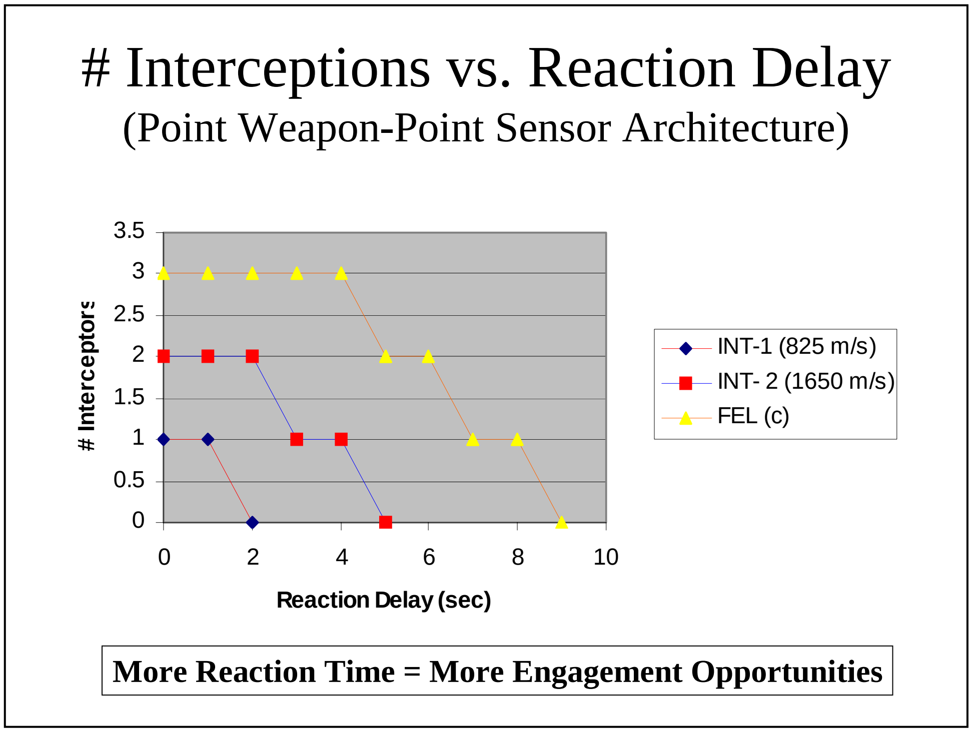


Figure V-16 Point Weapons-Point Sensors Reaction Time Analysis

Figure V-16 demonstrates that in a point weapons-point sensor architecture, the FEL dominates with an additional four seconds of reaction delay available when compared to Interceptor 2 and an additional seven seconds of reaction delay available when compared to Interceptor 1. The longer available reaction delays can be used to generate additional engagement opportunities.

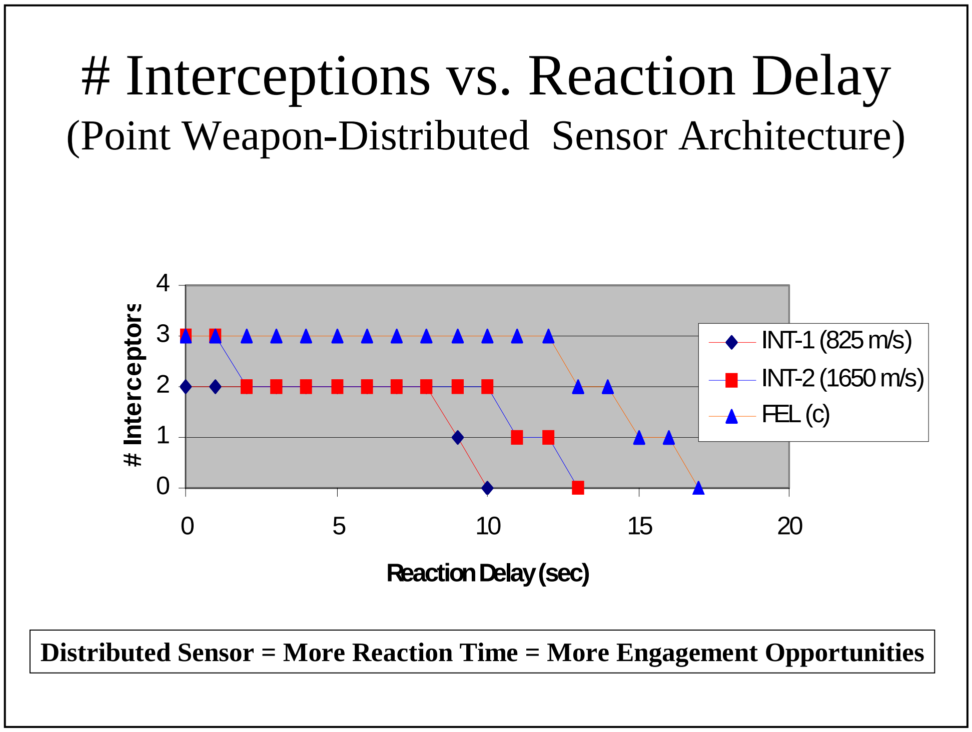


Figure V-17 Point Weapons-Distributed Sensors Reaction Time Analysis

Figure V-17 demonstrates that in a point weapon-distributed sensor architecture, the FEL not only provides an additional four seconds of reaction delay when compared to Interceptor 2 and an additional seven seconds when compared to Interceptor 1, as in the previous example, but the distributed sensors provide an additional reaction delay of eight seconds to all of the weapons systems. Again, these longer available reaction delays can be used to generate more engagement opportunities.

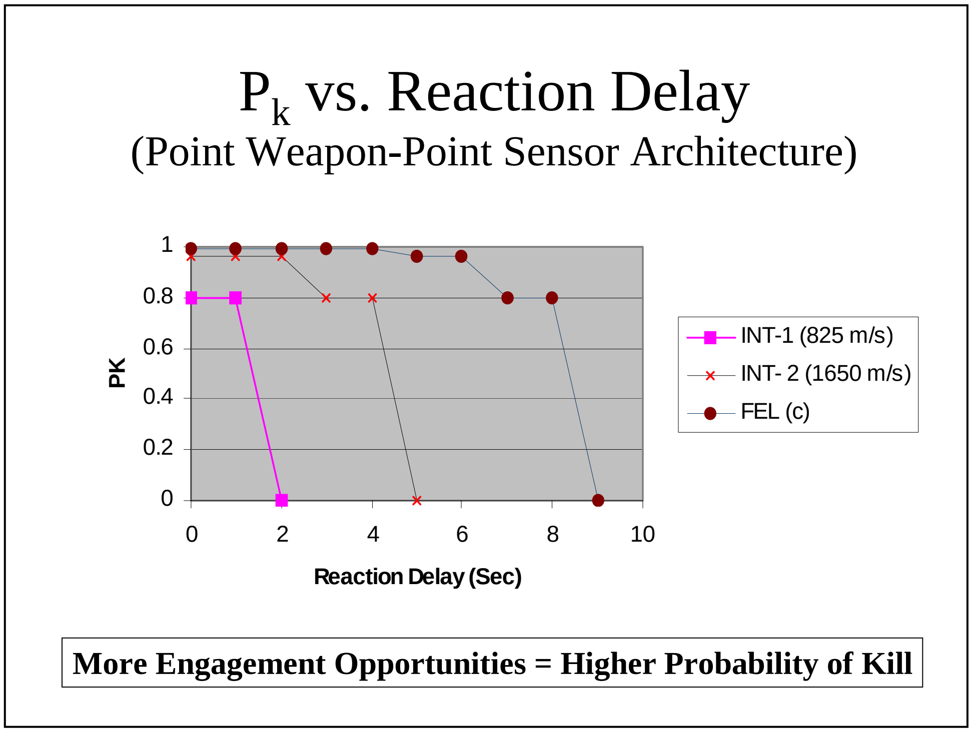
From the reaction delay analysis, it may be reasonably concluded that for high-speed, short-notice threats, the use of the distributed sensor is the primary factor in the ability of the system to generate more available reaction delay and therefore more engagements for a given weapon system. While clearly secondary factors, the models also demonstrate that a defensive weapon's speed and minimum engagement range may be more important than its maximum engagement range when defending against the high-speed, short-notice threats. Furthermore, by determining the number of interceptions that are possible against a given target, the total probability of kill can be calculated (P_k).

If each interceptor or shot has a 0.80 P_k against ASCM-3, then the resulting total P_k versus ASCM-3 may be found by the formula:

Equation (47) Total $P_k = 1-(1-(P_k))^N$ where,

Total P_k = Sensor-Weapon Architecture Total Probability of Kill
P_k = Interceptor Probability of Kill
N = Number of Interceptors Fired at Threat

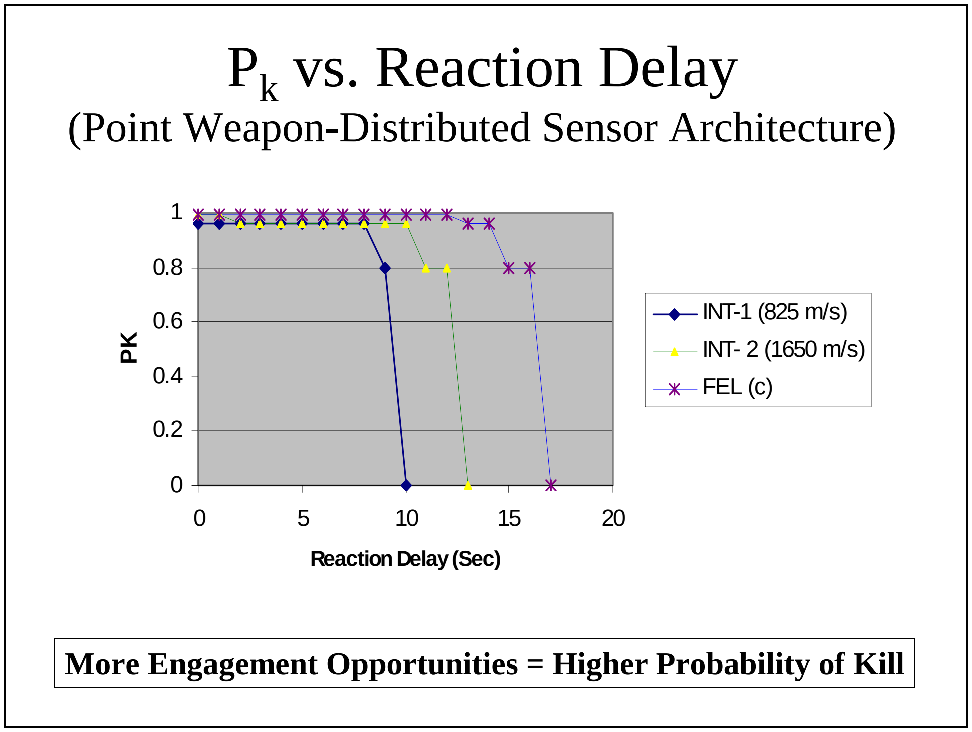
The resulting total probabilities of kill versus reaction delays for the point weapons-point sensor architecture and the point weapons-distributed sensor architecture are displayed in Figure V-18 and Figure V-19, respectively.



More Engagement Opportunities = Higher Probability of Kill

Figure V-18 Point Weapons-Point Sensors Probability of Kill Analysis

From the engagement analysis models, the FEL is able to provide the operator with more available reaction delay and can therefore provide more engagement opportunities. As displayed in Figure V-18, the increased engagement opportunities generate higher probabilities of kill for the FEL system compared to Interceptor 1 or Interceptor 2 for the point weapons used with the point sensor systems.



P_k vs. Reaction Delay

(Point Weapon-Distributed Sensor Architecture)

More Engagement Opportunities = Higher Probability of Kill

Figure V-19 Point Weapons-Distributed Sensor Probability of Kill Analysis

From the engagement analysis models, the distributed sensors are able to provide the operator with more available reaction delay when compared to the point sensor system, and subsequently provide more engagement opportunities. As displayed in Figure V-19, the increased engagement opportunities generate higher probabilities of kill for all of the weapons systems analyzed. Again, the FEL system, when compared to Interceptor 1 or Interceptor 2, is able to achieve greater reaction delays and higher probabilities of kill for the point weapons used in conjunction with the distributed sensor system.

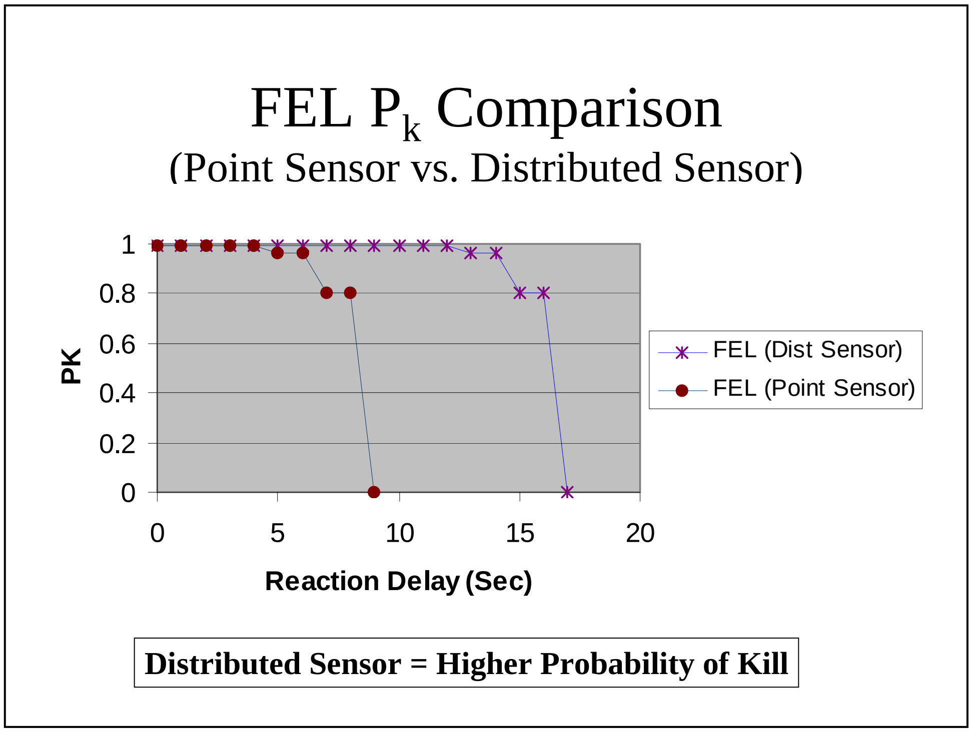


Figure V-20 FEL Probability of Kill

Figure V-20 provides a comparison of FEL used with the point and distributed sensor systems. This graph reveals that the distributed sensor affords the operator an additional eight seconds of possible reaction delay. This eight-second increase in available time was found to hold constant for the threat-weapons pairs (ASCM-3 vs. Int 1, Int 2, FEL) modeled using the point and distributed sensor architectures.

The analysis of the above figures shows that the reaction delay is the most critical factor for determining the probability of kill against high-speed, short-notice threats (ASCM-3). An increase in the reaction delay generates fewer firing opportunities with a corresponding decrease in the total probability of kill. If only the above hard kill options are considered, and if the ASCM is assumed to function properly, then the probability that a high value unit is hit is represented by the following equation:

Equation (48) $P_h = 1 - (\text{Total } P_k)$ where:

P_h = Probability of High Value Unit Being Hit
Total P_k = Sensor/Weapon Architecture Total Probability of Kill

The biggest factor then in reducing the probability of hit, thereby improving the force survivability, is the ability to generate more interceptions by increasing the possible reaction delay. The distributed sensor architecture provides this capability by detecting the threat further away from the high-value units. From the graphs, greater weapon speed and reduced minimum intercept range are secondary factors, but do appear to enhance the probability of kill if longer reaction delays are desired against high-speed, short-notice threats.

For undersea threats, the timeline analysis revealed that the ability to detect the threat platform is the key to its defeat. The response times from detection were very large when compared to the surface and air threats. From the Search Analysis, the point sensor model was unable to detect the threats, particularly the submarines, at sufficient ranges to prevent short-notice weapons release. The result was an inability to effectively counter the threat torpedoes. This leads to the conclusion that the submarine threat must be detected far enough from the protected assets to prevent unmitigated torpedo launches. Because of the point sensor system's limited detection ranges and the threat torpedoes' long range, the means of achieving this goal might be reached through the distributed sensor architecture modeled in the Search Analysis.

b. Distributed Weapons System

Engagement analysis and reaction delay models similar to the ones used for the point weapons system were used to determine the probability of kill that could be attained against any threat based on the threat assumptions and the distributed weapons assumptions, as well as the time required to obtain a 0.95 probability of detection from the Search Analysis. From the Search Analysis, ACFT-2 presented the lowest TTGIs for the UAV platforms of the distributed sensor system and therefore was chosen as the "baseline" threat analyzed in the distributed weapons model. The results of the total probability of kill versus reaction delay are displayed in Figure V-21.

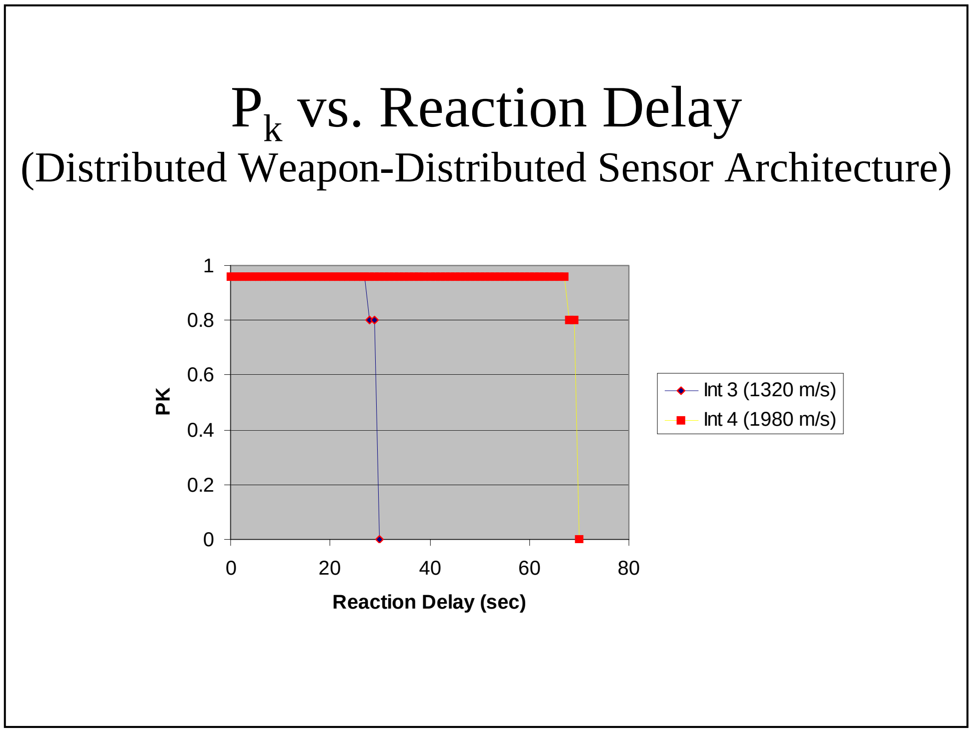


Figure V-21 Distributed Weapons Probability of Kill

For both Interceptor 3 and Interceptor 4, the UAV's distributed sensor provides the initial detection. The UAV can only carry two interceptors, which limits the maximum probability of kill to 0.96; however, it is readily apparent that the superior speed and range of Interceptor 4 are desirable if longer reaction times are required.

5. Conclusions

From the models, it is readily apparent that the ability to detect a threat at a longer range leads to a greater probability of kill for a given weapon system. The models prove that a weapon's range is largely irrelevant if the sensor's range is limited in comparison. The weapon's speed, however, is a desirable attribute, particularly if longer reaction times are required; but it is clearly secondary to the sensor's search speed and range. This rationale is predicated on the assumption that you cannot shoot what you cannot see. Therefore, the ability to expand the sensor coverage and improve the sensor search speed will allow the force to capitalize on a defensive weapon's potential speed and range advantages, which, in turn, will create more engagement opportunities, thereby increasing the probability of kill against the postulated threats.

E. SUPPORTING STUDIES

1. Expeditionary Warfare Integrated Project

a. Purpose

In April 2002, OPNAV N75, the office of the Deputy Chief of Naval Operations for Expeditionary Warfare tasked the Wayne Meyer Institute of Systems Engineering to conduct an expeditionary warfare study. The Institute then charged Systems Engineering Integration Team Three (SEI-3) to engineer an overarching set of system requirements for a system of systems to conduct expeditionary operations in littoral regions and to explore interfaces and system interactions. The team then had to compare current, proposed, and conceptual sea-based platforms against the identified requirements. SEI-3 was also tasked to examine the effects of speed, reduced footprint ashore, Sea Basing, modularity of design and reduced manning.

b. Methodology

The SEI-3 group applied elements of the Systems Engineering Management Process (SEMP). They first developed an architecture that clearly defined all the requirements of expeditionary warfare. The SEI-3 group then conducted a functional decomposition of expeditionary warfare and determined required capabilities. The required capabilities were then evaluated and compared to the capabilities expected from programs of record in the Department of Defense (DOD).

SEI-3 developed and compared three expeditionary architectures: current, proposed, and conceptual. SEI-3 generated requirements for the Aeronautical Engineering Design Group, Total Ship System Engineering (TSSE) Design Group, and a Space Operations Design Group for the design of platforms for the conceptual architecture. Furthermore, SEI-3 developed models to compare the three architectures.

Two of the SEI-3 modeling efforts were of particular importance to the SEA-4 study for the following reasons. One of the models was developed to analyze Sea Base supporting operations. The supporting operations analysis focused on developing platform requirements for force protection. The second model developed by SEI-3 focused on modeling the entire expeditionary process. The expeditionary process model was SEI-3's primary tool for comparing the current, proposed, and conceptual architectures.

SEI-3 used the Enhanced ISAAC Neural Simulation Toolkit (EINSTein) in the supporting operations analysis study to examine force protection concepts against various surface threats. EINSTein is a beta-version, agent-based simulation where entities are given "attributes" to describe mission, capabilities, and aggressiveness. Agents are represented as individual combat units from troops, to aircraft, to capital ships. Entities, such as ships, are free to move, act, engage, and disengage opposing forces according to these attributes. Agents move using a stochastic time-step simulation. EINSTein was originally designed to model small unit ground combat, but is now used as an artificial-life model to explore self-organized emergent behavior in land or maritime combat.

The supporting operation analysis explored the survivability of the Sea Base against ASCM attacks. A baseline defensive escort force of one CG, one DDG, and one FFG for each of the ExWar architectures (current, planned, and conceptual) was implemented against a baseline enemy force of 10 patrol craft and eight frigates. The supporting operation analysis also explored the use of the littoral combat ship (LCS) as an escort. From the baseline, escorts were added until the set goal of "80% of task force ships alive" was achieved.

SEI-3 utilized EXTEND to model the expeditionary warfare logistics process. EXTEND is a discrete event simulation tool that uses components, or blocks, and interconnections to model complex processes. Creating block diagrams where each block describes a part of a process, allows users to create a series of simple block definitions to describe complex processes.

The SEI-3 conceptual expeditionary model replaced the Iron Mountain with a Sea Base to host the logistics depot. In the model, a Marine Expeditionary Brigade (MEB)-sized force was built at an assembly area before proceeding as a task force (TF) to the launching area. Once the TF arrived at the launching area, forces were deployed in scheduled waves to the objective. Once all scheduled waves were launched, logistic ships stationed at the assembly area began their logistic sustainment operation. The entire operation continued for a 90-day period.

Numerous factors and variables were included in the expeditionary process model. The design factors for the model were: architecture (current, planned, conceptual), replenishment means (high-speed vessels or existing large medium-speed roll-on/roll-off (LMSR) replenishment ships), and ship to objective proximity. The model also accounted for environmental effects, mine threats, attrition/casualty of troops, and reliability/serviceability of vehicles.

c. Findings

The supporting operations analysis with EINSTein found that the conceptual architecture with the baseline escort force was no better than the current or planned architectures in terms of survivability. The number of amphibious ships in the conceptual architecture was less than the number of ships in the planned or current architectures due to the introduction of the larger conceptual amphibious ship design (ExWar ship). The more concentrated conceptual force made the Sea Base more susceptible to enemy actions. For the conceptual architecture, the Measure of Effectiveness (MOE) to have more than 80% of the task force unharmed was achieved by a combined force of three CGs, three DDGs, and three FFGs. An excursion on the substitution of escort ships with LCSs for the conceptual architecture provided a rough order of equal capability of one CG, one DDG, and one FFG to equal about six LCS.

The expeditionary process model using EXTEND found that the conceptual architecture projected 80% of the MEB ashore faster than the planned and current architectures. This was due to the newly designed ExWar ships that had an increased number of aircraft and surface craft that, in turn, increased lift capability. The conceptual architecture possessed an air-heavy replenishment system that was less affected by adverse weather conditions than surface craft. The Sea Base functioned better, with the respect to force replenishment, through the use of High-Speed Vessels (HSVs) operating from the Offshore Base. Although proximity to the objective did not significantly affect the time to build up the forces ashore, closeness to the objective provided more stable resource levels at the objective. This indicated that launching forces from far offshore can occur without acute delays, but the process of sustaining the forces would preferably be conducted after the littoral waters have been secured, nearer to shore.

d. Conclusions

The SEI-3 Expeditionary Warfare Integrated Project is the foundation for the SEA-4 study. The SEI-3 study established the conceptual expeditionary force architecture. The architecture dictates the number of ExWar ships and the number of air and surface transport assets to be protected.

The SEA-4 Team examined SEI-3's conceptual model to assess the feasibility of using the model to answer force protection related issues. Since the model uses inputted attrition rates for troops, air, land, and sea vehicles, the model does not allow investigation of the effects of specific threats to the conceptual expeditionary force. Additionally, the model does not provide a means to add force protection assets such as CGs, DDGs, FFGs, or LCSs. Due to the logistics nature of the SEI-3 expeditionary process model, the SEA Team deemed it best to create a new model focused on force protection.

The SEI-3 supporting operations study provided a baseline for determining the number of escorts for the Sea Base. Although the study primarily focused on an ASCM threat from surface combatants, the SEA-4 Team felt that the multi-warfare capabilities of escort ships such as CGs, DDGs, FFGs, and LCSs provides a sufficient baseline to protect against the generic threats identified in the Threat Analysis.

2. Exploratory Analysis of Littoral Combat Ships' Ability to Protect Expeditionary Strike Groups

a. Purpose

The SEA-4 Team conducted a mini-study exploring various conceptual capabilities that might be given to a LCS augmenting defenses of an Expeditionary Strike Group (ESG). The LCS capabilities explored included: speed, stealth, common operational picture, an organic helicopter, and a high volume of close-in fires. The mini-study revealed that the combination of stealth and an organic helicopter provided the most consistent protection for the force. However, the team felt that the quick nature of the mini-study required validation from other means. The team compared and validated their results to the thesis of LT Efimba, USN, and "An Exploratory Analysis of Littoral Combat Ships' Ability to Protect Expeditionary Strike Groups."

LT Efimba's thesis explored the LCS's ability to help defend an ESG in an anti-access scenario against a high-density small boat attack. The thesis investigated the employment various ships including cruisers, destroyers, frigates, and LCS's. Additionally, the thesis explored capabilities such as speed, stealth, common operational picture, helicopters or unmanned combat aerial vehicles (UCAVs), and firepower.

b. Methodology

LT Efimba used EINSTein as the modeling and simulation tool for the LCS study. The study focused on a high-density surface threat of 30 high-speed, small boats. The small boat threat possessed characteristics similar to small boat three (SB-3) described in the Threat Analysis. The force structure for the ESG included three amphibious ships and three cruiser/destroyer (CRUDES) ships. This became the baseline ship architecture for the blue force. From the baseline, CRUDES ships were varied in number from zero to two and were combined with one to seven LCSs. In addition to varying the force structure, LT Efimba's design of experiments tested the design characteristics of the LCS (helicopter/UCAV, stealth, speed, firepower). The MOE for the experiment was the number of amphibious ship survivors and amphibious ships damaged. Other MOEs related to CRUDES survival, LCS survival, and helicopter/UCAV survival. LT Efimba ran 50 replications of 16 run-sets and examined 19 ship combinations.

c. Findings

The presence of aircraft was the single most influential factor to force effectiveness. For example, in Figure V-22 a comparison of stealth (r2) to stealth + helicopter/UCAV (r3) showed that aircraft have a beneficial effect on preventing ship loss. For r3, there were zero ship losses with approximately three LCSs or more, while r2 performed consistently worse by two ship losses. LT Efimba's thesis may be referenced for further details regarding subsequent runs or differing designs of experiments.

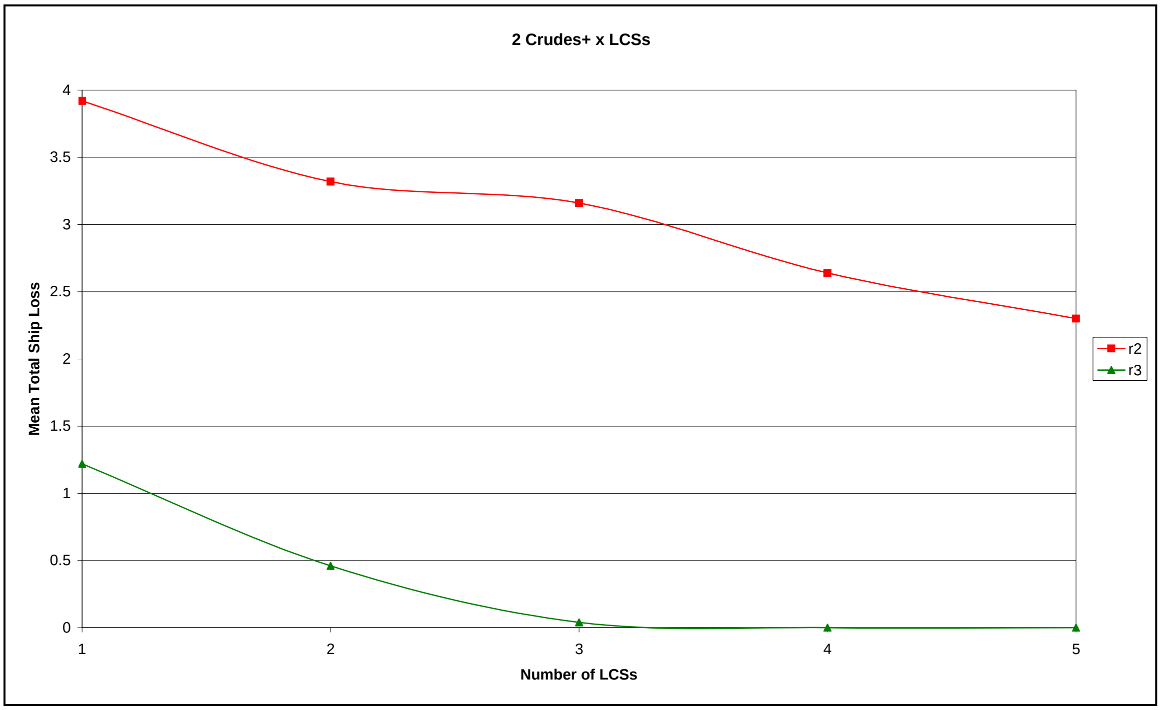


Figure V-22 2 CRUDES + X LCS, Ship Loss vs. Number of LCS, r2 and r3

The second most influential factor in preventing ship losses was stealth. The combination of helicopter/UCAV with stealth is the next most influential term, having both aircraft and stealth makes an ESG well protected. LT Efimba assumed all factors cost the same and only two could be implemented onboard the LCS. The combination of helicopter/UCAVs and stealth proved to be the best choice. Firepower ranked fourth in LCS characteristics beneficial to the ESG.

Simulation runs with the characteristic of speed produced interesting results. Runs utilizing speed as a factor showed speed had a potentially detrimental effect. The speed factor caused the LCS to charge ahead of the CRUDES ships. The aggressive LCS dispersed the ESG's protection and allowed the threat to engage the blue force piecemeal.

d. Conclusions

EINSTein provided a conceptual-level analysis of the employment for the LCS playing a role in force protection of the Sea Base. LT Efimba's thesis concluded, "Being able to control aircraft is the most influential factor for minimizing ship losses." An LCS with a hangar to support helicopters or UCAVs would be ideal. However, since the combination of stealth with helicopters/UCAVs was highly effective in reducing ship losses, a hangar may reduce the stealth of a ship hull. With such trade offs in mind, the SEA-4 Team generated requirements for the TSSE group.

The requirements for the LCS design were general in nature and left the decision to include a hanger on the ship up to the TSSE Team. TSSE conducted a trade analysis of LCS capabilities that were required and decided to include a hangar in the final ship design. Details of the TSSE ship design can be found in Appendix B.

3. Cooperative Radar Network (CRANK): Concept Exploration for Defending the Sea Base

a. Purpose

The Combat Systems Science and Technology Sensor Team conducted a study to propose a suitable sensor system to protect the Sea Base against airborne attacks by threats such as low-flying UAVs and cruise missiles. The fundamental issue identified by the Sensor Team was to detect, identify, and track the cruise missiles or UAVs upon entry into the sensor envelope of coverage and throughout their flights. From the Expeditionary Warfare requirements, the system's sensor envelope of coverage was chosen to be a radius of 200 nautical miles (nm) around the Sea Base.

b. Methodology

The Sensor Team identified three main categories of sensors available for the detection of the UAV and cruise missile threats. The three categories identified were radar, electro-optical, and acoustic. Based on the operational requirement to provide up to 200 nm of coverage, radar was selected as the most suitable candidate. The reasons for this were twofold:

- Radar is the least affected of the three categories by weather
- Radar has the best detection range against airborne targets

Furthermore, the Sensor Team recognized two inherent limitations to radar's ability to detect targets:

- Atmospheric refraction (sensor height of eye)
- Advances in low observable technologies particularly stealth

The sensor height of eye determines the radar’s horizon range and therefore the maximum range at which a given target could be seen. The Sensor Team concluded that a conceptual radar should have a greater height of eye in order to extend its horizon against low-flying threats.

A common misconception identified by the Sensor Team with respect to stealth is that stealth aircraft are completely invisible. In truth, however, stealth aircraft are primarily designed to minimize the frontal radar cross section (RCS). The contouring of stealth aircraft is further designed to avoid reflecting a radar signal directly back in the direction of the radar transmitter. These factors lead the Sensor team to choose a target RCS of .01 square meters for use in their modeling. To overcome the stealth features of the conceptual target, the Sensor Team concluded that a bi-static or multi-static radar system would greatly increase the odds that at least one receiver would detect a reflected signal.

c. Findings

From the preceding information, the Sensor Team concluded that a multi-static system should be able to provide 360^o coverage for the Sea Base assets. The Sensor Team also determined that the radar sensors should not be static as in a classic bi-static system, but should be able to change in order to support the force protection requirements of the Sea Base.

The sensor system could achieve the detection range required in one of two ways: either increasing the transmitter power, or reducing the range between the receiver and the target. The Sensor Team also considered trade-offs between sea-borne and airborne platforms. The airborne sensors were determined to have the advantage of quick set-up and redeployment necessary to meet the operational requirements of changes in network configuration. Furthermore, airborne sensors were determined to be able to achieve a greater radar horizon range and were judged as less cumbersome logistically when compared to seaborne platforms.

The airborne transmitter and receiver system designed by the Sensor Team is the CRANK. The system uses a Single-Transmitter and Multiple Receiver Radar Arrangement (STAMRA) (see Figure V-23). For STAMRA to provide long-range and 360^o coverage will require sufficient power to be transmitted in all directions. This is necessary in order that the strength of the return signal, or signal-to-noise ratio (SNR), will be above the minimum threshold for the maximum desired detection range. The SNR determined by the Sensor Team was 0 decibels (dB). The minimum number of receivers required based on geometry was determined to be $\pi R/r$. In this formula, R is the deployment range of the receivers from the transmitter, and r is the radius of each individual receiver's sensor coverage.

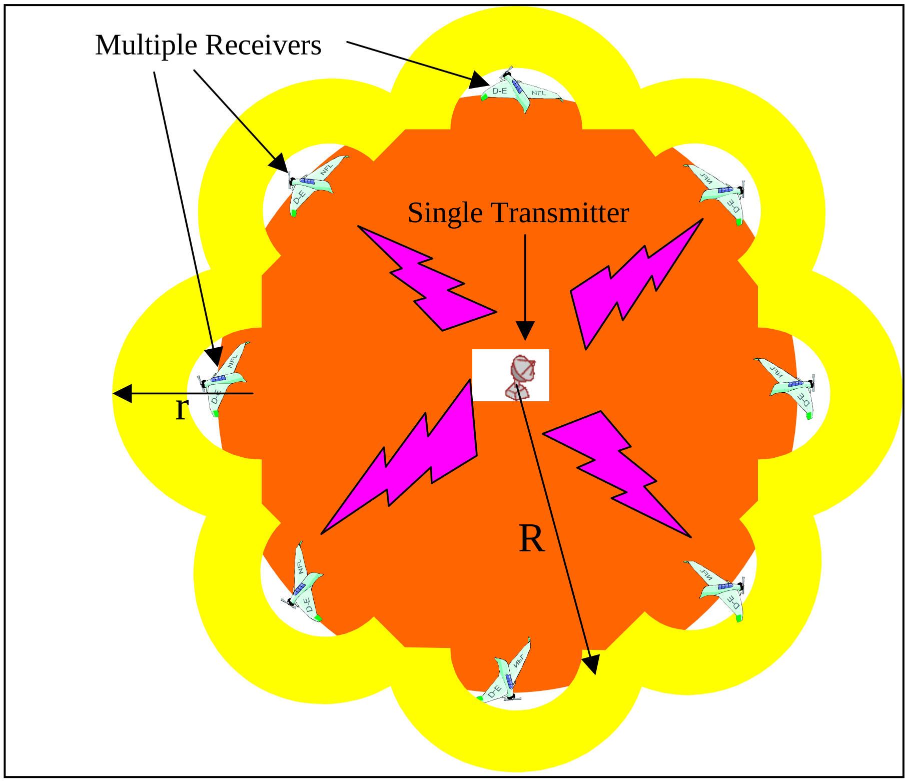


Figure V-23 Single-Transmitter and Multiple Receiver Radar Arrangement (STAMRA)

A main weakness of the STAMRA concept is that the single transmitter can become a single point failure of the whole system. If the transmitter does not work, the whole system will fail. To address this problem, the individual CRANK receivers would possess monostatic radars to operate in a degraded, or secondary, mode. The setback of the degraded mode is that the detection range is likely to be shorter since the airborne receiver platform would likely be smaller and have more limited transmitter power.

From the requirements set forth by the Sensor Team, each receiver should be capable of a detection range of 50 nm (r = 50) against a .01 square meter target. If the deployment range is 200 nm (R = 200), the number of receivers required is 13 to provide 360^{o} coverage. For a 3 GHz radar, the power requirement for a .01 square meter target is 1640 megawatts. Other frequency and power requirements are listed in Table V-38.

Frequency (GHz)	**Bi-static RCS (m^2)**	**Range from Transmitter to Target (nm)**	**Range from the Receiver to the Target (nm)**	**Transmitter Power (MW)**
3.0	0.01	200	50	1640
3.0	0.1	200	50	164
3.0	0.01	100	25	35.2
3.0	0.1	100	25	3.52
10.0	0.01	200	50	428
10.0	0.1	200	50	42.8
10.0	0.01	100	25	5.4
10.0	0.1	100	25	0.54

Table V-38 Bi-static Frequency and Power Requirements

d. Conclusions

The transmitter power required to detect a .01 square meter target at 200 nm using a 3 GHz or 10 GHz multi-static system is too great to be realized by current technology for airborne platforms. One way to reduce this power requirement may be through the use of pulse compression. Pulse compression would permit the power requirement to be greatly reduced; however, it is not known if pulse compression has been studied or implemented in a multi-static radar system.

CRANK offers a viable option for a distributed sensor network that may allow future threats to be detected at greater ranges from the Sea Base and therefore afford greater reaction times to the force protection assets. Employing the UAV sensor network in the degraded, or secondary, mode will permit the use of existing mono-static radar capabilities and may still prove able to provide long-range detection of low-flying cruise missiles or UAVs. The implementation of this sensor system will also facilitate the future use of bi-static or multi-static capabilities if pulse compression or future power generation capabilities prove able to make the primary mode a reality.

4. Quantifying SSGN Contributions to a Complex Joint Warfare Environment

a. Purpose

The purpose of this study was to determine potential SSGN's contributions to a complex joint warfare environment using simple circulation model (see Figure V-24). Two related Measures of Effectiveness (MOEs) were used as measures of the SSGN's contributions. The two MOEs used were: additional missions per unit, and force multiplying factor.

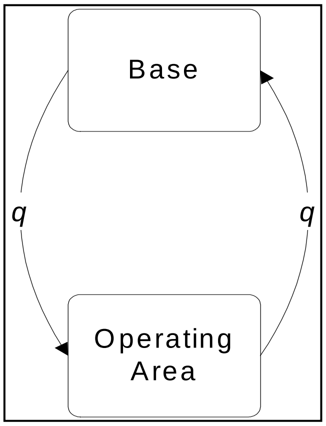


Figure V-24 Simple Circulation Model

b. Methodology

The SSGN study assumed that in future conflicts an SSGN would be used to prepare the battle space through cruise missile strikes and special operations activities. Preparation of the battle space, in turn, implied reduced enemy lethality and greater probabilities of survival for friendly forces.

c. Findings

The SSGN study used a simple circulation model to convert the improved survivability due to SSGN battlespace preparation into mathematical equations capable of being used in both MOEs. On each leg of the mission there is a half-mission survivability of q. If X is the number of missions that a friendly unit completes, then $E[X]$ is the expected number of completed missions given in Equation (49).

Equation (49) $$E[X] = q/(1-q^2)$$

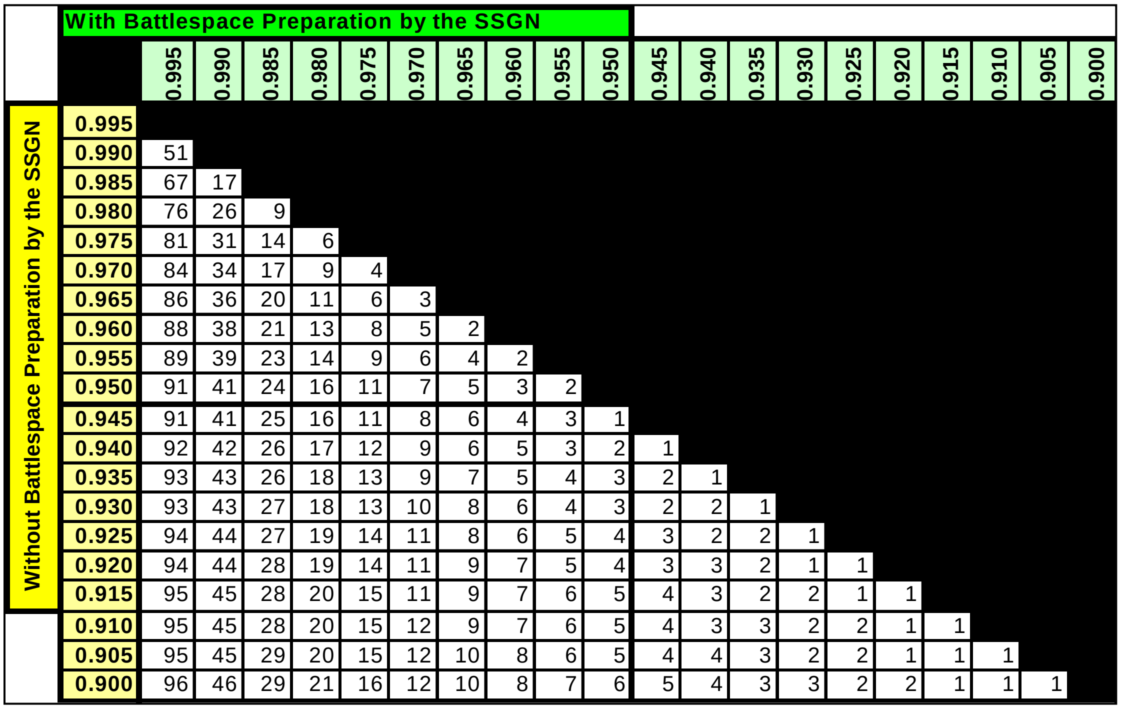
The first MOE, additional missions per unit, simply compares *E[X]* with and without SSGN battle space preparation. The mathematical representation of this MOE is:

Equation (50) $$\text{Number of Additional Missions} = E[X_{withSSGN}] – E[X_{withoutSSGN}]$$

If $q_{withoutSSGN}$ and $q_{withSSGN}$ are substituted into Equation (50), the result is:

Equation (51) $$\text{Number of Additional Missions} = q_{withSSGN} /(1- q^2_{withSSGN}) - q_{withoutSSGN} / (1- q^2_{withSSGN})$$

Table V-39 represents various combinations of Equation (51). The table's values represent the expected number of additional missions made possible through SSGN battlespace preparation.



		With Battlespace Preparation by the SSGN																			
		0.995	0.990	0.985	0.980	0.975	0.970	0.965	0.960	0.955	0.950	0.945	0.940	0.935	0.930	0.925	0.920	0.915	0.910	0.905	0.900
Without Battlespace Preparation by the SSGN	0.995																				
	0.990	51																			
	0.985	67	17																		
	0.980	76	26	9																	
	0.975	81	31	14	6																
	0.970	84	34	17	9	4															
	0.965	86	36	20	11	6	3														
	0.960	88	38	21	13	8	5	2													
	0.955	89	39	23	14	9	6	4	2												
	0.950	91	41	24	16	11	7	5	3	2											
	0.945	91	41	25	16	11	8	6	4	3	1										
	0.940	92	42	26	17	12	9	6	5	3	2	1									
	0.935	93	43	26	18	13	9	7	5	4	3	2	1								
	0.930	93	43	27	18	13	10	8	6	4	3	2	2	1							
	0.925	94	44	27	19	14	11	8	6	5	4	3	2	2	1						
	0.920	94	44	28	19	14	11	9	7	5	4	3	3	2	1	1					
	0.915	95	45	28	20	15	11	9	7	6	5	4	3	2	2	1	1				
	0.910	95	45	28	20	15	12	9	7	6	5	4	3	3	2	2	1	1			
	0.905	95	45	29	20	15	12	10	8	6	5	4	4	3	2	2	1	1	1		
	0.900	96	46	29	21	16	12	10	8	7	6	5	4	3	3	2	2	1	1	1	

Table V-39 Mission Gain through SSGN Battlespace Preparation Spreadsheet

To put Table V-39 values into perspective, consider the example of an aircraft carrier (CV) or airwing with 24 aircraft conducting strike operations. If $q_{withoutSSGN}$ is .95 and $q_{withSSGN}$ is .98, each aircraft could be expected to complete an additional 16 missions because of the SSGN's battle space preparation. This would equate to 384 additional missions for the 24 aircraft in question.

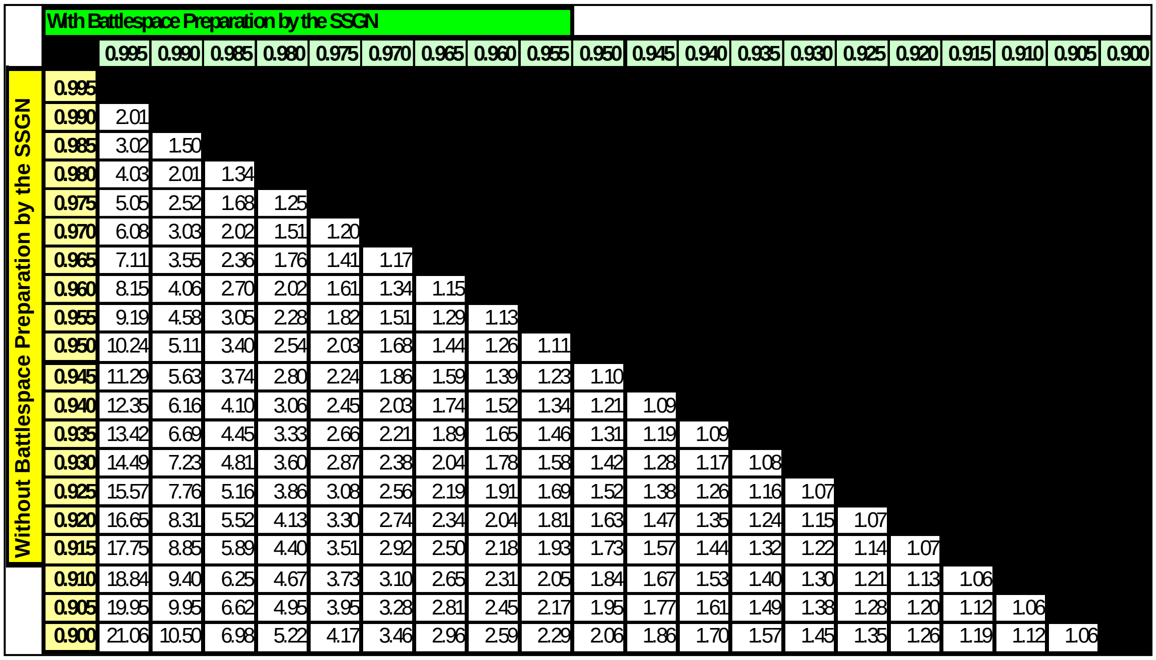
The second MOE, the force-multiplying factor, is the expected number of completed missions with SSGN battle space preparation, divided by the expected number without.

Equation (52) Force Multiplying Factor = $E[X_{withSSGN}]/E[X_{withoutSSGN}]$

If $q_{withoutSSGN}$ and $q_{withSSGN}$ are substituted into Equation (52), the result is:

Equation (53) Force Multiplying Factor = $q_{withSSGN} /(1- q^2_{withSSGN}) / q_{withoutSSGN} /$
$(1- q^2_{withSSGN})$

Table V-40 represents various combinations of Equation (53). The table's values represent the force-multiplying factor of SSGN battlespace preparation.



		With Battlespace Preparation by the SSGN																			
		0.995	0.990	0.985	0.980	0.975	0.970	0.965	0.960	0.955	0.950	0.945	0.940	0.935	0.930	0.925	0.920	0.915	0.910	0.905	0.900
Without Battlespace Preparation by the SSGN	0.995																				
	0.990	2.01																			
	0.985	3.02	1.50																		
	0.980	4.03	2.01	1.34																	
	0.975	5.05	2.52	1.68	1.25																
	0.970	6.08	3.03	2.02	1.51	1.20															
	0.965	7.11	3.55	2.36	1.76	1.41	1.17														
	0.960	8.15	4.06	2.70	2.02	1.61	1.34	1.15													
	0.955	9.19	4.58	3.05	2.28	1.82	1.51	1.29	1.13												
	0.950	10.24	5.11	3.40	2.54	2.03	1.68	1.44	1.26	1.11											
	0.945	11.29	5.63	3.74	2.80	2.24	1.86	1.59	1.39	1.23	1.10										
	0.940	12.35	6.16	4.10	3.06	2.45	2.03	1.74	1.52	1.34	1.21	1.09									
	0.935	13.42	6.69	4.45	3.33	2.66	2.21	1.89	1.65	1.46	1.31	1.19	1.09								
	0.930	14.49	7.23	4.81	3.60	2.87	2.38	2.04	1.78	1.58	1.42	1.28	1.17	1.08							
	0.925	15.57	7.76	5.16	3.86	3.08	2.56	2.19	1.91	1.69	1.52	1.38	1.26	1.16	1.07						
	0.920	16.65	8.31	5.52	4.13	3.30	2.74	2.34	2.04	1.81	1.63	1.47	1.35	1.24	1.15	1.07					
	0.915	17.75	8.85	5.89	4.40	3.51	2.92	2.50	2.18	1.93	1.73	1.57	1.44	1.32	1.22	1.14	1.07				
	0.910	18.84	9.40	6.25	4.67	3.73	3.10	2.65	2.31	2.05	1.84	1.67	1.53	1.40	1.30	1.21	1.13	1.06			
	0.905	19.95	9.95	6.62	4.95	3.95	3.28	2.81	2.45	2.17	1.95	1.77	1.61	1.49	1.38	1.28	1.20	1.12	1.06		
	0.900	21.06	10.50	6.98	5.22	4.17	3.46	2.96	2.59	2.29	2.06	1.86	1.70	1.57	1.45	1.35	1.26	1.19	1.12	1.06	

Table V-40 Force Multiplication thru SSGN Battlespace Preparation Spreadsheet

For example, if $q_{withoutSSGN}$ is .96 and $q_{withSSGN}$ is .98, the force-multiplying factor is 2.02. This means that the CV or airwing with SSGN battlespace preparation is equivalent to 2.02 CVs or airwings without battlespace preparation.

d. Conclusions

The simple circulation model provides a simple way to quantify an SSGN's contributions to improved mission completion and force multiplication. For both MOEs, the benefits of SSGN preparation of the battlespace are clearly evident. For the Sea Base, the SSGN provides a means of reducing enemy lethality and contributes to an increased survivability for the expeditionary warfare assets.

5. Defending Multiple High-Value Units (HVUs) Against High Density Threats (HDTs)

a. Purpose

The purpose of this supporting study done by an Operations Research (OR) group was to analyze force posture and force composition of assets associated with protecting HVUs, such as ExWar ships in a Sea Base. The OR group felt that defense of the HVUs in a Sea Base was different from the defense of a Carrier Battle Group due to the number of HVUs that need protection and the relative proximity to shore. The relative proximity to shore presents an increased chance of being overwhelmed by HDTs.

b. Methodology

The OR group developed analytical models and simulation models to gain insight into the process of defending the Sea Base. The analytical model was used to prescribe the distance at which a defender should be placed from a HVU, and to calculate a threat sector that could be defended with a .90 probability of success. Outputs from the analytical model were utilized in the simulation model. The results from both models were compared to validate their design.

The analytical model addressed the issue of defending multiple HVUs against HDTs. Specifically, the model determined how HVU positioning and defender positioning affects the quality of force protection, with respect to various targets. The model was generically designed to allow users to input parameters based on the user's defined scenario. The parameters of the analytical model include: target velocity, defender velocity, defender fire rate, defender weapons range, detection range, single shot probability of kill given an engagement, and target sector. The following were assumptions made for the analytical model:

- HVUs are stationary
- Targets head directly for HVUs
- Target speeds are greater than defender speeds

- Changes in velocity are instantaneous
- Identification of enemy is instantaneous
- Perfect battle damage assessment

The analytical model was systematically developed in three phases. The first phase investigated the interactions of one HVU, one defender, and one target. The second phase explored the effects of multiple HVUs, one defender, and one target. The third phase included multiple HVUs, one defender, and multiple targets representing a HDT attack.

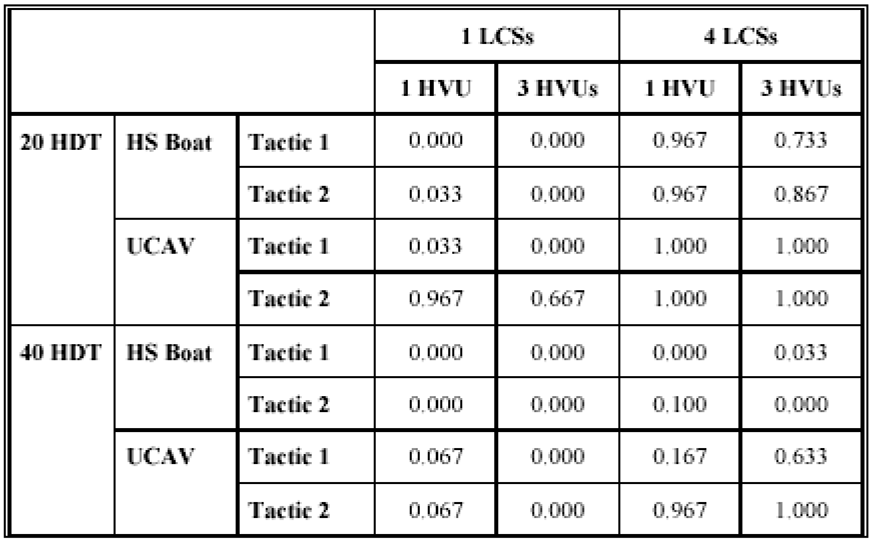
The OR group then developed a simulation model to verify the analytical model. The purpose of the simulation model was to simulate enemy forces attacking the Sea Base to determine the optimal positioning of defending forces relative to the HVUs. The agent-based simulation EINSTein was selected as the tool for the simulation model due its ease of use and the speed of its stochastic runs.

The design factors for the simulation model include LCSs, high-speed boats (HSB), UCAV, and HDT tactics. In the simulation model, the LCS represented the defender. The number of LCSs was 1 or 4. The threat types consisted of either HSBs or UCAVs. The number of HSBs or UCAVs was 20 or 40 to represent HDTs. The HDTs employed one of two tactics. Tactic 1 was a concentrated attack on a single location. Tactic 2 was a multi-axis attack from two separate perpendicular axes.

c. Findings

Various applications of the analytical model provided the OR group with numerous insights and conclusions. One application of the analytical model was to determine the maximum threat sector and number of defenders required to protect a HVU. Given a target with a speed of 500 kts and a defender with the following characteristics: 30 kts speed, 200 nm detection range, and 30 nm weapons range, the effective threat sector was found to be approximately 28^o. The minimum number of defenders required for 360^o coverage, without overlap, is approximately 13. The analytical model also allowed investigation of the effect of detection range on maximum threat sector. By increasing the radar detection range by 50 nm—from 200 nm to 250 nm—the resulting maximum threat coverage sector by a single defender changed to 38.56^{o}. This resulted in a decrease from 13 defenders to only 10 defenders required for 360^{o} coverage.

The simulation model provided insight into HVU survivability. The design of experiments included 30 runs for each category for a total of 960 trials. Table V-41 shows the probability that all HVUs survive.



			1 LCSs		4 LCSs	
			1 HVU	3 HVUs	1 HVU	3 HVUs
20 HDT	**HS Boat**	**Tactic 1**	0.000	0.000	0.967	0.733
		Tactic 2	0.033	0.000	0.967	0.867
	UCAV	**Tactic 1**	0.033	0.000	1.000	1.000
		Tactic 2	0.967	0.667	1.000	1.000
40 HDT	**HS Boat**	**Tactic 1**	0.000	0.000	0.000	0.033
		Tactic 2	0.000	0.000	0.100	0.000
	UCAV	**Tactic 1**	0.067	0.000	0.167	0.633
		Tactic 2	0.067	0.000	0.967	1.000

Table V-41 Probability All HVUs Survive

An estimated probability of mission achievement for the LCS was then calculated by dividing the number of cases where no HVU was destroyed by the total number of runs (30). HVUs identified as “Injured” by EINSTein were considered alive in the analysis.

The probability of HVU survival is much higher for HDT-UCAV compared to HDT-HSB across all parameters. This finding was explained by the fact that the UCAVs had few opportunities to target LCS, due to their high speed and their attribute to primarily engage the HVUs. Conversely, the LCS’ were able to engage the slower HSBs and therefore placed themselves within the HSB engagement range longer. This finding demonstrates that the LCS should use its sensor and weapons range advantages when engaging threats.

d. Conclusion

The OR study provides insight into the optimal placement of defenders with respect to parameters such as threat sector, minimum detection range, target and defender velocity, and defender weapon ranges. With inputs from a scenario, design factors such as weapons range, probability of kill, and radar detection range can be investigated to see their affects on Sea Base defenses.

Findings from both the analytical and simulation models are applicable to this study. The analytical model recommends the use of 10-13 defenders. Although the analytical model assumes that HVUs are stationary, it is likely that the HVU would continue to "make way" to conduct air operations and landing craft operations, while keeping mobile in order to mitigate the enemy. For this study's simulation purposes, the 10-13 defenders would have to keep a relative station within a given sector around HVUs. Insight from the OR simulation model recommends that defenders employ sensors and weapons at their maximum range.

6. Information Assurance Plan for the Protection of the Sea Base Information Systems (IS)

a. Purpose

The purpose of the Information Assurance Team study is to focus on establishing an Information Assurance (IA) plan to protect and defend the information and information systems of the Sea Base. IA is a process that involves the ability to protect information and IS, detect events that may interfere with information or IS, and properly react to situations where information or IS may have been compromised. The IA plan would help to ensure the confidentiality, integrity, and availability of information systems.

b. Methodology

The IA Team conducted their study in three stages. The first stage identified potential challenges for the Sea Base in implementing the current Department of the Navy IA policy. The second stage of the IA study investigated technologies (current and future) that may be employed in an IA defense-in-depth strategy. The third stage applied the Information Assurance Analysis Model (IAAM) to technologies from the second stage of the study to evaluate the relative costs and effects in implementing the technologies.

c. Findings

The Department of the Navy policy “Introduction to Information Assurance Publication, May 2000” promotes a layered defense. The IA Team used the policy as the baseline policy for the Sea Base and identified several implementation challenges. The following are the implementation challenges identified by the IA Team:

- **Risk Management** - Determining the frequency of threat and vulnerability reviews for high-value information systems.
- **Documentation** - Documenting updates to deployed systems.
- **Updating Policy, Standards, and Procedures** - Updating written standard operating procedures (SOPs).
- **Software Development** - Ensuring unintentional errors and malicious software are avoided during data operations when using commercial over the shelf (COTS).
- **Communications** - Preventing unauthorized backdoor entry into a secured network.
- **Legacy Systems** - Safeguarding vulnerable legacy systems.
- **Configuration Management** - Insuring compatibility and interoperability of new software to the network.
- **National Information Infrastructure** - Protecting systems that connect directly to the Internet.
- **Email Addresses** - Avoiding exploitation of user accounts through email address source codes.

The second stage of the study identified nine technologies that could be used as part of the Department of the Navy defense-in-depth requirement. The technologies’ relevance to the Sea Base information systems varies from concepts to systems. The IA Team identified the following technologies:

- **E-Bomb** - Electromagnetic Bomb with a warhead designed to damage targets with a very intense pulse of electromagnetic energy.
- **Physical Access Control-Biometrics** - Devices that allow authorized personnel to enter specific sites by verifying a person’s identity by unique, unalterable physical characteristics, such as hand dimensions, eye features and/or measurements, fingerprints, or voice.
- **Laser Communications** - Wireless communication means that provides a higher bandwidth and limits the accessibility to eavesdropping.

- **Secure Tunnels** - A private connection between two machines or networks over a shared public network.
- **Intrusion Prevention Systems** - A perimeter defense against network-based attacks that recognizes unusual behavior and blocks it in real-time before the intrusion can execute.
- **Intelligent Software Decoy** - Employing deception techniques to deceive the attacker into believing the software decoy is the object it intended to attack and reveals the presence of the attacker with the appropriate response.
- **System Redundancy** - Improving the self-sufficiency and survivability of systems through back-up systems.
- **Security through Obscurity** - Enhancement of system security through the use of encryption algorithms, security hardware, and network configuration.
- **Sim Security** - Security education and training through the use of simulations.

The third stage of the IA study found that the IAAM provided a means of comparing differences in IA strategies and highlights the impact of information assurance on system operational capabilities and resource costs. The IAAM is composed of three separate value hierarchies: IA, Impact of IA on System Operational Capability (IOC), and Impact of IA on Resource Costs (IRC). Each of the value hierarchies is given weights by the user. The user is then able to compare information system technologies based on the given weights.

d. Conclusion

The SEA-4 threat analysis primarily focused on physical threats. The IA study, however, forms the basis for defense of the Sea Base in terms of Information Systems. The "technology look ahead" conducted by the IA Team provides a template of what is possible in the realm of protecting information systems. Additionally, the study provides an example of how to analyze the impact of IA systems on operational capabilities and resource costs through the use of the IAAM. With the growing reliance of technology in networking combat systems, protecting the Sea Base information systems cannot be overlooked.

7. A Sensory Perspective to the Protection of the Sea Base

a. Purpose

The purpose of this study conducted by the Electrical Computer Engineering (ECE) Team was to propose ways to create a more responsive and robust sensor architecture that processes information faster than the enemy's architecture. The ECE Team looked at ways a sensor network could effectively fuse data from multiple sensors to enhance target classification and engagement. Sensors needed to detect and track low radar cross-sections and fast targets using advance signal processing methods.

b. Methodology

The ECE Team identified threats to the Sea Base as high-speed, sea-skimming threats. The detection of these targets would be difficult for shipboard sensors due to the inherent low signatures and interference from surface clutter and multi-path effects. Through research, the ECE Team identified different ways to improve Sea Base defenses by improving data fusion, sensor collaboration, and communications.

c. Findings

Three ways to fuse data are through centralized fusion, autonomous fusion, and hybrid fusion. The data fusion method would depend on the various types of resources available, communication bandwidth, and degree of preciseness. Centralized fusion shows all sensors transferring raw observational data to a centralized node for classification. Centralized fusion represents the most accurate method to fuse data. With autonomous fusion, the tracking and classification process are executed at the individual sensor. This means that each sensor determines the target's velocity and position before sending information to a data fusion. In general, autonomous fusion is not as accurate as data level fusion due to some information loss. Hybrid fusion combines centralized fusion and autonomous fusion. When more accuracy is needed, data level fusion is executed. Though flexibility is one advantage for hybrid fusion over the other two methods, hybrid fusion also represents more time to examine and to decide which fusion method to utilize. The challenge with data fusion was to decide what to filter, what to relay, and what to transmit. Varying computational capacity of each sensor added to the complexity. Over or under filtering was found to produce delays and misinformation that could possibly lead to tactical decision-making errors.

Collaborating a large number of sensors would also pose a challenge for the Sea Base sensor architecture. Dealing with a massive network spawns issues relating to command and control, power consumption, interoperability, sensing algorithms, and levels of interdependence. The ECE Team found that relation based processing might facilitate collaboration of sensors. A collaborative sensor system adopting a relation-based sensing algorithm would promote a high level of comprehensive awareness, support efficient decision-making, and allow for efficient local and global updates.

With regard to communications, the ECE Team explored ways to maximize the data rate transfer between platforms with minimal energy and resources. Two possible solutions were the Mobile Ad Hoc Wireless Sensor Network and the Smart Antenna System.

Ad hoc networks are network architectures that could be rapidly deployed without the need of pre-existing infrastructures. Mobile ad hoc wireless sensor architectures provide ease of deployment, low cost and maintenance, improved engagement quality, and increased battle space awareness. The Smart Antenna System could provide a secure data link between platforms of the Sea Base by minimizing the ability of the enemy to exploit radiation signatures. The Smart Antenna System could be employed onboard UAVs as part of an airborne sensor network providing secure connectivity between ExWar ships and units on land.

d. Conclusions

The sensor study conducted by the ECE Team revealed that one way to enhance the force protection architecture of the Sea Base is to build a scalable, robust and mobile sensor network. As technological advances allow significant increases in throughput and capacity, well-designed communications architectures will be needed to manage and support the large amount of data residing in C4ISR systems. The insight gained from the ECE study will be used in developing concepts for a distributed sensor architecture for the SEA-4 study.

8. Exploratory Study of the Flapping Wing Micro-Air Vehicle (MAV)

a. Purpose

The Mechanical Engineering (weapons) Team conducted a study to propose a means to enhance the forward line of defense for the Sea Base through the concept of "See First, Understand First, and Strike First" (Chan, 2003). The study involved detailed analysis of threats to the Sea Base and research into the use of MAV in surveillance operations.

b. Methodology

The Mechanical Engineering (weapons) Team used a Systems Engineering approach in their development of a MAV. The group conducted a threat analysis to identify a key threat and possible technologies that could be employed against the threat. Following the threat analysis, the team completed a requirements analysis that included an analysis of alternatives between a flapping wing MAV and a fixed wing MAV. The analysis of alternatives led to the selection of the flapping wing MAV. The group then identified desired operational capabilities and investigated design concepts for the flapping wing MAV. Areas examined included aerodynamic characteristics, structures, materials, power supplies, cameras, navigation, and flight control.

c. Findings

The Mechanical Engineering (weapons) Team identified the key threat to the ExWar ship as precision-controlled, supersonic, cruise missiles. The flapping wing MAV design was selected to fulfill the requirements for a low-altitude, close-proximity, surveillance vehicle in support of the concept of "See First, Understand First, and Strike First" for the first line of defense. A flapping wing MAV designed at the Naval Postgraduate School exhibited flight stability, maneuverability, and good obstacle avoidance capability. All of these characteristics made the MAV an excellent platform for surveillance missions. Hundreds of MAVs could be deployed from a larger UAV to locate enemy units in obstacle-filled environments, such as forests or jungle.

However, due to size, weight, and power requirements, the fielding of the flapping wing MAV was not achievable using COTS items and current technologies. Customization of components would increase the performance of the MAV at the expense of cost. The trend in the advancement of miniaturization technologies showed that the fielding of the flapping wing MAV could be possible in the future.

d. Conclusions

The MAV offers a viable option as part of a distributed sensor system to include in the overall system of systems to protect the Sea Base. The Mechanical Engineering (weapons) study highlights the importance of battle space preparation in expeditionary warfare operations. The MAV could provide a means to locate enemy weapon systems and a means to obtain intelligence on the objective. The use of MAVs offers a means of saving lives and money by reducing the need for special operations units and the need of larger, more costly surveillance systems.

9. Littoral Combat Ship Anti-Air Warfare Self Defense Combat System Concept

a. Purpose

The students of the Master of Science in Systems Engineering (MSSE) Cohort 1 at Port Hueneme conducted a study to propose a suitable system to provide an Anti-Air Warfare (AAW) self-defense combat system for the LCS. Their study involved detailed analyses of sensors, sensor integration, command and control, weapons, and manning. The weapons analysis was of particular interest in terms of Sea Base force protection. The MSSE Team explored missiles and missile launchers, gun systems, electronic warfare (EW) and decoys, and weapons layered defense.

b. Methodology

The MSSE group was comprised of several Integrated Project Teams (IPT); each with a specific task. The hard kill IPT was tasked to perform a parametric analysis and assess candidate missile and gun weapon system options. The hard kill IPT considered several weapon suites of missile and gun system configurations optimized to provide self-defense for the LCS from anti-ship missiles (ASM) launched from the land, sea, or air. In their analysis, the team used combination of Probability of Kill (P_k), maximum effective Range (R_{max}), minimum effective Range (R_{min}), missile guidance type, velocity, availability and origin, size, and weight as factors in selecting a preferred weapon concept. The soft kill IPT was tasked to develop an EW weapon system solution for protection on the LCS. Their overarching requirement was to meet a probability of raid annihilation of 0.95. In their analysis, the team used weight, space, manning, and engagement timelines as factors in developing an optimal EW system.

The methodology involving the selection of the gun system was unique because several additional operational and logistical factors had to be taken into account. As with the missile system, the gun system had to reliably demonstrate threat lethality and equipment modularity with a very high operational availability. The design of the gun system would require multi-mission capabilities needed to respond to various threats including defeat of “swarm attacks” by high-speed, armed, small boats in both symmetric and asymmetric warfare environments. Multi-mission requirements are essential for most weapon systems deployed in the U.S. military; however, the MSSE study focused primarily on the self-defense AAW mission capabilities that such gun systems would provide. Requirements dictated that the gun system be capable of quick installation and removal and impose a small modular equipment suite design with no deck penetration. Reduced LCS manning requirements added the constraint of an unmanned automatic gun system operation with manual back-up capabilities and minimum maintenance requirements to keep the gun system fully operational. Therefore, major factors in selecting a gun system were simple design and few moving parts. Additionally, the types of gun system rounds available vary widely and had to be matched with the capabilities of the gun system and the missions it was expected to perform. Therefore, the projectile was considered as part of the gun system and several projectiles with various capabilities were considered as well.

At the completion of the analysis, the hard kill IPT selected a missile system (missile and missile launcher), and a gun system (gun and projectile) from several candidate systems. The soft kill IPT developed a design for an EW/decoy system optimized for LCS self defense.

c. Findings

The conceptual weapons systems were divided into the missile system, the gun system, and the soft kill suite. The conceptual requirements that each IPT developed are shown in Table V-42.

HARD KILL	**CONCEPTUAL REQUIREMENTS**
Missile	RF / IR guidance 1-9.4 km range Velocity of Mach 2 Trainable launcher 21-round magazine
Gun	35mm revolving cannon 0.2-3 km range 1000 rounds / minute 500-round magazine Airburst with sub-munitions 2 mounts required for 360° coverage
SOFT KILL	**CONCEPTUAL REQUIREMENTS**
EW	2-18 GHz frequency coverage 81 dBm power, mono-pulse DF arrays 24-track capacity Automatic 16 target simultaneous engagement capacity 370 km maximum range
Seduction	210 round chaff magazine 2 rounds of active decoys
Active stealth	Water Camouflage Automatically controlled salt water spray of superstructure

Table V-42 MSSE Weapons System Conceptual Requirements

(1) Missile System

The missile system selected by the MSSE hard kill IPT was designed to provide surface ships with an effective, low-cost, lightweight, self-defense system that provided an improved capability to engage and defeat incoming ASMs. The system consisted of a smaller diameter airframe and dual mode, passive radio frequency/infrared (RF/IR) guidance. Initial homing consisted of RF, using an ASM's RF seeker emissions. If the ASM's IR radiation was acquired, the system transitioned to IR guidance. The design incorporated cueing as provided by the ship's EW suite or radar. The missile also had IR "all-the-way" homing guidance mode to improve performance against evolving passive and active ASMs. Two IR guidance modes were available: IR-only and IR Dual Mode Enable (IRDM). The IR-only mode guided on the IR signature of the ASM. The IRDM guided on the IR signature of the ASM, while retaining the capability of using RF guidance if the ASM RF signature became adequate. The magazine was designed to hold 21 rounds, and the system used a trainable launcher, which would affect the ship's radar cross section. Maximum range of missile was approximately 9 km, and minimum range was 1 km. Selected missile parameters are shown in Table V-43.

PARAMETER	**MISSILE**
Probability of System Availability (Reliability, Maintainability &Availability (RM&A))	0.9
Probability of Availability (2007 Initial Operating Capability (IOC))	Yes
System Size / Weight Estimate	9 tons
Probability of Kill, Single Shot	0.9
Maximum Range	9.4 km
Minimum Range	1 km
Active / Semi / Passive	Radio Frequency Homing (RFH) / Infrared Homing (IRH)
Launcher Type (fixed / trainable)	Trainable
Coverage (full azimuth / elevation with min # of launchers)	2
Magazine Size	21
All-Weather Performance	No
Guidance	RF/IR
Weapon Rate of Fire	Single or multi salvo 3 secs / rd
Signature (Radar Cross Section (RCS) / Infrared (IR)) Contribution	Significant
Velocity	Mach 2+
Illuminator Required (yes / no)	No
t_{accel}	0.91 sec

Table V-43 MSSE Missile System Parameters

(2) Gun System

The gun system selected by the MSSE Hard kill IPT was a 35mm, 1000 round per minute revolver cannon. The use of airburst munitions in this gun system made it capable of defeating guided missiles at ranges exceeding 1.2 km. The firepower provided by this gun system provided self-defense capability in the following areas:

- Cost to kill and flexible firepower—fewer rounds required on target due to higher hit and kill probabilities
- Higher stowed engagement capacity (>200) without reload
- Shorter reaction in swarm attack scenarios
- Very effective air target defeat including against anti-ship missiles; a cost-effective means to achieve a viable measure of ship self-defense capability at an affordable cost
- Growth potential in key rate of fire and ammunition payload areas compatible with newly built warship life cycles due to power and size of the 35mm caliber

Additionally, the selected gun system could perform in a multi-mission environment and could provide the following engagement functions:

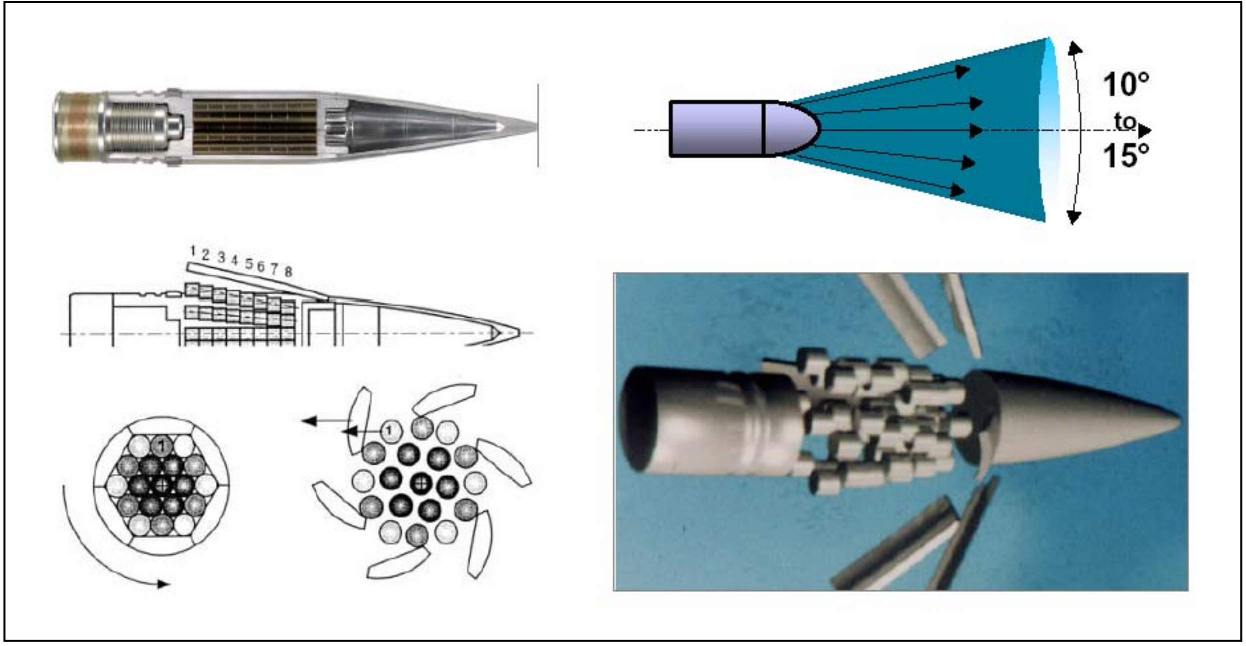
- Anti-Air Warfare
  - Engagement of anti-ship missiles
  - Engagement of aircraft, helicopters and UAVs
- Anti-Surface Warfare
  - Engagement of fast, small boats
  - Policing engagements
- Naval Gunfire Support

Selected gun system parameters are shown in Table V-44.

PARAMETER	**GUN SYSTEM**
Probability of System Availability (RM&A)	0.9
Probability of Availability (2007 IOC)	Yes
System Size / Weight Estimate	4 tons
Launcher Type (fixed / trainable)	Single barrel
Coverage (full azimuth / elevation with min # of launchers)	2
All-Weather Performance	Sensor Dependent
Guidance	Any Sensor
Signature (RCS/IR) Contribution	Minimal
Illuminator Required (yes / no)	Yes
Weapon Reaction Time (assign to engage)	1.1 sec
Weapon Rate of Fire	1000 rounds / min
Magazine Size	500 rounds
Munitions Type	Airburst (pre-fragmented)
Probability of Kill, Burst	0.8 (0.95 advertised)
Probability of Kill, Round	0.139
Maximum Range	3.0 km
Minimum Range	0.2 km
Round Velocity	1.0 km / sec
Gun Burst Period	1.2 sec
Time Between Bursts (kill eval, etc.)	1.1 sec
# Rounds in Burst	20 rounds
Round Acceleration	1.0×10^6 m / sec^2

Table V-44 MSSE Gun System Parameters

As previously stated, the gun system was considered as a whole with a specific projectile. The projectile selected for the gun system was matched to the overall mission capabilities of the LCS. The selected projectile was a Kinetic Explosive Timed Fuse (KETF) type of ammunition. The projectile used a time fuse along with a pre-fragmented projectile. Ideally, the round would be fired toward the point of impact so that, at a distance between 10 and 40 m in front of the target, a small charge would detonate the projectile and cause the dispersion of sub-projectiles to be released. This cloud of sub-projectiles would fly toward the approaching target, and penetrate the target body to destroy missile control surfaces, seeker, and other vital components. Due to their high kinetic energy, the sub-projectiles would cause massive damage to the missile. The pre-fragmented payload consisted of 152 cylindrical, tungsten alloy sub-projectiles each weighing 3.3 grams. The sub-projectiles were released by detonation of a small ejection charge of less than 1.0 gram so that their dispersion pattern was well formed just in front of the target pass-through point. Pre-fragmentation of the projectile enabled individual sub-projectiles to be spin-stabilized and to form a lethal cone of fragments, which significantly increased hit probability, particularly at extended ranges. An illustration is shown in Figure V-25.



V-25 Gun System Projectile

This airburst projectile was also assessed to be effective against small, fast, swarming surface targets. Additionally, other types of ammunition such as high mass armor piercing discarding sabot (APDS), high explosive timed fuse (HETF), and practice rounds with inert projectiles could be fired from the gun. For the purposes of the MSSE study, only KETF rounds were considered.

(3) Soft Kill Suite

The soft kill suite designed by the MSSE Team uses EW and decoys as a complement to the LCS self-defense system. EW can be used to provide counter-targeting and counter-surveillance by means of long-range target detection and identification, denying ability to locate and target friendly forces, measuring target motion, confirming target identification, and denying ability to hit friendly forces. Ideally, the use the soft kill suite would conserve costly hard kill weapons for threats that leaked through the soft kill defenses.

The EW system was composed of electronic attack (EA), active decoys, and active stealth. It was designed as a modular system that would automatically identify and jam threat emitters. The jammer would be capable of handling 16 different threats simultaneously. The MSSE soft kill IPT broke down the EW System into three distinct functional elements: EW (EA, Electronic Protection (EP)), seduction (active decoy, passive decoy), and active stealth. The team derived the soft kill suite requirements by using the LCS mission scenarios. The system was designed with an overarching requirement to meet a Probability of Raid Annihilation (P_{ra}) of 0.95. In addition, other requirements included weight, space, manning, and engagement timelines.

The selected EW system was a modular, 2-18 GHz system intended to counter most known radar threats. An automated system was used to identify and jam threat emitters. One important capability was the subsystem that handled multiple simultaneous threats. It was composed of two transmitters stabilized in pitch and roll to maximize jamming strength. Selected EW system parameters are shown in Table V-45.

PARAMETER	**EW SYSTEM**
Probability of System Availability (RM&A)	0.9
Probability of Availability (2007 IOC)	Yes
Size / Weight Estimate	200 kg
Probability of Correct Emitter ID	0.9
Probability of Soft kill, Single Engagement	0.4
Probability of Correct Technique-Automated Doctrine	0.5
Weapon Prep / Deploy Time	10 sec
Magazine Size	210 rounds
Max Range	370 km
Min R	2 km
Salvo Size	Track 24; Engage16 tgts
All-Weather Performance	Yes
Signature (RCS / IR) Contribution	RCS

Table V-45 MSSE EW System Parameters

The seduction system consisted of both passive and active decoys. The active decoy system selected was a system capable of hovering in the vicinity of the ship. Once launched, the active decoy would radiate a large, ship-like radar cross section, while flying a trajectory that would seduce incoming ASMs away from the ship. The decoy would be an autonomous flight vehicle, capable of operating over a wide range of environments and of positioning with a high level of accuracy. The decoy was required to counter a wide variety of present and future radar ASM guided threats by radiating a large radar cross section signal, while traversing a ship-like trajectory to permit decoying multiple threats. Once launched, the decoy would operate autonomously and follow a programmed flight path, thus presenting a more attractive target to incoming missiles. Active decoy system capabilities included:

- Rapid reaction time with minimal threat data
- Effective in all weather
- Fully integrated with other shipboard EW elements
- Performance independent of ship maneuver
- System capable of fully automatic operation
- Capable of decoying multiple anti-ship missiles simultaneously
- Capable of producing RF responses while moving away from ship

The passive decoy system uses chaff as a radar countermeasure against anti-radiation missiles and flares as an IR countermeasure against IR-seeking missiles. Chaff and flares remain common forms of passive decoys used to lure threats away from any ship. They were still judged to be inexpensive and very effective on some threats for the given time period. Passive decoy system capabilities required:

- Shipboard management of expendable chaff cartridges via a computer-controlled countermeasure system used with deck-mounted launchers
- The chaff system must be highly effective for managing anti-ship decoy tactics
- System must be fully integrated with EW element, as well as shipboard wind and navigation sensors
- System must provide and implement automated tactics for every scenario

Selected seduction system parameters are shown in Table V-46.

PARAMETER	SEDUCTION ELEMENT	
	ACTIVE DECOY	CHAFF
Probability of System Availability (RM&A)	0.85	0.95
Probability of Availability (Yes / No)	Yes	Yes
Size / Weight Estimate	4607 kg	207 kg unloaded
Probability of Correct Emitter ID	0.9	N/A*
Probability of Soft kill, Single Engagement	0.5	0.4
Probability of Correct Technique-Automated Doctrine	N/A	N/A*
Weapon Prep / Deploy Time	6 s	30-60 s for warning 1-2 s for chaff to bloom to 10 times ship RCS
Hovering Time	5 s	N/A*
Magazine Size	2 rounds	210 rounds
Max Range	5 km	22 km
Min Range	50 m	2 km
Salvo Size	1 round	12 salvo / 2 launchers
All-Weather Performance (Yes / No)	Yes	Yes
Signature (RCS / IR) Contribution	RCS	RCS

*Not Applicable.

Table V-46 MSSE Seduction System Parameters

The active stealth component of the soft kill suite was designed to manage the ship's IR signature. The radar signature is inherent to the design of the ship and thus contributes to the passive stealth system. A ship's IR signature is composed of two main components: internally generated and externally generated. Internally generated signature sources include rejected heat from engines and other equipment, exhaust products from engines, waste air from ventilation systems, and heat losses from heated internal spaces. The main ship's internal source results from the engines and generators. External sources result from the ship absorbing and/or reflecting radiation received from the sun, sky radiance, and sea radiance. The soft kill IPT only explored active stealth options that would reduce the IR signature of the platform. The goals of signature management were to:

- Prevent or delay detection of the ship by hostile forces
- Prevent, confuse, or delay accurate identification
- Prevent lock-on of missile seekers
- Reduce lock-on distance of missile seekers
- Increase effective engagement range of EW
- Increase seduction effectiveness of all types of decoys
- Decrease decoy mass required to mask the ship

The proposed active stealth technique consisted of actively monitoring and cooling the heated parts of the ship's surface with seawater. To attain full effect, the level of the signatures must be reduced to be about the same as, or lower than, the environmental background noise. The design goal would be achieved when the signatures are so low that even if the ship were detected, identification and engagement would be extremely difficult. Active stealth technology was assessed to be a critical technology area related to the survivability of weapon platforms. Active signature control makes detection by an adversary more difficult through concealment from sensor systems.

The selected Water Camouflage (WC) system was designed to be capable of reducing sources of self-generated IR emissions and reducing solar heating from ship surfaces. The objective of the WC system was to blend the ship into its background. This system had a series of water spray nozzles carefully located around the ship in order to effectively water cool the heated surfaces. The nozzles would be grouped into many sections that had their temperatures continually monitored with a control system. Each section was individually controlled in order to achieve constant temperature throughout the external ship surface. The WC system would be integrated with the soft kill weapon suite and the overall self-defense system, providing automatic IR signature monitoring and control.

d. Conclusions

Review of the MSSE report yields the following conclusions from the hard kill and soft kill IPTs:

- A robust gun system can perform in both AAW and SUW roles.
- Combined with LCS' speed of 30-50 knots, decoys were viable soft kill weapons for this class of ship.
- LCS was designed to operate in the littoral environment. When LCS operates close to land, it must be recognized that the battle space is limited. The reaction time to counter the threats must be accomplished in limited time due to the constrained battle space created by land. Shore-based ASMs can travel short distances when LCS is close to land. This factor forces a new requirement to automate many functions now performed manually, in order for the detection, identification, track, and engage sequence to be effective. The LCS soft kill suite was designed to be fully automatic with no human in the loop. Command and control elements will provide the computing resources for weapon scheduling and kill evaluation.

- The use of hard kill weapons only is not the best choice in order to achieve the desired probability of kill. The use of both hard kill and soft kill mechanisms in a layered defense scheme will be far more effective in achieving the required P_{ra} of 0.95 for an incoming ASM.
- Signature management is the LCS' first line of defense with respect to breaking the threat kill chain. Signature management reduces LCS emissions that enemy aircraft and missiles use for fire control solutions in order to home on LCS. Various ASMs with limited range, typically used in the littorals, employ IR guidance. In an attempt to reduce the IR signature of LCS, innovative techniques such as the employment of a WC system (active stealth) to cool the surface of LCS is used.

It should be noted that the critical performance parameters and detail analysis information of electronic warfare technology is a highly classified subject. The scope of the MSSE project was limited to open source material or using first principle calculations with stipulated assumptions. The probability of kill and the engagement timeline for the soft kill elements were derived either from open source material or by using academic principles.

The missile system, gun system, and soft kill suite conceptualized by the MSSE Team offer a viable option for systems to include in the overall system of systems to protect the Sea Base. The missile and the gun system were designed to be compact, lightweight, and highly automated. These could also be viable candidate weapon systems for the TSSE-designed LCS. A lightweight, low-cost, self-defense missile system and gun system selected for the LCS could also be adapted for use on other Sea Base platforms. The conclusions regarding the need for hard kill systems to be complemented by a soft kill suite were particularly important. The MSSE Team's design for a soft kill suite would be an ideal model to use as a basis for soft kill suites on all Sea Base ships and escorts.

F. PROPOSED ARCHITECTURES

This section consolidates findings from the Sensor, Search, and Engagement Analyses to propose force protection capabilities for the Sea Base. The Sensor Analysis, Search Analysis, Engagement Analysis, and supporting studies of Chapter V represent the feasibility screening of the concepts identified through alternatives generation. The alternatives generation identified five functions associated with force protection: detect, defeat, prevent, withstand, and deploy. Through careful research during the feasibility screening, the SEA-4 Team decided to focus their efforts on the functions of detect, defeat, and deploy. Since many of the platforms have already been designed, the capabilities of platforms in the force protection composition address the functions prevent and withstand. Keeping in line with these functions, the SEA-4 Team proposed the following categories as a framework for examining force protection capabilities:

- Sensor architecture
- Weapon architecture
- Force composition

Each of these categories addresses the functions of detect, defeat, and deploy. The sensor category is related to the detect function. Analytical modeling of radar, lidar, IR, and sonar helped to determine the best sensors to detect threats to the Sea Base. Subsequently, radar, IR, and active sonar were the resulting sensors of choice. The weapons category relates to the defeat function. This study's engagement analysis addressed the use of various weapons, including missiles, guns, torpedoes, and directed energy weapons. These weapons were used to evaluate the effects of speed and range on force survivability. Force composition is related to the deploy function by associating sensor and weapon systems with specific platforms. Various platforms, including ships and unmanned vehicles (UAV, UUV, USV, and aerostat), were considered as the means by which to employ the selected sensors and weapons.

The details from each of these three categories are described in greater detail in the following sections and will contribute to the final proposed force protection architecture.

1. Sensor Architecture

a. Sensor Type

The type of sensors employed will describe the sensor architecture for the Sea Base. The types of sensors analyzed in the Sensor Analysis were conventional microwave radar, lidar, IR, and sonar. Because different sensors are better suited for certain applications over other sensors, the Sea Base should have the capability to use each type of sensor in a cooperative manner. For example, radar could be used for search with IR acting as an additional cueing sensor, while a different radar could then provide target identification or tracking information.

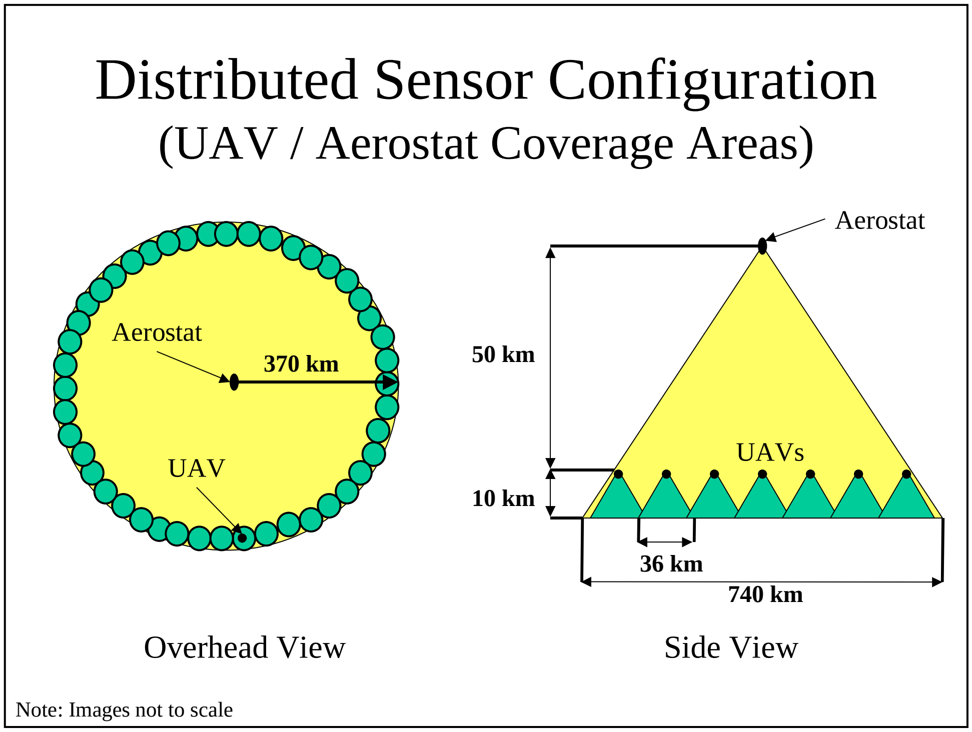
b. Sensor Configuration

Another means of describing the sensor architecture is by how the sensors are configured throughout the force. The Search Analysis describes sensor configuration as either point or distributed. In a point sensor architecture, search, track, and targeting data originate from individual platforms. Ships in a Sea Base operating in close proximity to one another within a large operating area can be approximated to be a single point source. However, due to the height of eye limitations addressed in the Sensor Analysis, the point sensor architecture alone cannot provide the necessary coverage for an extended search volume. The Sensor Analysis also shows the advantage of increased radar detection ranges by achieving off-axis aspect angles with respect to the threat analyzed. This is achieved in the distributed sensor architecture. As described in the Search Analysis, a distributed sensor architecture can provide search, track, and targeting data from an aerostat, UAV, USV, or UUV. With a distributed sensor architecture, the Sea Base could greatly extend its search volume. Such an architecture would significantly benefit the Sea Base during Phase I (staging and build-up in the operating area) where the Sea Base could begin to collect locating data on threats, while remaining out of the enemy's detection and weapons reach. For example, the Sea Base could remain 200 nm from a hostile coast during the build-up phase, while a distributed sensor network provides targeting information to the force protection assets, thereby providing increased survivability. As threats are mitigated, the Sea Base could move closer to the launching area in preparation for Phase II (assault), while remaining under the coverage of a distributed sensor system. As the Sea Base approaches the launch area, the Search and Engagement Analyses demonstrated that distributed sensor architectures would improve the Sea Base's reaction time against inbound threats. Because of the Sea Base's similar offshore operating distances during Phase III (sustainment), the distributed sensor system again might provide additional reaction time against any expected short notice threats that may emerge during the sustainment of the forces ashore. The cooperative radar network (CRANK) and MAV supporting studies provide additional information on the benefits of distributed sensor architectures.

The Search Analysis determined that such an architecture, in order to achieve a 360^o sensor coverage out to a range of 370 km, would have to employ an aerostat operating at an altitude of 50 km and 62 UAVs operating at 10 km in order to protect the Sea Base from above/on the water threats. The Search Analysis also determined that 163 USVs or UUVs operating on the water or at depths up to 300 m were required to counter on/below the water threats. Resource limitations, however, may dictate the use of fewer unmanned vehicles. It was decided, after analyzing some initial modeling results, that this study would accept the UAV requirement (62), but would lower the USV/V requirement to 23. This lower number obviously will not provide the Sea Base sensor coverage out to 370 km, but will provide 360^o coverage out to 50 km. This study felt that was reasonable because the longest-range underwater threat came from TORP-1 at 37 km. Figure V-59 and Figure V-60 demonstrate how overhead and side views of the distributed sensor architectures described above might look.

c. Proposed Sensor Architecture

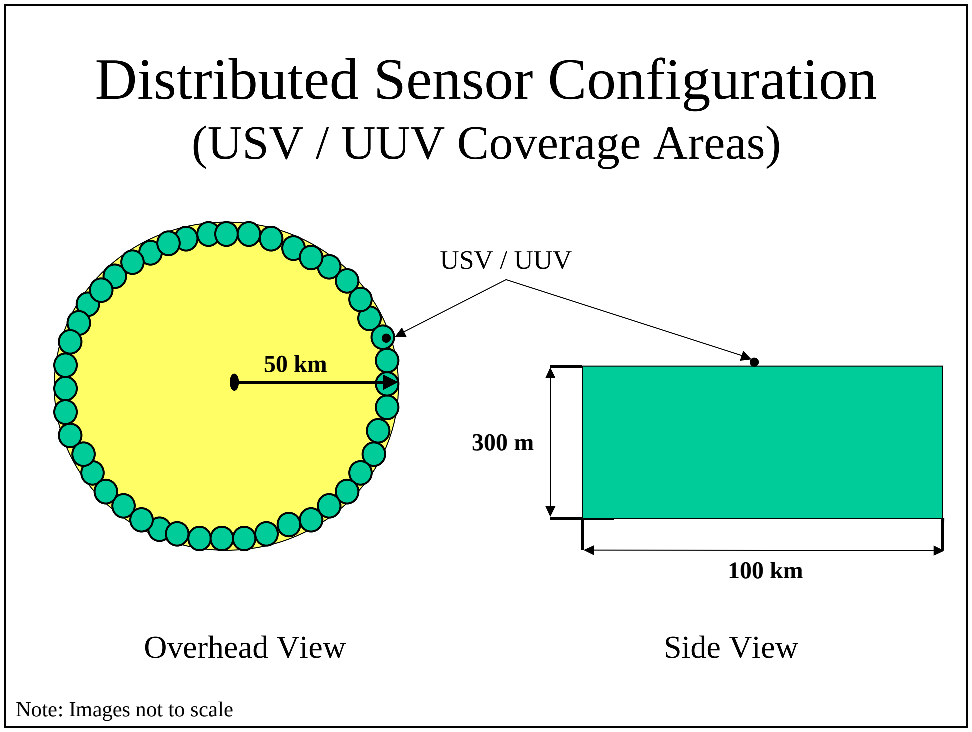
From the Sensor and Search Analyses, the Sea Base should have the capability to deploy distributed sensor architectures (as seen in Figure V-26 and Figure V-27) that consist of radar, IR, and active sonar sensors. Furthermore, these sensors should be cooperative in order to provide cueing or uninterrupted track data throughout the battle space. This, in turn, will reduce uncertainty and lead to an increase in the force’s probability of survival. The specifics of the distributed sensors can be found in the Search Analysis.



Distributed Sensor Configuration
(UAV / Aerostat Coverage Areas)

Note: Images not to scale

Figure V-26 Distributed Sensor Configuration (UAV / Aerostat)



Distributed Sensor Configuration
(USV / UUV Coverage Areas)

Note: Images not to scale

Figure V-27 Distributed Sensor Configuration (USV / UUV)

2. Weapon Architecture

a. Weapon Type

Weapons defeat threats to the Sea Base. The Engagement Analysis shows a weapon's capability can be largely limited by a sensor's range. Since the proposed distributed sensor architecture provided an increased sensor range, the team decided to explore the effects of increasing the weapons' speeds and ranges. With this in mind, the SEA-4 Team categorized weapon types as either current or conceptual. Current weapons were defined as weapons presently employed by ships, aircraft, or submarines and will be available in the 2016 timeframe. Though not analyzed in the Engagement Analysis, several weapons exist that may be present onboard Sea Base force protection assets. The current weapons' capabilities that may reside onboard assets of the Sea Base are summarized in Table V-47.

WEAPON DESCRIPTION	RANGE	SPEED	LAUNCH PLATFORM
Surface-to-air missile (INT-1)*	80 nm	Mach 2.5	CG, DDG
Surface-to-air missile	30 nm	Mach 3.6	TSSE LCS
Surface-to-air missile	18 nm	Mach 2.5	FFG
Surface-to-air missile	6 nm	Mach 3.6	ExWar
Anti-ship cruise missile	67 nm	462 kts	CG, DDG, FFG
Helicopter launched anti-ship missile	25 nm	Mach 1.2	SH-60
Air-to-air missile	10 nm	Mach 2	JSF
Air-to-ground anti-armor missile	2 nm	640 kts	AH-1Z
Air-to-ground anti-armor missile	3 nm	Mach 1.25	AH-1Z
Air-to-air missile against aircraft (INT-3)*	29 nm	Mach 4	UAV
Land attack missile	600 nm	475 kts	CG, DDG, SSN, SSGN
Surface or air launched torpedo (T-1)*	4 nm	40 kts	CG, DDG, FFG, UUV, USV
Submarine launched torpedo	25 nm	40+ kts	SSN, SSGN
Anti-submarine rocket: travels through air; then water	air: 6 nm submerged: 4 nm	air: Mach 1 submerged: 40 kts	CG, DDG
Naval gunfire against surface, air, and shore targets	13 nm	2650 ft / sec rate: 20 rounds / min	CG, DDG
Naval gunfire against surface and air targets	9 nm	3363 ft / sec rate: 220 rounds / min	TSSE LCS
GPS-guided bombs	5 nm	Launch platform dependent	JSF

*Current weapon modeled in Engagement Analysis.

Table V-47 Current Weapon Characteristics

Furthermore, the Engagement Analysis offers some conceptual weapons that are improved from current weapons by range and speed and focuses on conceptual weapons that provide an intercept capability against missiles, aircraft, or submarines. Conceptual weapons that may replace or augment current weapons are listed in Table V-48.

WEAPON DESCRIPTION	RANGE	SPEED	LAUNCH PLATFORM
Surface-to-air missile (INT-2)*	200 nm	Mach 5	CG, DDG
Air-to-air missile against aircraft and missiles (INT-4)*	50 nm	Mach 6	UAV
Surface or air launched torpedo (T-2)*	6 nm	50 kts	CG, DDG, FFG, UUV, USV
Naval gunfire against surface, air, and shore targets	63 nm	2650 ft / sec rate: 10 rounds / min	CG, DDG
Free-Electron Laser (FEL)*	5 nm	light speed	CG, DDG
Free-Electron Laser (-)	2.5 nm	light speed	TSSE LCS

*Conceptual weapon modeled in Engagement Analysis.

Table V-48 Conceptual Weapon Characteristics

b. Weapon Configuration

Much like the sensor architecture, weapons can be analyzed as part of a point or a distributed weapon system. In a point weapon system, weapons are launched from individual platforms such as ships or aircraft located near the defined force center as defined in the Engagement Analysis (see Figure V-10). In a distributed weapon system, weapons are launched from a fixed or defined location within the area of concern as defined in the Engagement Analysis (see Figure V-11). This study assumes that distributed weapons are employed from the same unmanned vehicles utilized in the distributed sensor architecture. Weapons listed with unmanned vehicles as the launch platforms in Table V-47 and Table V-48 are considered distributed weapons.

c. Proposed Weapon Architecture

In line with the proposed sensor architecture, this study proposes that the Sea Base have the capability to deploy distributed weapons as seen in Figure V-28, Figure V-29, Figure V-30, and Figure V-31. When launched from the UAVs in the distributed sensor architecture, the distributed weapon system acts as the first line of defense for the Sea Base. In addition to the distributed weapon capability, Sea Base platforms must also retain their point weapons capability. Furthermore, with the expanded sensor coverage of a distributed network, the Sea Base should capitalize on the speed and range advantages of conceptual weapons. As concluded in the Engagement Analysis, conceptual weapons in the distributed sensor architecture provide more engagement opportunities, thereby increasing the probability of kill against threats.

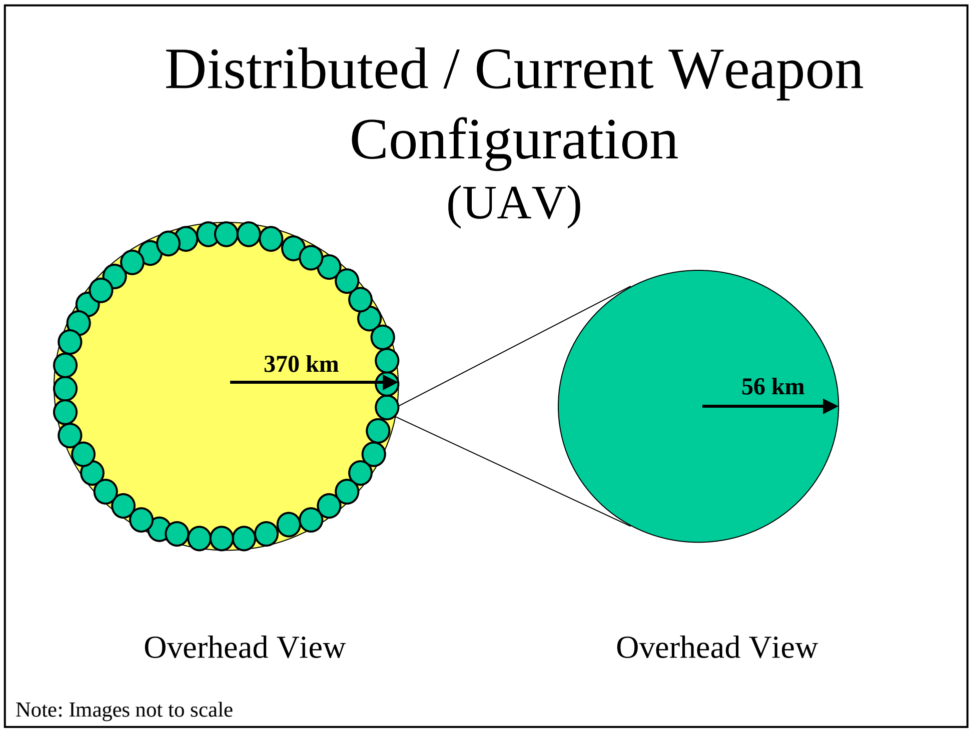


Figure V-28 Distributed / Current Weapon Configuration (UAV)

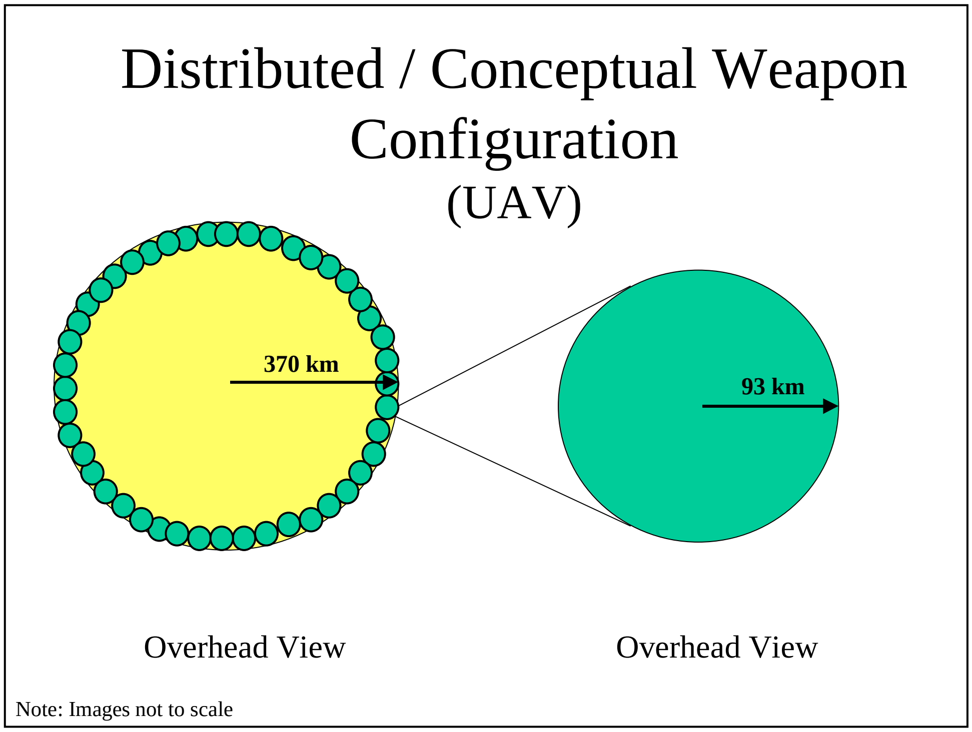


Figure V-29 Distributed / Conceptual Weapon Configuration (UAV)

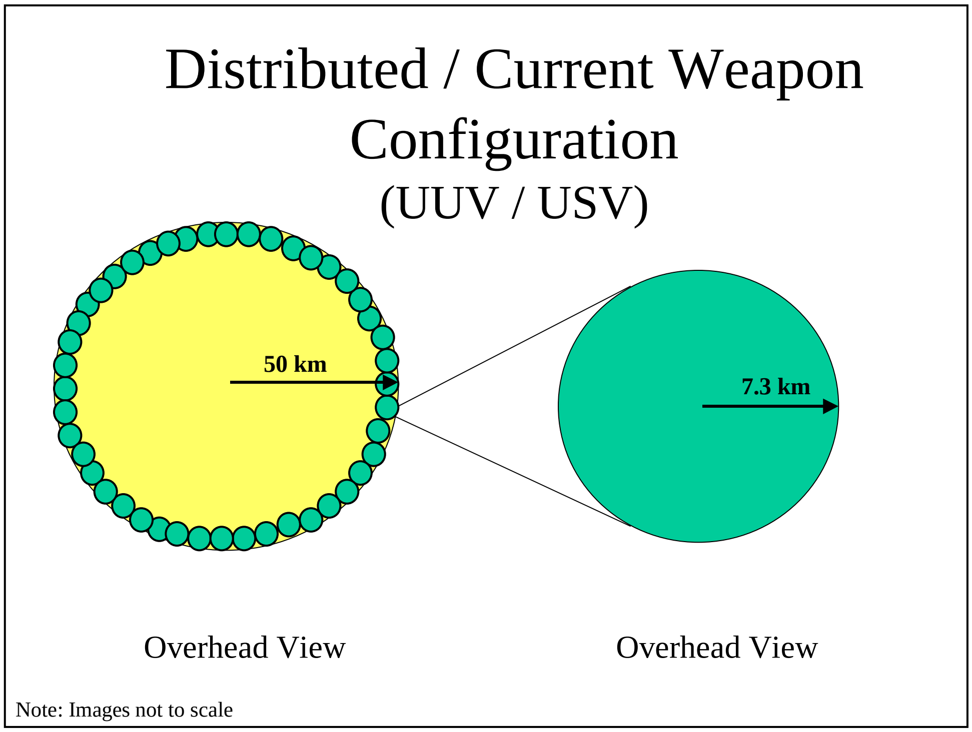


Figure V-30 Distributed / Current Weapon Configuration (UUV / USV)

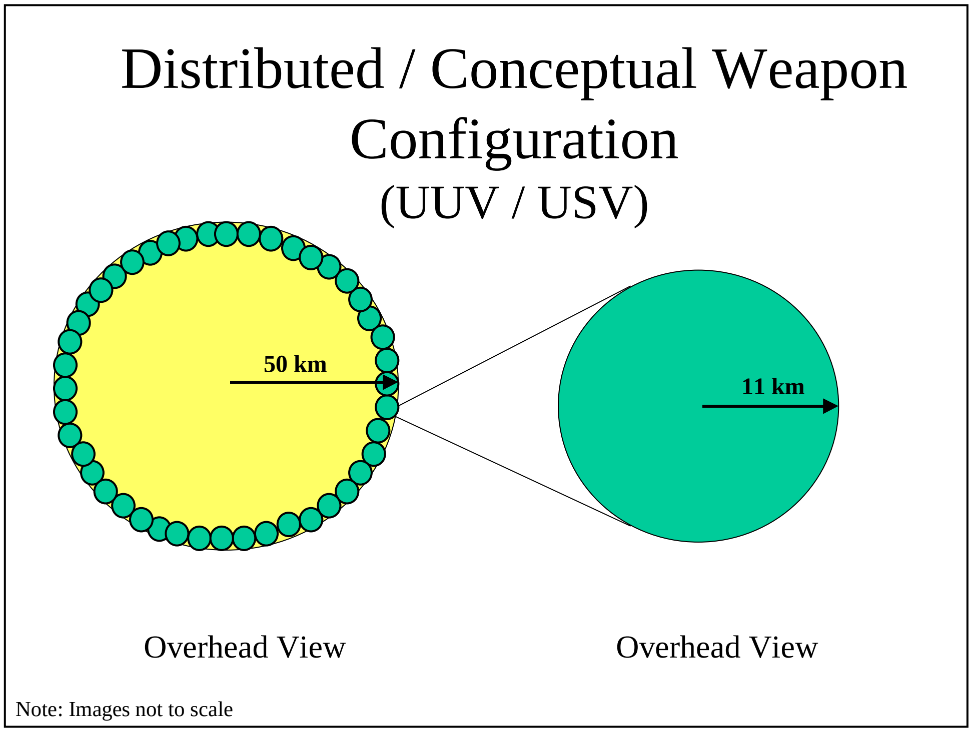


Figure V-31 Distributed / Conceptual Weapon Configuration (UUV / USV)

3. Force Composition

This study defines force composition as the number and type of assets in the Sea Base. The following supporting studies analysis assisted with determining the two force composition courses of action (COA). The SEI-3 supporting operation analysis portion of the Expeditionary Warfare Integrated Project proposed an escort force of three CGs, three DDGs, and three FFGs. The LCS concept of operations for protecting the Sea Base developed by the TSSE LCS Team is comprised of 12 LCSs operating with one CG and one DDG. The OR study's analytical model recommended 10-13 defenders to provide 360° coverage for the HVUs. Through these supporting studies, the SEA-4 Team felt two force compositions with similar capabilities could be designed. The two COAs proposed are: COA A—a force based on cruisers and destroyers (CRUDES); and COA B—a force based on LCSs. The total numbers of platforms from each COA would be analogous to the supporting study conclusions.

In addition to surface ships, the team felt that a submarine should be present in each COA to provide the capability to conduct undersea warfare (USW) missions, strike missions, or intelligence, surveillance, and reconnaissance (ISR) missions. The supporting study on SSGN contributions illustrates how the SSGN provides a means of reducing enemy lethality and contributes to an increased survivability for ExWar assets. Since COA B has a reduced strike capability when compared to COA A, the SEA-4 Team decided to add the SSN to COA A and an SSGN to COA B.

Along with the added surface and subsurface force protection assets, the ExWar ships have organic aircraft with force protection capabilities. ExWar ships are designed to carry AH-1Zs and JSFs. These aircraft are able to play a role in protecting transport areas by escorting air and surface transport assets and by patrolling landing zones. Furthermore, as mentioned in Table V-47, the ExWar ships will have surface-to-air missiles to defend against anti-ship missiles and enemy aircraft. Table V-49 summarizes the characteristics of the conceptual ExWar ship from the TSSE 2002 group design.

ExWar SHIP	
Length	1000 ft
Beam	150 ft
Displacement	70,000 ltons
Speed	30+ kts
Aircraft	6 HLACs, 14 MV-22s, 4 AH-1Zs, 6 JSFs, 4 UH-1s
Surface Craft	2 LCU(Rs), 3 HLCACs, 18 AAAVs

Table V-49 ExWar Ship Characteristics

Both of the COAs include six ExWar ships. The following will delineate the specific force protection assets of each COA.

a. Course of Action A (COA A)

The force protection assets for COA A include three CGs, three DDGs, three FFGs, and one SSN. Figure V-32 graphically represents COA A. Table V-50 summarizes the characteristics of each platform.

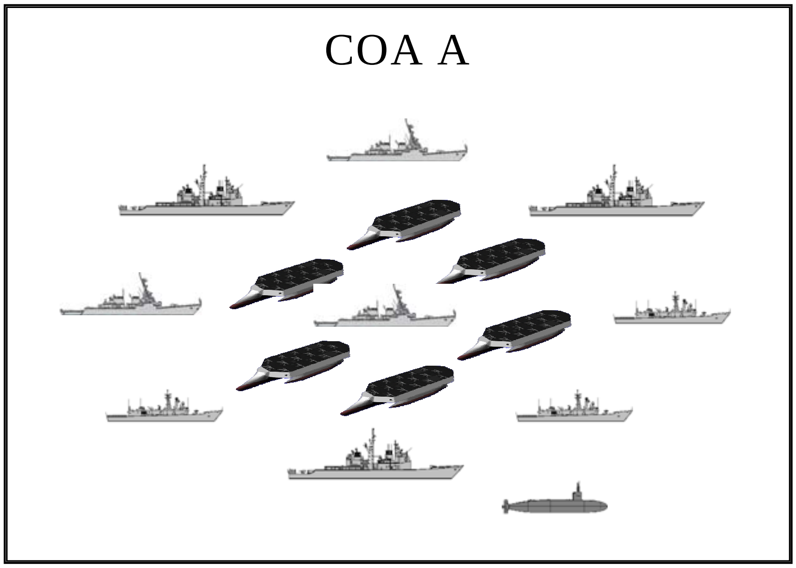


Figure V-32 COA A

CRUISER (CG)	
Length	570 ft
Beam	55 ft
Displacement	9,600 ltons
Speed	30+ kts
Aircraft	2 SH-60s
DESTROYER (DDG)	
Length	510 ft
Beam	60 ft
Displacement	9,200 ltons
Speed	30+ kts
Aircraft	2 SH-60s
FRIGATE (FFG)	
Length	450 ft
Beam	45 ft
Displacement	4,100 ltons
Speed	29+ kts
Aircraft	2 SH-60s
ATTACK SUBMARINE (SSN)	
Length	360 ft
Beam	30 ft
Displacement (submerged)	6,900 ltons
Speed	20+ kts

Table V-50 COA A Force Protection Asset Characteristics

b. Course of Action B (COA B)

The force protection assets for COA B include one CG, one DDG, 12 LCS, and one SSGN. Figure V-33 graphically represents COA B. Table V-51 summarizes the assets for each platform.

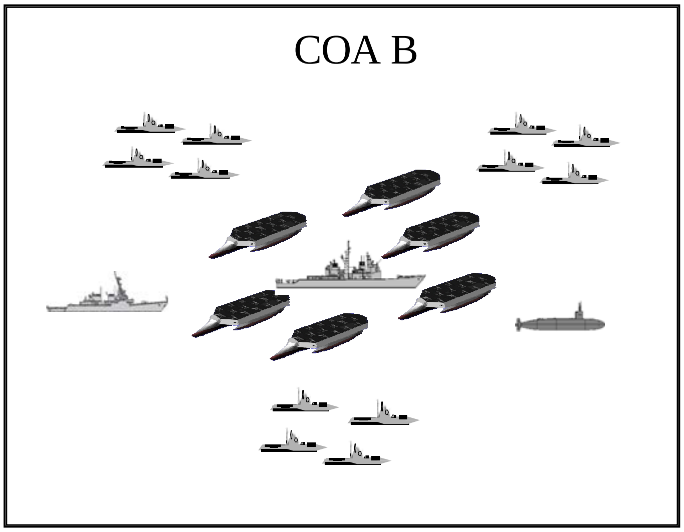


Figure V-33 COA B

CRUISER (CG)	
Length	570 ft
Beam	55 ft
Displacement	9,600 ltons
Speed	30+ kts
Aircraft	2 SH-60s
DESTROYER (DDG)	
Length	510 ft
Beam	60 ft
Displacement	9,200 ltons
Speed	30+ kts
Aircraft	2 SH-60s
TSSE LITTORAL COMBAT SHIP (LCS)	
Length	400 ft
Beam	98 ft
Displacement	1,500 ltons
Speed	45+ kts
Aircraft	2 SH-60s
GUIDED MISSILE SUBMARINE (SSGN)	
Length	560 ft
Beam	40 ft
Displacement (submerged)	18,750 ltons
Speed	20+ kts

Table V-51 COA B Force Protection Asset Characteristics

4. Conclusion — Proposed Force Protection Architecture

The product of the Design Chapter is a recommendation for a proposed force protection architecture. The SEA-4 Team proposes the Sea Base should employ a distributed sensor and weapon system. The Sea Base should take advantage of the increased sensor coverage offered by a distributed sensor network and utilize both point and distributed conceptual weapons in order to maximize total enemy engagements and thus increase the probability of kill against the enemy’s threats. Furthermore, the force composition should include the force protection platforms defined in COA A or COA B.

The next step is to test these proposed architectures and force compositions in order to determine which will possess a more robust force protection capability. Modeling and analysis provides a means to examine the proposed force protection architectures and their affects on force survivability.

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VI. ANALYSIS

A. OVERVIEW

1. Modeling Tools

Understanding the complex nature of force protection of the Sea Base required the use of modeling and simulation tools. The first step in determining which modeling tools to use for the study was to investigate and compare various modeling and simulation tools available. Modeling and simulation tools initially assessed included: Joint Army Navy Uniform Simulation (JANUS), Joint Theater Level Simulation (JTLS), Naval Simulation System (NSS), Enhanced ISSAC (Irreducible Semi-Autonomous Adaptive Combat) Neural Simulation Toolkit (EINSTein), EXTEND, and Microsoft Excel.

a. JANUS

“JANUS is an interactive, multi-sided, closed, stochastic, ground combat simulation featuring precise high-resolution graphics. The simulation provides sufficient resolution to model individual fighting systems for soldiers and can realistically model up to brigade-size maneuver forces.” (U.S. Army Modeling and Simulation Office, 2001)

b. JTLS

“JTLS is an interactive, computer-assisted simulation that models multi-sided air, ground, and naval combat. The forces simulated in the model are given Logistics, Special Operations Forces (SOF), and Intelligence capabilities. JTLS was originally designed as an analysis tool for use in development of joint and combined (coalition) operation plans, but is frequently used as a training support model. Its greatest use has been as an exercise driver for high-level military staff training, such as the CINC and JTF Commanders’ training provided by the Joint Warfighting Center. Using JTLS substantially reduces the cost of such training exercises.” (Roland & Associates Corporation, 2002)

c. NSS

"The Naval Simulation System (NSS) is an object-oriented Monte Carlo modeling and simulation (M&S) tool under development by Space and naval Warfare Systems Command Program Manager, Warfare-131 and Metron, Inc. for Chief of Naval Operations (CNO), Command and Control (C2) Systems Division (N62). NSS is a multi-warfare mission area tool designed to support operational commanders in developing and analyzing operational courses of action at the group / force level. Its capacity to replicate Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) entities and organizations robustly makes it unique among M&S tools." (Metron, Inc., 2000)

d. EINSTein

EINSTein is a beta-version, agent-based simulation where entities are given "attributes" to describe mission, capabilities, and aggressiveness. Agents represent individual combat units from troops to aircraft to capital ships. Entities, such as ships, are free to move, act, engage, and disengage opposing forces according to these attributes. Agents move using a stochastic time-step simulation. EINSTein was originally designed to model small unit ground combat, but is now used as an artificial-life model to explore self-organized emergence in land combat.

e. EXTEND

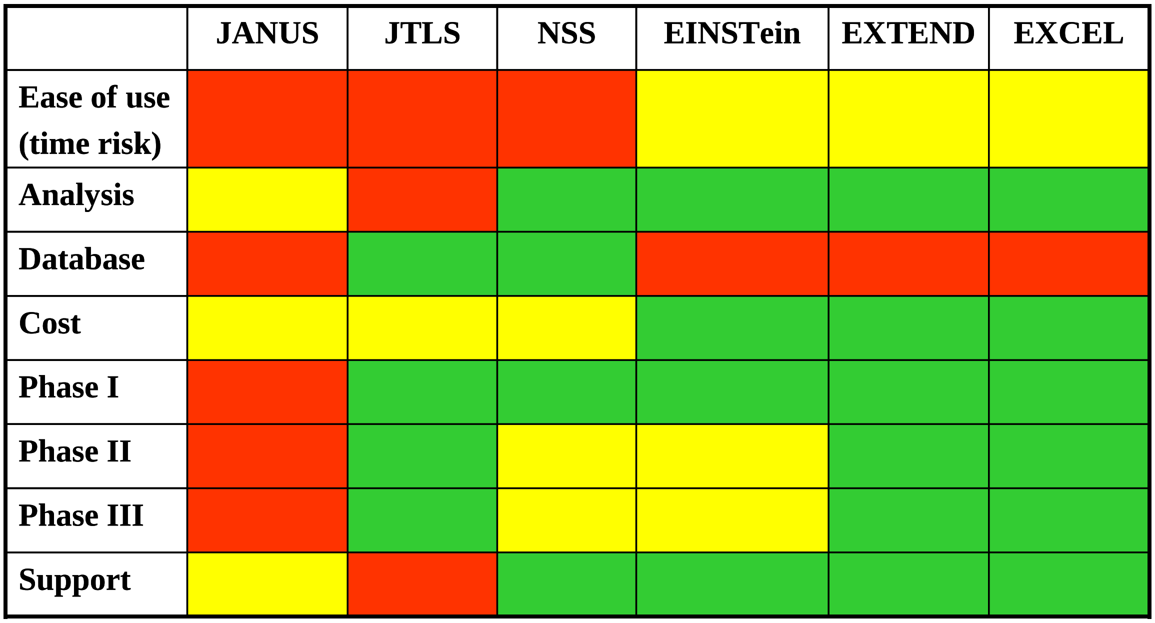
EXTEND is a process-based, discrete-event, modeling and simulation tool that uses components, or blocks, and interconnections to model complex processes. Creating block diagrams, where each block describes a part of a process, allows users to use a series of simple block definitions to describe complex processes.

f. Microsoft Excel

Microsoft Excel is a powerful spreadsheet that allows for simple calculation, but also can be applied as a simulation tool. Though it does not provide the level of detail that most simulation specific applications afford, it can be used to build simple simulations that may provide useful insight to complex problems. This insight can be translated into other, more robust, modeling and simulation applications.

2. Model Selection

All of the systems were compared in terms of ease of use (which directly relates to risks relating to time), analysis capability, database of platforms, weapons, and sensors, applicability to amphibious force states, and technical support availability. Figure VI-1 depicts the initial assessment of the modeling tools. The colors red, yellow, and green represent high, medium, and low threat, respectively.



	JANUS	**JTLS**	**NSS**	**EINSTein**	**EXTEND**	**EXCEL**
Ease of use (time risk)	🟥	🟥	🟥	🟨	🟨	🟨
Analysis	🟨	🟥	🟩	🟩	🟩	🟩
Database	🟥	🟩	🟩	🟥	🟥	🟥
Cost	🟨	🟨	🟨	🟩	🟩	🟩
Phase I	🟥	🟩	🟩	🟩	🟩	🟩
Phase II	🟥	🟩	🟨	🟨	🟩	🟩
Phase III	🟥	🟩	🟨	🟨	🟩	🟩
Support	🟨	🟥	🟩	🟩	🟩	🟩

Figure VI-1 Assessment of Modeling and Simulation Tools

After assessing the options, two of the six choices were eliminated. JANUS was eliminated since it focused on land combat. JTLS was eliminated due to its lack of robust analysis capability, excessive set up time, and little available technical support. JTLS is not capable of conducting numerous runs autonomously. This greatly hinders its analysis capability, since the results of a wargame are only taken from a single run. In terms of ease of use, the SEA-4 Team has had no formal training in the system and would require funding for contractor support. Although funding contractor support would have been possible, running the scenario requires another large support group. Since JTLS is primarily a staff-training tool, extra players would be required to play numerous roles for a complex scenario.

The team decided to include NSS, EINSTein, EXTEND, and Microsoft Excel as part of the study. Although EINSTein, EXTEND, and Microsoft Excel do not have databases that include platforms, weapons, and sensors, the SEA-4 Team was familiar with the systems from use in various courses required for degree completion. Furthermore, with the support of Naval Postgraduate School (NPS) staff, the team felt they could develop appropriate aggregate and high-resolution models with systems that would not require contracting costs.

The team then decided that models developed with EINSTein, EXTEND, and Microsoft Excel would require validation. In order to validate the student-developed models, the team selected NSS as an additional modeling tool. Although the team is not proficient in using NSS, funding and contractor support was available for the study. Findings from various Excel models and the threat document provided inputs to NSS. The results and insights gained from EXTEND and Microsoft Excel models could then be compared to results from NSS as a means of validation.

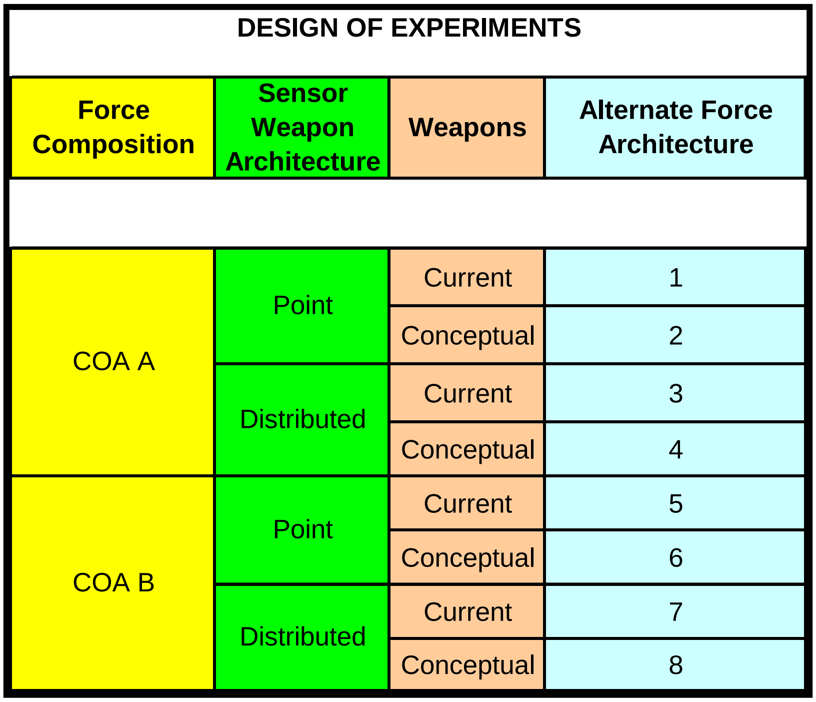
B. DESIGN OF EXPERIMENTS AND MEASURES OF EFFECTIVENESS

1. Design of Experiments

In order to adequately determine the relative performance of the proposed architectures developed by the team, a systematic design of experiments was developed to focus the model runs.

The primary characteristics (variables) of the proposed architectures are force composition, sensor and weapons architecture, and weapon types. Using the notion of a 2^n factorial design, two levels of each characteristic were developed. The force composition levels are course of action (COA) A and B. The sensor and weapons architecture are point and distributed. Weapon types are current and conceptual weapons. Figure VI-2 defines the various alternate force architectures that were tested in the modeling runs.

It was determined that the previously defined Phase II (amphibious assault) would be the most challenging scenario for our system, and therefore would be the basis for our modeling runs. Furthermore, the team determined that the first 24 hours of Phase II would present the most threats to the system.



DESIGN OF EXPERIMENTS

Force Composition	Sensor Weapon Architecture	Weapons	Alternate Force Architecture
COA A	Point	Current	1
		Conceptual	2
	Distributed	Current	3
		Conceptual	4
COA B	Point	Current	5
		Conceptual	6
	Distributed	Current	7
		Conceptual	8

Figure VI-2 Design of Experiments

2. Measures of Effectiveness

From the functional analysis, survivability was determined to be the key function in force protection of the Sea Base. Therefore, the primary measure of effectiveness (MOE) of protecting the Sea Base was determined to be survivability of the Sea Base and its transport assets. There are three primary MOEs that the team used to evaluate the ability of the alternative force architectures to protect the Sea Base. These MOEs are as follows:

- Number of ExWar Ships Surviving/Number of ExWar Ships at the Beginning
- Number of Transport Aircraft Surviving/Number of Transport Aircraft at the Beginning
- Number of Transport Surface Craft Surviving/Number of Transport Surface Craft at the Beginning

These MOEs ultimately helped shape the flow of the models, and ensured that the team had a clear goal for the information that the model should produce.

C. EXTEND

1. Overview

As a method to determine which of the competing architectures was preferred, a detailed process simulation model was developed using EXTEND. The EXTEND model provided a macro-view of sensor architecture-threat interactions. The model's overarching goal was to represent the formation level interactions between the threats, sensors, weapons, and platforms of the proposed architectures. Although it would have been possible with EXTEND to model every asset of the force as an individual asset, it was determined that the formation level model would provide the team with the necessary outputs to determine the driving factors of a force protection system.

2. Development

After the threats to the Sea Base were determined, the team started looking at the ways those threats would affect expeditionary warfare operations. It became immediately obvious that a model representing the threats would need to be built. The basic flow on the model was first laid out on paper to ensure the modeling effort would proceed in the correct direction. Figure VI-3 represents the top-level flow of the model.

Several assumptions drove the flow of the model. Because the model represents the Sea Base at the formation level, threats were assumed to arrive along a common, but unspecified, threat axis. A sensor and weapon were assumed to be along this axis as well. Threats must be detected in order for the system to defeat them through hard or soft kill means. If the threat is not detected, then only point defense systems and the threat own inaccuracy and reliability can prevent it from hitting a friendly platform. Because of the process flow nature of the EXTEND model, there must be a break point at which the detection sensors stop attempting to detect a threat. The assumption used is that the sensors will continue to search for a threat unit the threat is inside the minimum engage range of the force protection weapons.

In order to scope the modeling effort, the team determined the most significant threats and platforms from the threat analysis to be represented. All anti-ship cruise missile (ASCM) and surface-to-air missile (SAM) types from the threat analysis were included in the model.

TORP-1 and DW-1 were modeled as the representative type of torpedo (TORP) and dumb weapon (DW), respectively. ACFT-2, SB-3, and SUB-1 were modeled as the representative type of aircraft (ACFT), small boat (SB), and DW, respectively. The functionality to incorporate all platforms and weapons is resident in the model. Although the capability to generate mines exists in the model, it was determined that EXTEND was not the best tool to model the mine threat.

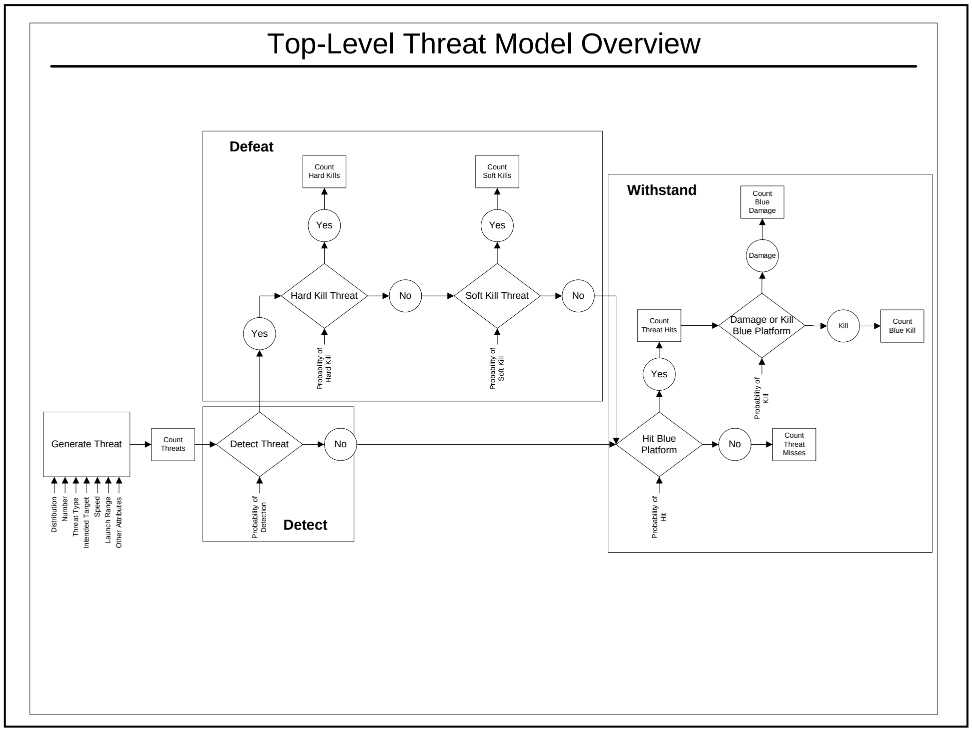
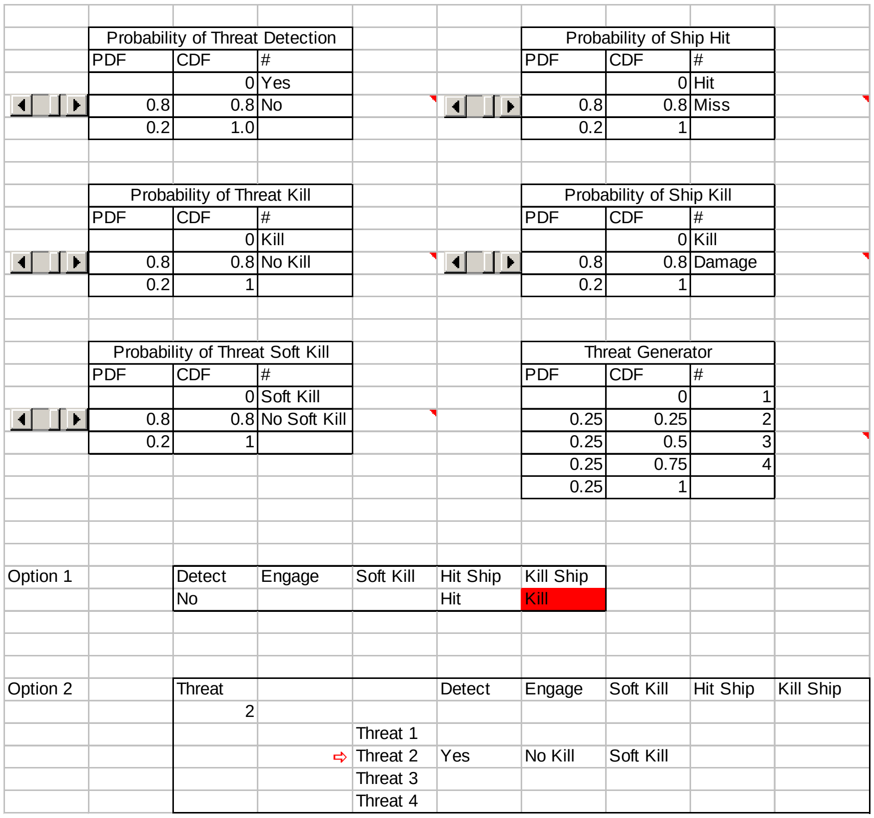


Figure VI-3 Top-level Overview of the Threat Model

From the top-level overview of the model, a rudimentary Excel model, depicted in Figure VI-4, was developed to determine if the model could be completed at the lowest level of detail possible. Although this model was functionally correct, it did not provide the level of detail desired to accurately model the sensor and search theory presented in the search and sensor analysis models.



Probability of Threat Detection		
PDF	CDF	#
	0	Yes
0.8	0.8	No
0.2	1.0	

Probability of Ship Hit		
PDF	CDF	#
	0	Hit
0.8	0.8	Miss
0.2	1	

Probability of Threat Kill		
PDF	CDF	#
	0	Kill
0.8	0.8	No Kill
0.2	1	

Probability of Ship Kill		
PDF	CDF	#
	0	Kill
0.8	0.8	Damage
0.2	1	

Probability of Threat Soft Kill		
PDF	CDF	#
	0	Soft Kill
0.8	0.8	No Soft Kill
0.2	1	

Threat Generator		
PDF	CDF	#
	0	1
0.25	0.25	2
0.25	0.5	3
0.25	0.75	4
0.25	1	

Option 1	Detect	Engage	Soft Kill	Hit Ship	Kill Ship
	No			Hit	Kill

Option 2	Threat			Detect	Engage	Soft Kill	Hit Ship	Kill Ship
	2							
			Threat 1					
		⇨	Threat 2	Yes	No Kill	Soft Kill		
			Threat 3					
			Threat 4					

Figure VI-4 Basic Excel Threat Model

In order to accurately represent the sensors and weapons, the team decided to build a detailed process model using EXTEND. Figure VI-5 shows the top layer of the threat model.

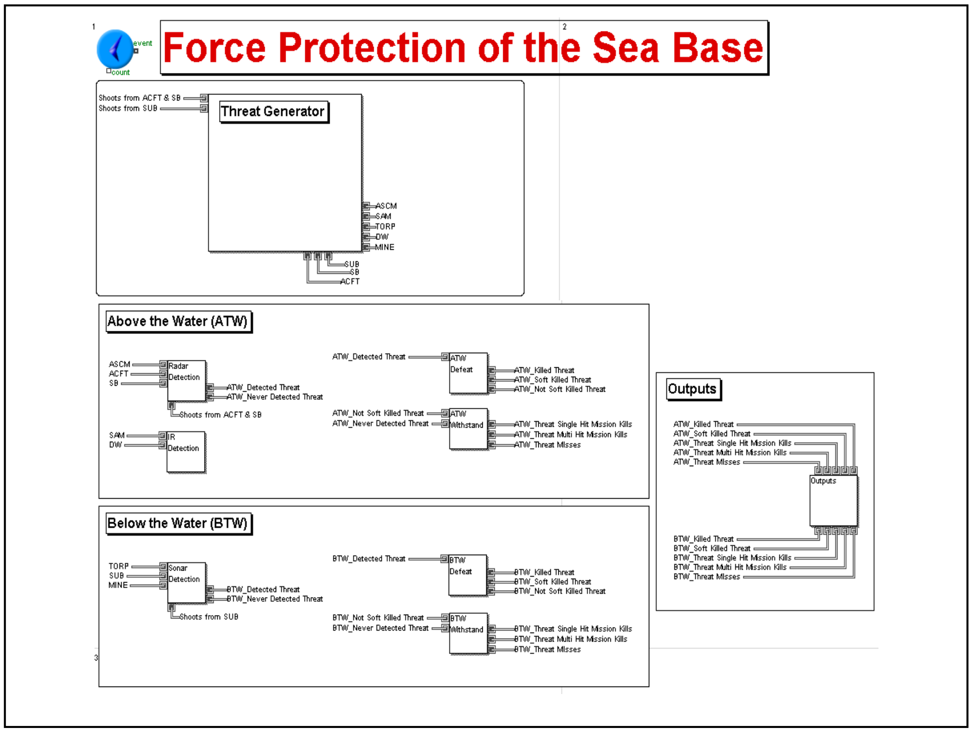


Figure VI-5 EXTEND Model Top Layer

The EXTEND model is composed of four primary blocks: threat generator, above the water, below the water, and outputs. Each of these blocks will be discussed in detail, and specific inputs and values can be found in Appendix B of this study.

a. Threat Generator

The threat generator is responsible for generating enemy platforms and weapons at a given rate and number. The threats were generated based on a poisson process with independent interarrival times. Each platform has attributes that are used throughout the model. These attributes include speed, launch range, altitude, raid size, and maximum weapon range. The threats have similar attributes, including speed, launch range, altitude, raid size, and intended target. These values were determined from the threat analysis. Figure VI-6 is an expanded view of the threat generator block.

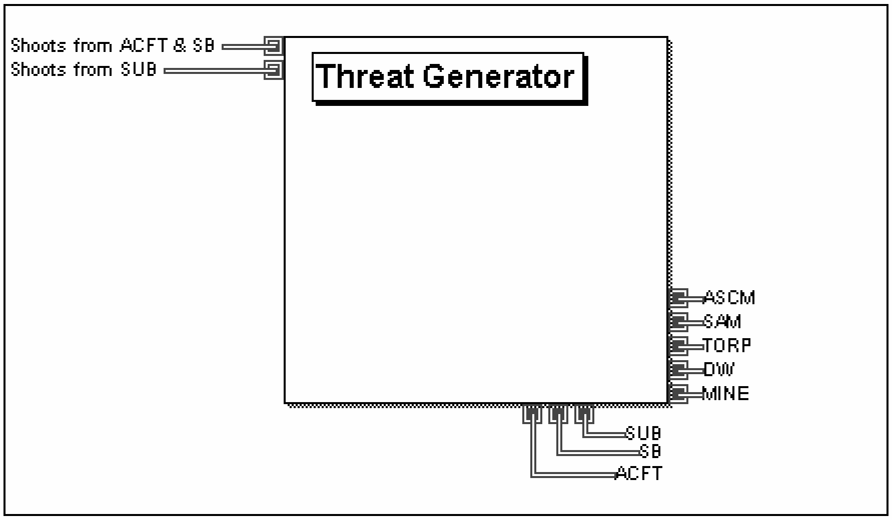


Figure VI-6 Threat Generator

The threat generator shows direct linkage of the enemy platforms to weapons. Where applicable platforms must be generated and survive the force protection architecture in order for it to subsequently fire its associated weapon. An example would be an aircraft firing an anti-ship cruise missile.

b. Above the Water

Platforms and weapons that are a threat to the Sea Base above the water leave the threat generator and go to the above the water block. These threats would be ACFT, SBs, ASCMs, SAMs, and DWs.

The above the water block is further divided into four other blocks: radar detection, infrared (IR) detection, defeat, and withstand. From the threat generator, threats were routed to the appropriate sensor. Figure VI-7 is an expanded view of the above the water block.

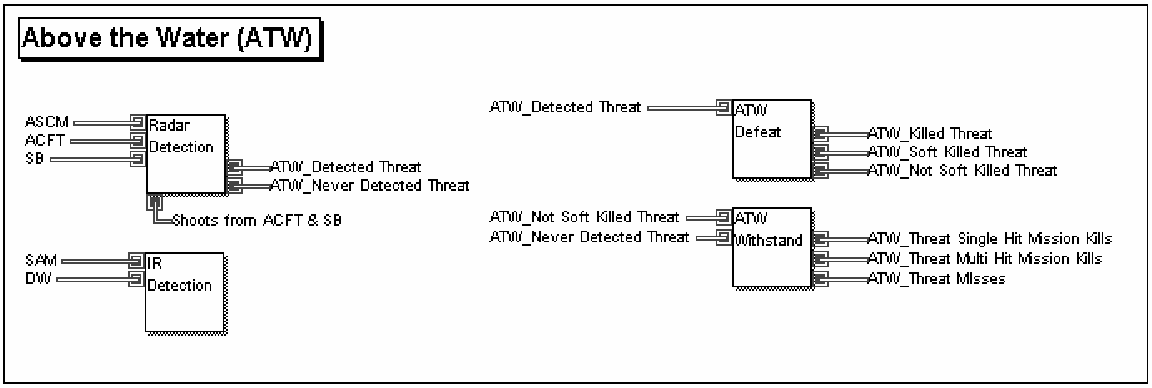


Figure VI-7 Above the Water

(1) Radar Detection

The radar detection block is a detailed process model of the point and distributed radar sensor architectures proposed by the team. Probability of detection was calculated using the first principle equations used in the search analysis. These equations were applied stochastically in the model to determine probability of detection based on search time. Aircraft, small boats, and anti-ship cruise missiles are routed to this block. For flexibility, the block can be reconfigured to represent any of the radar architectures proposed by the team.

If detected, the threat continues through the model to the defeat block. If it reaches the minimum engagement range of the force protection weapons, it continues to the withstand block. If it reaches its maximum weapons range, it returns to the threat generator where it triggers an associated weapon if applicable. If a threat weapon is not detected, it is routed to the withstand block.

(2) IR detection

The IR detection block is a detailed process model of the point and distributed IR sensor architectures proposed by the team. Probability of detection was calculated using the first principle equations used in the search analysis. These equations were applied stochastically in the model to determine probability of detection based on search time. The IR detection block is specifically designed to detect SAMs and DWs. From the search analysis, it was concluded that IR would be the best detection sensor for these threats, and when Unmanned Aerial Vehicle (UAV)-based, as in the distributed architecture, it is also the only sensor in close proximity to the threat. SAMs and DWs are routed to this block. For flexibility, the block can be reconfigured to represent any of the IR sensor architectures proposed by the team.

Because there are no current or conceptual weapons that are capable of hard killing SAMs and DWs in flight, the architecture does not attempt to hard kill SAMs or DWs. Whether or not a SAM or DW is soft killed or a SAM or DW mission kills a friendly platform is determined in this block rather than the defeat and withstand blocks. The result of this interaction is passed to the output block.

(3) Defeat

The defeat block is a detailed process model of the point and distributed weapon architectures with current or conceptual weapons proposed by the team. If the radar block detects a threat, the defeat block then models the process of the friendly weapon's chance to defeat the threats through hard kill and soft kill methods. For flexibility, the block can be reconfigured to represent any of the weapon architectures proposed by the team.

Threats that have been killed by the defeat block are routed to the outputs block. Threats that were not killed are routed to the withstand block.

(4) Withstand

The withstand block is a detailed process model of the threat's probability of hit, and subsequently, the probability of mission killing given hit of the friendly platforms. Probability of mission kill given a hit was determined by gross level ship structure analysis assuming a uniform hit distribution across the hull. A point defense system is modeled where appropriate to the platform. Results of the interaction between the threats and friendly platforms are routed to the outputs block.

c. Below the Water

Platforms and weapons that are a threat to the Sea Base below the water, leave the threat generator and go to the below the water block. These threats would be submarines (SUBs), TORPs, and mines.

The below the water block is further divided into three other blocks: sonar detection, defeat, and withstand. From the threat generator, threats were routed to the sonar detection block. Figure VI-8 is an expanded view of the below the water block.

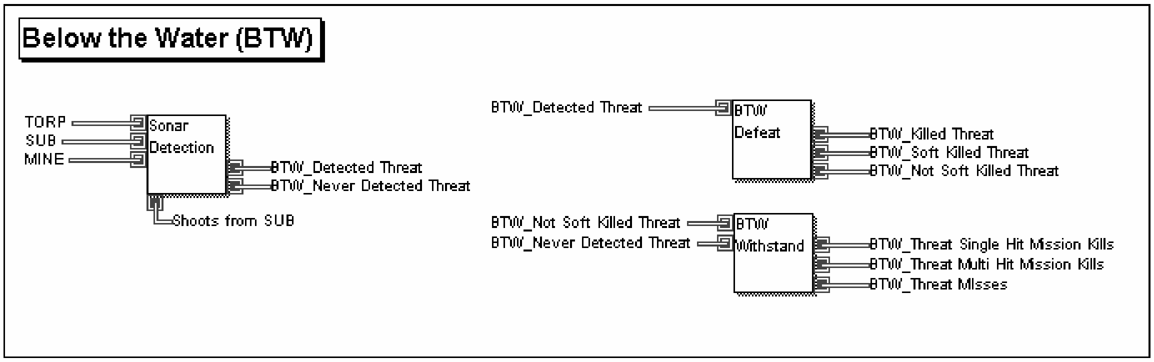


Figure VI-8 Below the Water

(1) Sonar Detection

The sonar detection block is a detailed process model of the point and distributed sonar sensor architectures proposed by the team. SUBs and TORPs are routed to this block. For flexibility, the block can be reconfigured to represent any of the sonar architectures proposed by the team.

If detected, the threat continues through the model to the defeat block. If it reaches the minimum engagement range of the force protection weapons, it continues to the withstand block. If it reaches its maximum weapons range, it returns to the threat generator where it triggers an associated weapon if applicable. If a threat weapon is not detected, it is routed to the withstand block.

(2) Defeat

The defeat block is a detailed process model of the point and distributed weapon architectures proposed by the team. If the sonar block has detected a threat, the defeat block now models the process of the friendly weapon’s chance to defeat the threats through hard kill and soft kill methods. For flexibility, the block can be reconfigured to represent any of the weapon architectures proposed by the team.

Threats that have been killed by the defeat block are routed to the outputs block. Threats that were not killed are routed to the withstand block.

(3) Withstand

The withstand block is a detailed process model of the threats chance of hitting, and subsequently, mission killing the friendly platforms. Results of the interaction between the threats and friendly platforms are routed to the outputs block.

d. Outputs

The outputs block accumulates the data required to evaluate the alternate force architectures. It accumulates the data from both the above the water and the below the water blocks.

The outputs compiled are the number of each type of friendly platforms mission killed and the number of mission kills attributed to each type of threat weapon. Figure VI-9 is an expanded view of the outputs block.

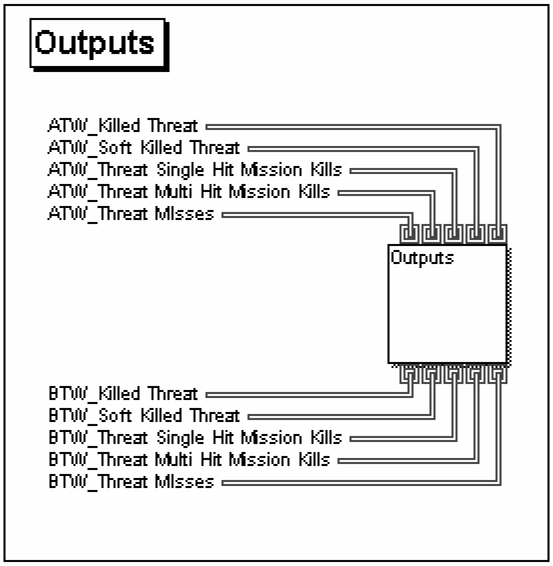


Figure VI-9 Outputs

3. Results

The model was run 100 times for the individual alternate force architectures developed in the design of experiments. The results were then compiled and analyzed to determine if there was a statistically significant difference between the different architectures. Table VI-1 contains the average number of mission capable assets, standard deviation, and upper and lower 95% confidence intervals for the various alternate force architectures. Figure VI-10 through Figure VI-15 are graphical representations of Table VI-1.

Figure VI-16 represents the percentage of assets mission capable for the various alternate force architectures.

Figure VI-17 represents the comparison of the torpedo and ASCM threat to the ships of the Sea Base.

Alternate Force Architecture	**Statistics**	**Asset (Initial Number)**					
		ExWar (6)	**LCU(R) (12)**	**HLCAC (18)**	**AAAV (108)**	**LRHLAC (36)**	**MV-22 (84)**
1	Upper 95% CI	3.57	9.46	16.59	107.10	33.12	81.01
	Lower 95% CI	2.99	8.78	15.97	106.54	32.52	80.23
	Average Mission Capable	3.28	9.12	16.28	106.82	32.82	80.62
2	Upper 95% CI	3.63	9.46	16.50	107.36	32.77	81.07
	Lower 95% CI	3.09	8.72	15.90	106.94	32.05	80.47
	Average Mission Capable	3.36	9.09	16.20	107.15	32.41	80.77
3	Upper 95% CI	5.88	11.99	18.01	108.00	36.01	84.00
	Lower 95% CI	5.69	11.91	17.97	107.92	35.95	83.92
	Average Mission Capable	5.78	11.95	17.99	107.96	35.98	83.96
4	Upper 95% CI	5.85	11.85	17.91	107.93	35.97	83.95
	Lower 95% CI	5.65	11.65	17.77	107.77	35.86	83.83
	Average Mission Capable	5.75	11.75	17.84	107.85	35.91	83.89
5	Upper 95% CI	3.41	9.12	16.44	107.28	32.95	80.92
	Lower 95% CI	2.87	8.38	15.78	106.92	32.25	80.18
	Average Mission Capable	3.14	8.75	16.11	107.10	32.60	80.55
6	Upper 95% CI	3.30	9.34	16.49	107.44	33.14	80.66
	Lower 95% CI	2.72	8.56	15.93	107.08	32.42	79.98
	Average Mission Capable	3.01	8.95	16.21	107.26	32.78	80.32
7	Upper 95% CI	5.88	12.00	17.99	108.01	36.01	83.98
	Lower 95% CI	5.67	11.93	17.89	107.95	35.95	83.88
	Average Mission Capable	5.78	11.97	17.94	107.98	35.98	83.93
8	Upper 95% CI	5.86	11.93	18.00	108.01	35.97	84.00
	Lower 95% CI	5.66	11.79	17.92	107.95	35.85	83.94
	Average Mission Capable	5.76	11.86	17.96	107.98	35.91	83.97

Table VI-1 Results of EXTEND Modeling Runs

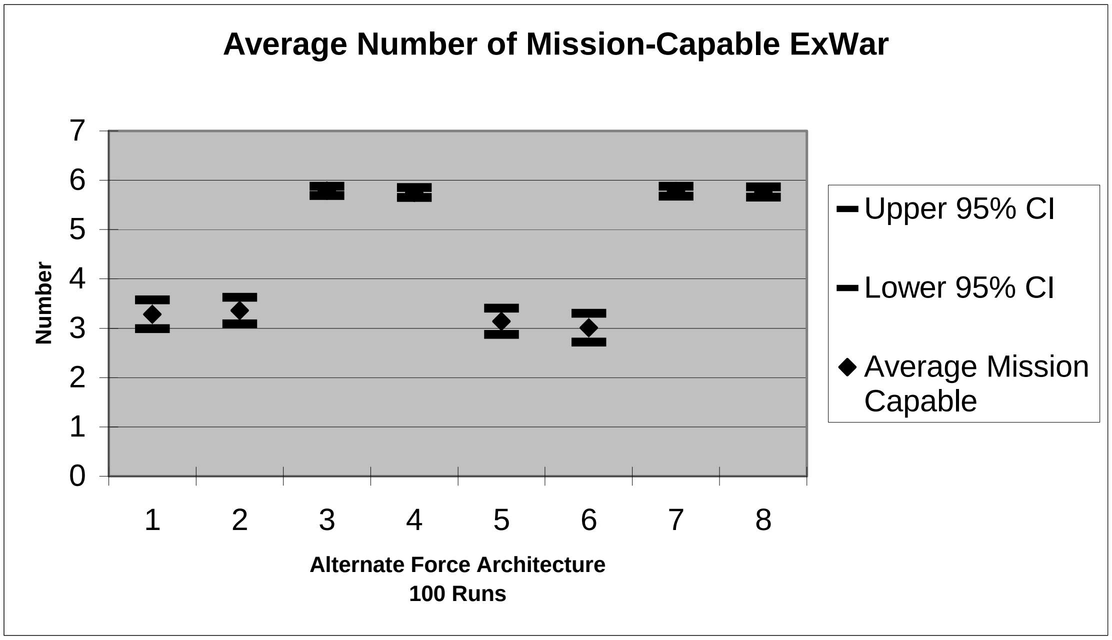


Figure VI-10 Number of Mission-Capable ExWar

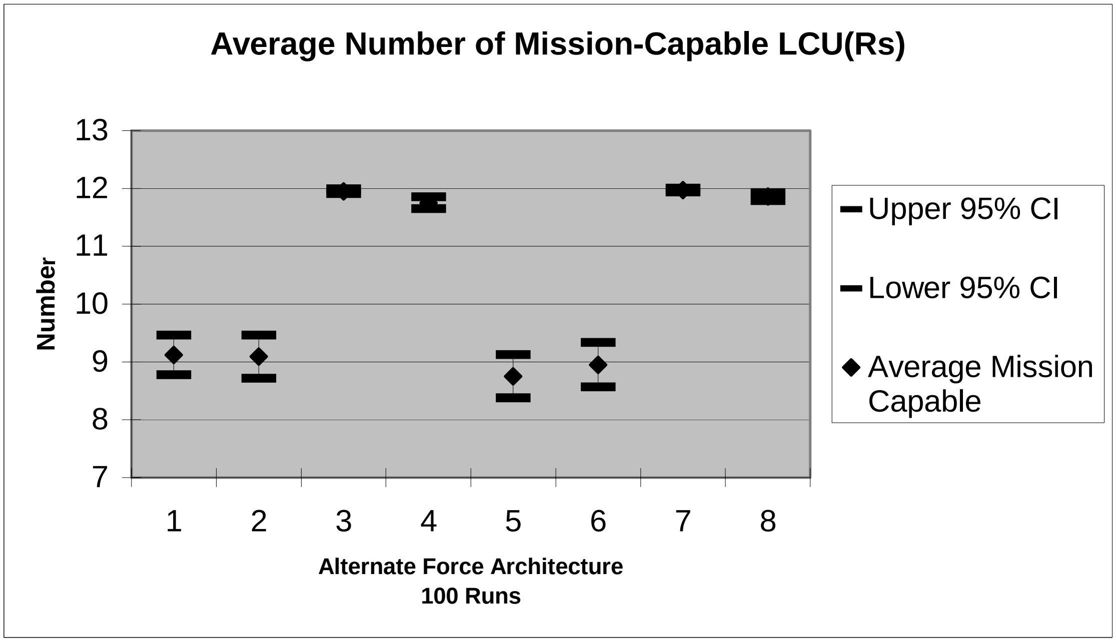


Figure VI-11 Number of Mission-Capable LCU(Rs)

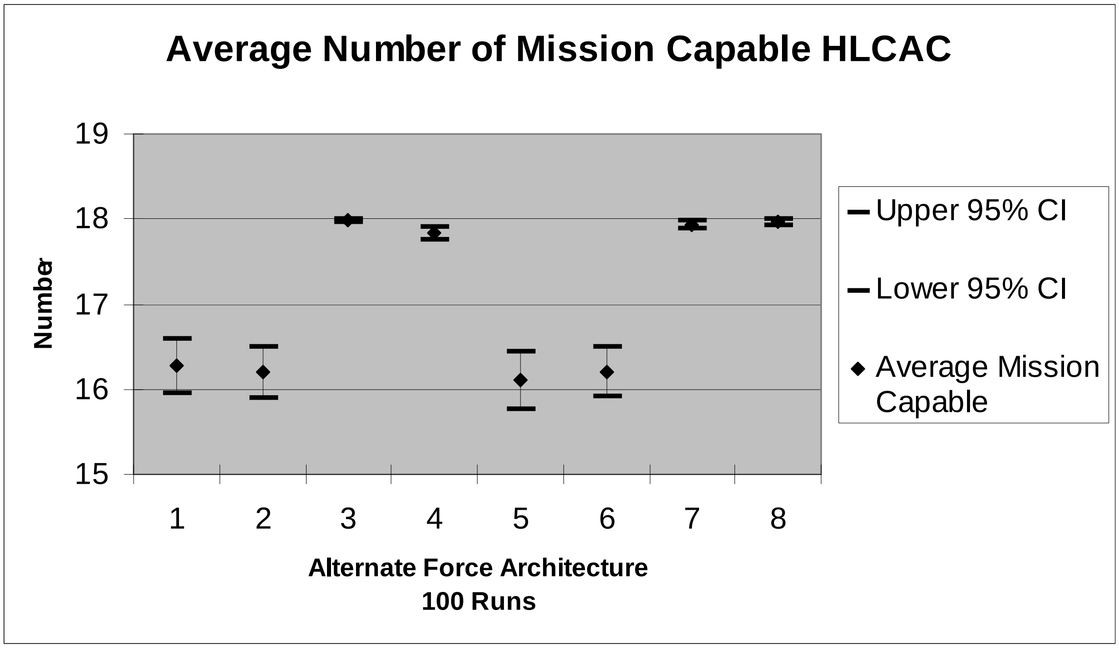


Figure VI-12 Number of Mission-Capable HLCACs

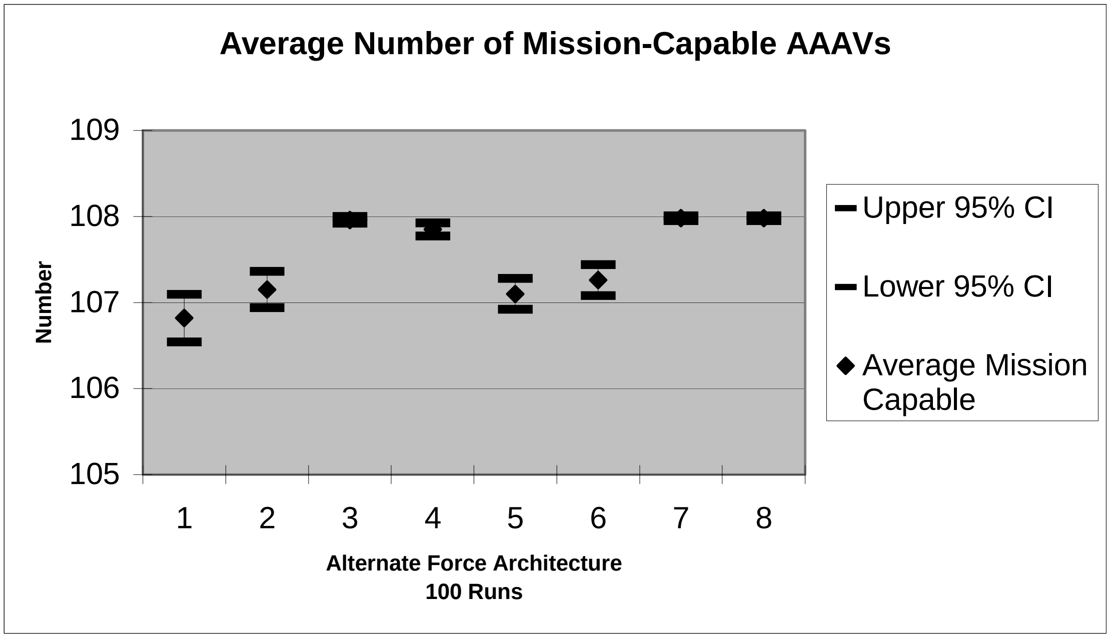


Figure VI-13 Number of Mission-Capable AAAVs

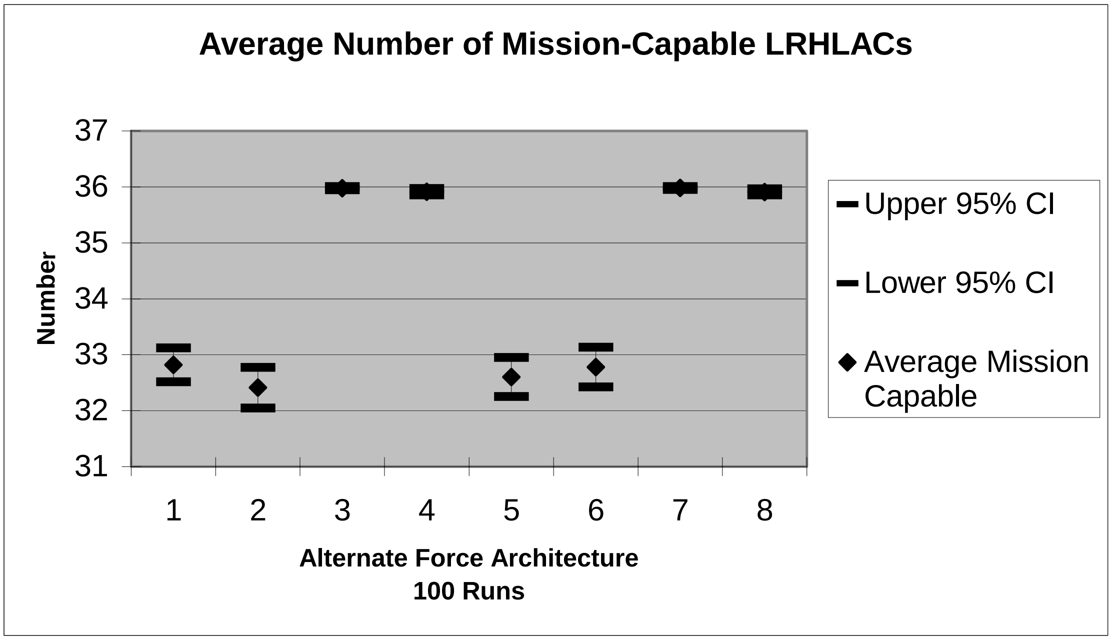


Figure VI-14 Number of Mission-Capable LRHLACs

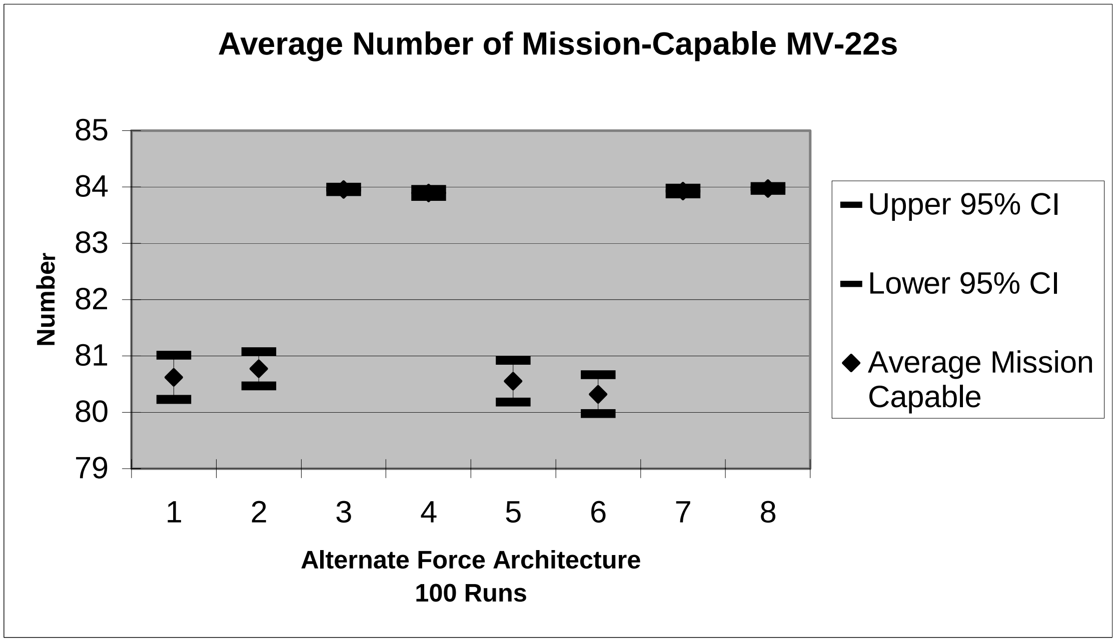
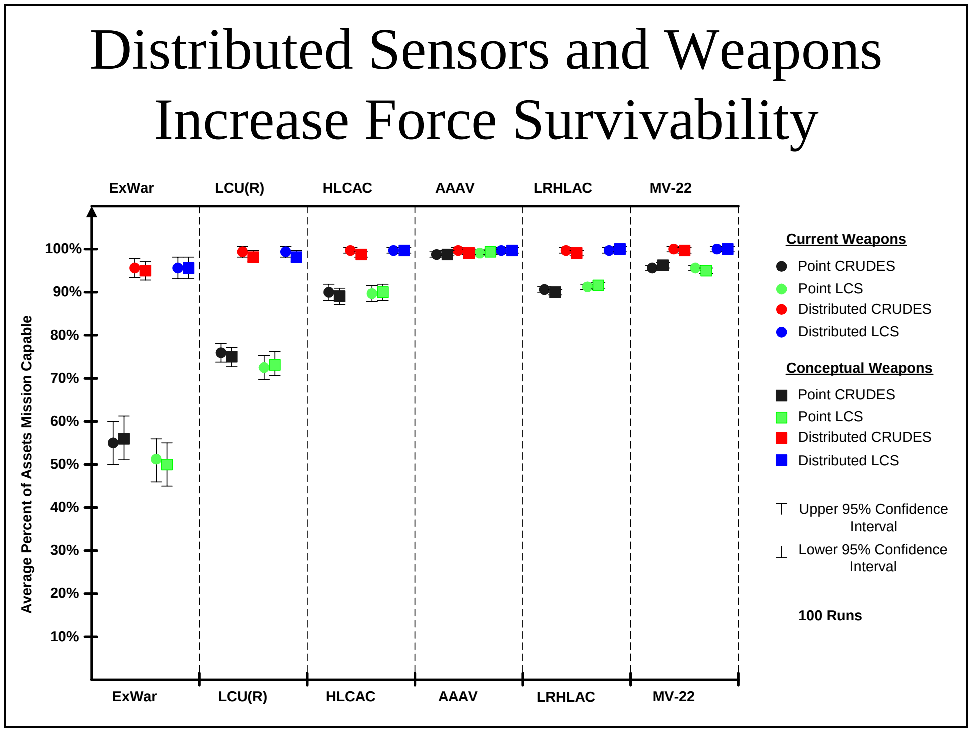


Figure VI-15 Number of Mission-Capable MV-22s



Distributed Sensors and Weapons Increase Force Survivability

Figure VI-16 Comparison of Alternate Force Architectures

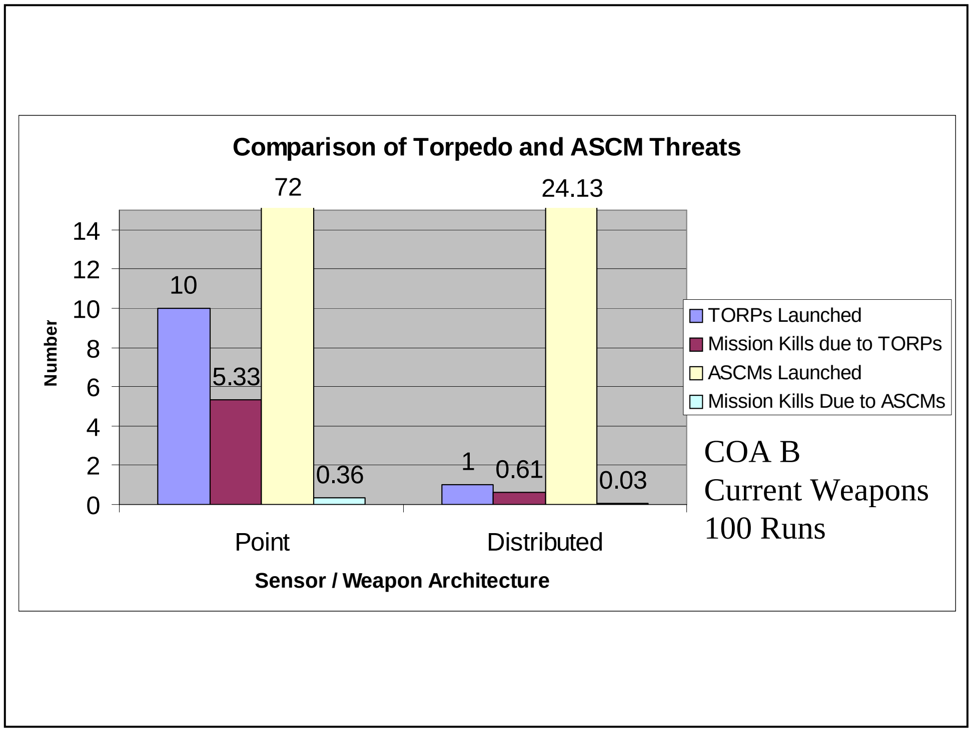


Figure VI-17 Comparison of Torpedo and ASCM Threats

4. Conclusions

From the results of the EXTEND model represented in the previous figures, there is a significant difference between the point and distributed architectures. There is not a significant difference between the CRUDES- or the LCS-based protection force, nor the current weapon or the conceptual weapon architectures.

The team has therefore concluded that in the EXTEND model, distributed sensors are the factor that most affects survivability of the Sea Base. Also, the LCS-based protection force provides a level of force protection to the Sea Base equivalent to that of the cruiser- and destroyer-based protection force. Furthermore, the longer range and speed of the conceptual weapons over that of the current weapons provides no improvement to the survivability of the Sea Base. In order to gain benefits from the increase in range and speed, the sensor detection range must be improved. This is exactly what the distributed sensors do for the system.

With regard to threats to the Sea Base, the submarines and torpedoes are by far the most significant threat. Figure VI-17 shows that torpedoes make up roughly 10% of the total threat (ASCMs and TORPs) to the Sea Base ships, but account for over 95% of the mission kills. Future requirements for force protection of the Sea Base should place high emphasis on Undersea Warfare (USW), and the need for a layered defense against torpedoes and other USW threats is a must.

The Systems Engineering and Analysis curriculum has used EXTEND with great success in recent integration projects, as well as Joint Campaign Analysis courses. EXTEND is an extremely easy modeling and simulation tool to learn. It lends itself to the modeling of very complex processes. In most cases it is very easy to troubleshoot, and visually represents the process being modeled. Although it may not be the right tool for every Systems Engineering problem, the team highly recommends EXTEND whenever it is applicable.

D. NAVAL SIMULATION SYSTEM (NSS)

1. Overview

NSS provided a means of analyzing the characteristics of the proposed force protection architectures. The ability of NSS to support the generic threats identified in this study and the various architectures proposed by the study made NSS a prime candidate for a modeling system. Furthermore, the team felt NSS's ability to set-up multiple replications of a single scenario and to collect data for the defined MOEs proved to be useful for this study. NSS allowed the team to investigate the proposed architectures as a system-of-systems by simulating the interactions between various entities such as ships, aircraft, landing craft, and weapons. This study intended to use NSS as a means to compare results of EXTEND and Excel models.

2. Development

The SEA NSS model was built in coordination with a representative from the Roland's and Associates Corporation. The model was developed incrementally with the development of a baseline scenario and database that was verified by the SEA Team. The SEA Team provided inputs for the scenario, while the representative from Roland's and Associates entered the data into NSS. As the baseline was built, the SEA Team concurrently verified the characteristics and employment of the platforms and weapon systems residing in the scenario. For example, the team had to verify the detection and capability of all of the platforms and weapons. Such verification ensured weapons did not perform outside of their intended capability, such as an anti-ship missile engaging an aircraft. Once the baseline passed the expectations of the team, the baseline was adapted to create separate databases for each of the alternate force architectures.

Various inputs relating to type of asset, asset employment, and time were needed in order for NSS to perform a simulation. Assets included ships, aircraft, submarines, and land-based weapon systems. In terms of asset employment, each of the assets was assigned a region or track and a tactic that defined how the asset would act in the case of detecting another asset. Lastly, a length of time had to be determined for the simulation. With these parameters, NSS simulated engagements between opposing forces by moving the assets in the prescribed manner for the defined length of time. As each asset moved according to its defined employment, NSS monitored sensor detection events and created weapon fires events based on defined tactics. NSS captured statistics from the simulation based on selected MOEs. Although MOEs are not required to be set in order to conduct a simulation of the scenario, they are required if the user intends to perform a statistical study.

The NSS model was developed to support the design of experiments previously discussed. The design of experiments included three factors: force composition, sensor and weapon architecture, and weapon type. These three factors were organized into eight alternate force architectures. Alternate Force Architecture One acted as the baseline. Subsequent force architectures were then adapted from the baseline. The remainder of this section will discuss the various inputs needed to develop the model: scenario, length of time, threats, force composition, sensor and weapon architecture, and weapon types.

a. Scenario

The NSS model utilized the scenario discussed in the Threat/Futures Analysis section of the Problem Definition study. The conceptual Marine Expeditionary Brigade (MEB)-sized amphibious force has been tasked with expelling Chinese forces from the Philippine island of Palawan. The NSS scenario was designed to model this study's definition of Phase II of an amphibious operation—the amphibious assault. As depicted in Figure VI-18, the amphibious force was placed in a sea echelon area 25 nm off the eastern coast of Palawan. The sea echelon area acted as the operating area for the ExWar ships and launching area for the transport assets. Two objectives that would support follow-on forces were identified on Palawan. Objective A was a seaport that could support large commercial vessels and ExWar logistic ships. The other objective was an airfield, Objective B, approximately 10 nm west of the seaport.

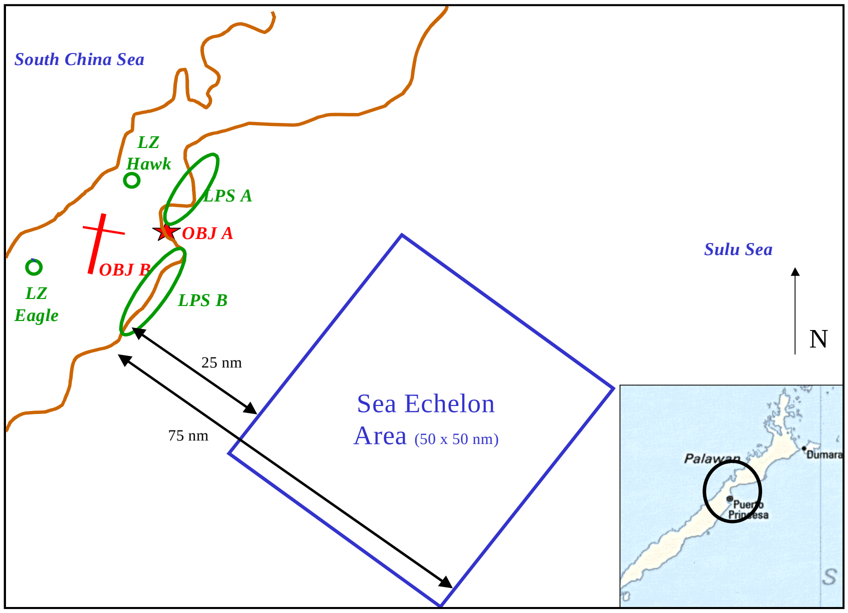


Figure VI-18 Palawan Area of Operations

As seen in Figure VI-18, landing areas for transport assets were identified for the NSS model. Two littoral penetration sites (LPS) to the north and south of Objective A would support the landing of surface transport assets, such as Heavy Lift Landing Craft Air Cushioned (HLCAC), Landing Craft Utility (Replacement) (LCU(R)), and Advanced Amphibious Assault Vehicle (AAAV). Two landing zones (LZ) would support the air transport assets such as MV-22 and the LRHLAC. A detailed assault schedule and landing area diagram can be found in Appendix B.

b. Length of Simulation

A period of 24 hours was determined to be the length of time for the NSS simulation. The start of Phase II was recognized as the point at which the transport assets began their movement to the objective. The end of Phase II occurs when the all of the needed landing force equipment, personnel, vehicles, and supplies for the main effort are on Palawan. Then Phase III, sustainment of the operation begins. In order to eliminate the ambiguities of defining the needed landing force equipment, personnel, vehicles, and supplies for this particular operation, the SEA-4 Team decided to model the first 24 hours of Phase II, as it represented the most threatening period of the Phase. This study utilized the surge sortie rates for transport assets identified in last year's Integrated Expeditionary Warfare study. Furthermore, preliminary analysis found that the initial threat level identified reached a steady-state before the end of the 24-hour period.

c. Threats

The NSS model utilized all of the threats identified in the Threat Analysis of this study. The majority of the threats to the Sea Base originated from Palawan. Other threats, such as the larger small boats (SB-3) and larger submarines (SUB-1, SUB-2), were assumed to be operating in the Sulu Sea. Threats employment varied from single weapon and platform attacks to large swarms of patrol boats and large ASCM raids. A detailed listing of the threats and their employment can be found in Appendix B.

d. Force Composition

The two COAs identified in the Proposed Architecture section of this study were represented on an individual entity level. In other words, NSS has the capability to simulate each individual platform in the NSS model. Figure VI-19 depicts COA A, with three CGs, three DDGs, three FFGs, one SSN, and six ExWar ships in vicinity of the sea echelon area.

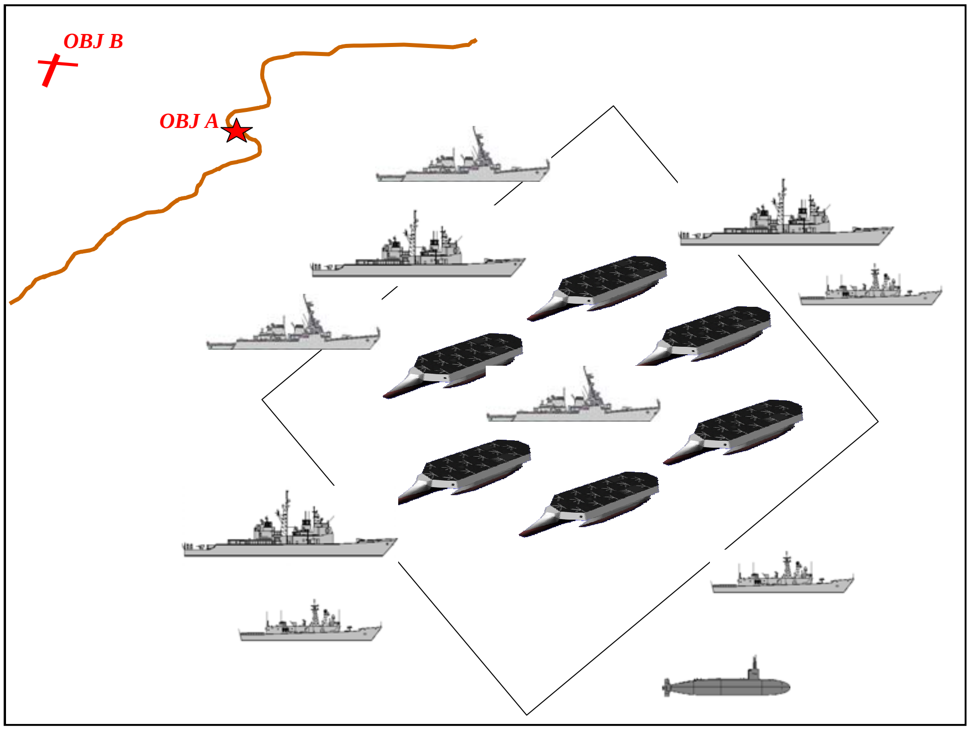


Figure VI-19 Force Composition (COA A): CRUDES-based

In COA A, a DDG was placed in the center of the ExWar ship formation to defend against any threats that bypass outer defenses. A CG and two DDGs were placed along the high threat axis between the sea echelon area and Palawan. A CG and FFG were each placed to the northeast and southwest of the Sea Echelon area, and a single FFG was placed on the southeast side of the sea echelon area. An SSN was free to patrol the entire Sulu Sea area.

In COA B (see Figure VI-20), 12 LCSs, one CG, one DDG, and one SSGN protect the ExWar ship formation. A single CG was placed in the center of the force to protect against threats bypassing outer defenses. A DDG was placed on the southeast side of the formation and three groups of four LCSs were placed along the other sides of the sea echelon area. A SSGN was able to patrol the Sulu Sea area freely.

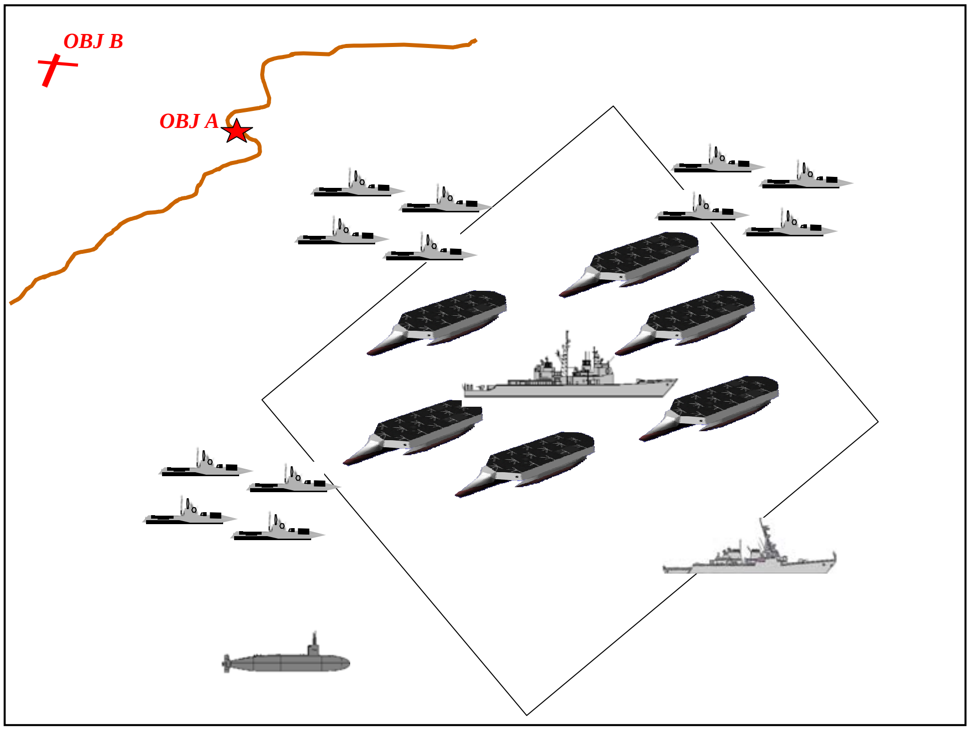


Figure VI-20 Force Composition (COA B): LCS-based

In addition to ships, aircraft were modeled in NSS. The CG, DDG, FFG, and LCS each had two embarked SH-60s available for undersea warfare and surface warfare roles. Furthermore, AH-1Zs and Joint Strike Fighters (JSFs) embarked on the ExWar ships were included in the model. Since the AH-1Z and JSF are considered landing force assets, the team decided to limit their role in the model to primarily interdicting land-based threats.

e. Sensor and Weapon Architecture

Both the point and distributed sensor and weapon architectures were modeled in NSS. For the point sensor and weapon architecture, the sensors and weapons originate from the platforms as depicted in the Force Composition section. Modifications had to be made to the proposed distributed architecture discussed in the Search Analysis. Due to the amphibious force's close proximity to the objective, the radius of the UAV sensors in the distributed sensor and weapon architecture had to be decreased. Instead of placing the UAVs on the 200 nm radius of the Aerostat coverage, the UAVs radius was decreased to approximately 45 nm to provide coverage against threats originating from Palawan. Keeping the UAV radius at 200 nm from the center of the force would have negated the usefulness of the UAV's sensors and weapons. The Aerostat coverage remained centered on the amphibious force with a radius of 200 nm. Figure VI-21 portrays the distributed sensor and weapon architecture in the NSS model.

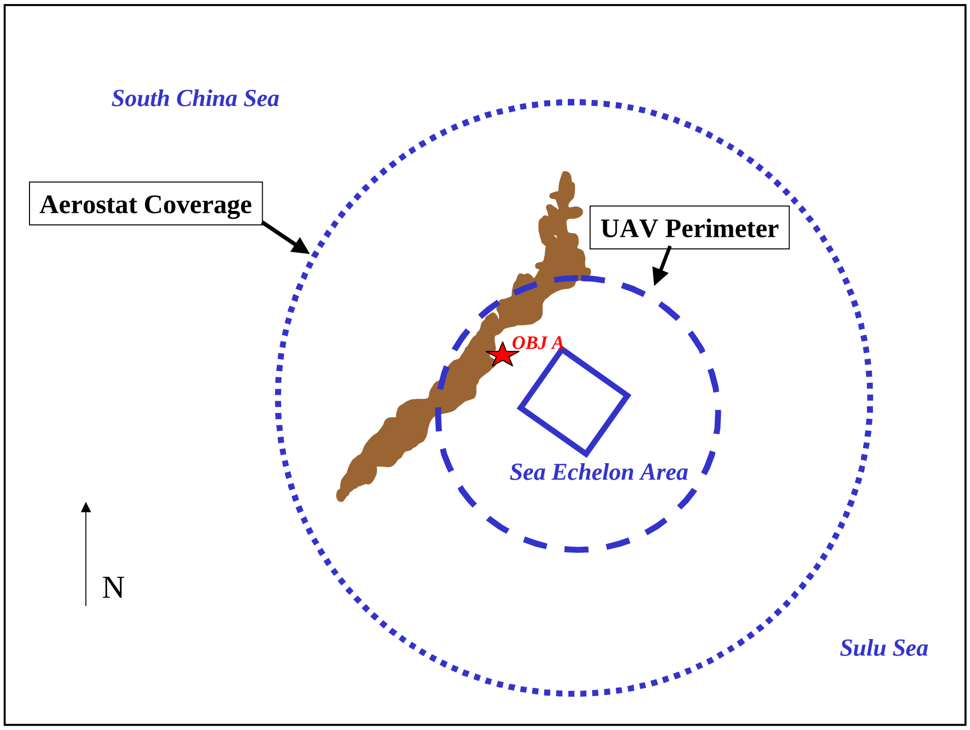


Figure VI-21 Distributed Sensor and Weapon Architecture Modeled in NSS

f. Weapon Types

Both current and conceptual weapon types discussed in the proposed architectures were modeled as systems onboard the platforms in the NSS model. Table VI-2 lists current weapons in the NSS model.

WEAPON DESCRIPTION	RANGE	SPEED	LAUNCH PLATFORM
Surface-to-air missile	80 nm	Mach 2.5	CG, DDG
Surface-to-air missile	30 nm	Mach 3.6	TSSE LCS
Surface-to-air missile	18 nm	Mach 2.5	FFG
Surface-to-air missile	6 nm	Mach 3.6	ExWar
Anti-ship cruise missile	67 nm	462 kts	CG, DDG, FFG
Helicopter launched anti-ship missile	25 nm	Mach 1.2	SH-60
Air-to-air missile	10 nm	Mach 2	JSF
Air-to-ground anti-armor missile	2 nm	640 kts	AH-1Z
Air-to-ground anti-armor missile	3 nm	Mach 1.25	AH-1Z
Air-to-air missile against aircraft (Distributed weapon)	29 nm	Mach 4	UAV
Land attack missile	600 nm	475 kts	CG, DDG, SSN, SSGN
Surface- or air-launched torpedo	4 nm	40 kts	CG, DDG, FFG
Submarine-launched torpedo	25 nm	40+ kts	SSN, SSGN
Anti-submarine rocket. Travels through air then water.	air: 6 nm submerged: 4 nm	air: Mach 1 submerged: 40 kts	CG, DDG
Naval gunfire against surface, air, and shore targets	13 nm	2650 ft / sec rate: 20 rounds/min	CG, DDG
Naval gunfire against surface and air targets	9 nm	3363 ft / sec rate: 220 rounds / min	TSSE LCS
GPS-guided bombs	5 nm	Launch platform dependent	JSF

Table VI-2 Current Weapons

Conceptual weapons replaced or augmented many of the current weapons. The surface-to-air missiles onboard the ships were replaced with longer range weapons. An improved naval gunfire system replaced the gun systems on the CG and DDG. A free-electron laser was added to the CG, DDG, and LCS. A summary of the conceptual weapons is listed in Table VI-3.

WEAPON DESCRIPTION	RANGE	SPEED	LAUNCH PLATFORM
Surface-to-air missile	200 nm	Mach 5	CG, DDG, TSSE LCS
Air-to-air missile against aircraft and missiles (Distributed weapon)	50 nm	Mach 6	UAV
Surface- or air-launched torpedo	6 nm	50 kts	CG, DDG, FFG
Naval gunfire against surface, air, and shore targets	63 nm	2650 ft / sec rate: 10 rounds / min	CG, DDG
Free-Electron Laser	5 nm	light speed	CG, DDG
Free-Electron Laser (-)	2.5 nm	light speed	TSSE LCS

Table VI-3 Conceptual Weapons

g. Phase I Excursion

Due to the close proximity of the amphibious force to the objective in the NSS scenario, the SEA Team decided to conduct an excursion to compare the point and distributed sensor and weapon architectures with a threat originating from a distance greater than 200 nm from the force. The team decided that this geography was representative of Phase I, the staging and build-up of forces. Since the excursion modeled Phase I, all of the transport assets remained onboard the ExWar ships.

The team limited the threats in the excursion to long-range airborne threats to reduce the amount of noise in the model and, in turn, allow greater resolution to the effects of a distributed versus point architecture. The threat included 800 ASCM-3s arriving in large raid sizes and 50 ACFT-2. A robust targeting capability for the enemy force was simulated using 10 UAVs. The UAVs were not capable of being targeted by the blue force, allowing the missiles and aircraft to receive targeting information throughout the excursion. The relative positioning of the ships remained the same as in the alternate force architectures.

Due to time limitations, the team used alternate force architectures five and seven for the excursion. In order to provide more insight into the effectiveness of the Total Ship Systems Engineering (TSSE)-designed LCS, the team decided to use the LCS-based force composition with current weapon for both the point and distributed sensor and weapon architectures.

Additionally, the team investigated the effects of enemy targeting. Using the same numbers of missiles and aircraft in the excursion, the team decreased the number of UAVs providing targeting information to enemy missiles and aircraft from 10 to one. The decreased number of UAVs represented the results of battle space preparation efforts to degrade the enemy's ability to detect amphibious forces.

3. Results

a. Mission-Capable Assets

All eight of the alternate force architectures developed in the design of experiments were run with 30 replications. The results were then compiled and analyzed to determine if there were statistically significant differences between different architectures. Table VI-4 contains the average number of mission-capable assets, standard deviations, and upper and lower 95% confidence intervals (CI) for the various alternate force architectures.

ALTERNATE FORCE ARCHITECTURE	STATISTICS	ASSET (INITIAL NUMBER)					
		ExWar (6)	LCU(R) (12)	HLCAC (18)	AAAV (108)	LRHLAC (36)	MV-22 (84)
1	Average Mission Capable	5.86	11.18	17.14	106.04	33.25	80.96
	Standard Deviation	0.36	1.31	1.27	3.62	2.44	2.44
	Upper 95% CI	5.98	11.65	17.60	107.33	34.12	81.84
	Lower 95% CI	5.73	10.71	16.69	104.74	32.38	80.09
2	Average Mission Capable	5.90	11.45	17.31	106.03	34.00	80.48
	Standard Deviation	0.31	0.83	1.26	3.77	1.93	2.82
	Upper 95% CI	6.01	11.74	17.76	107.38	34.69	81.49
	Lower 95% CI	5.79	11.15	16.86	104.68	33.31	79.47
3	Average Mission Capable	6.00	11.46	16.96	105.14	34.97	81.51
	Standard Deviation	0.00	1.07	1.50	4.10	1.03	2.49
	Upper 95% CI	6.00	11.85	17.50	106.61	35.34	82.40
	Lower 95% CI	6.00	11.08	16.43	103.68	34.60	80.62
4	Average Mission Capable	6.00	11.39	17.68	106.68	34.32	81.75
	Standard Deviation	0.00	0.88	0.77	2.33	1.66	1.58
	Upper 95% CI	6.00	11.71	17.95	107.51	34.91	82.31
	Lower 95% CI	6.00	11.08	17.40	105.85	33.73	81.19
5	Average Mission Capable	6.00	11.54	17.11	106.39	33.54	81.04
	Standard Deviation	0.00	0.84	1.66	2.82	1.91	2.65
	Upper 95% CI	6.00	11.84	17.70	107.40	34.22	81.98
	Lower 95% CI	6.00	11.24	16.51	105.38	32.85	80.09
6	Average Mission Capable	6.00	11.62	17.66	107.21	34.52	81.76
	Standard Deviation	0.00	0.68	0.81	2.50	1.66	2.20
	Upper 95% CI	6.00	11.86	17.95	108.10	35.11	82.55
	Lower 95% CI	6.00	11.38	17.36	106.31	33.92	80.97
7	Average Mission Capable	5.93	11.50	17.64	106.04	33.18	80.82
	Standard Deviation	0.26	0.92	0.73	3.66	1.56	2.80
	Upper 95% CI	6.02	11.83	17.90	107.34	33.74	81.82
	Lower 95% CI	5.83	11.17	17.38	104.73	32.62	79.82
8	Average Mission Capable	5.89	11.68	17.71	105.82	34.54	81.46
	Standard Deviation	0.31	0.77	0.76	4.69	1.93	2.83
	Upper 95% CI	6.01	11.95	17.99	107.50	35.23	82.48
	Lower 95% CI	5.78	11.40	17.44	104.14	33.84	80.45

Table VI-4 Average Number of ExWar Ships and Transport Assets Mission Capable

Figure VI-22 is a graphical representation of data from Table VI-4.

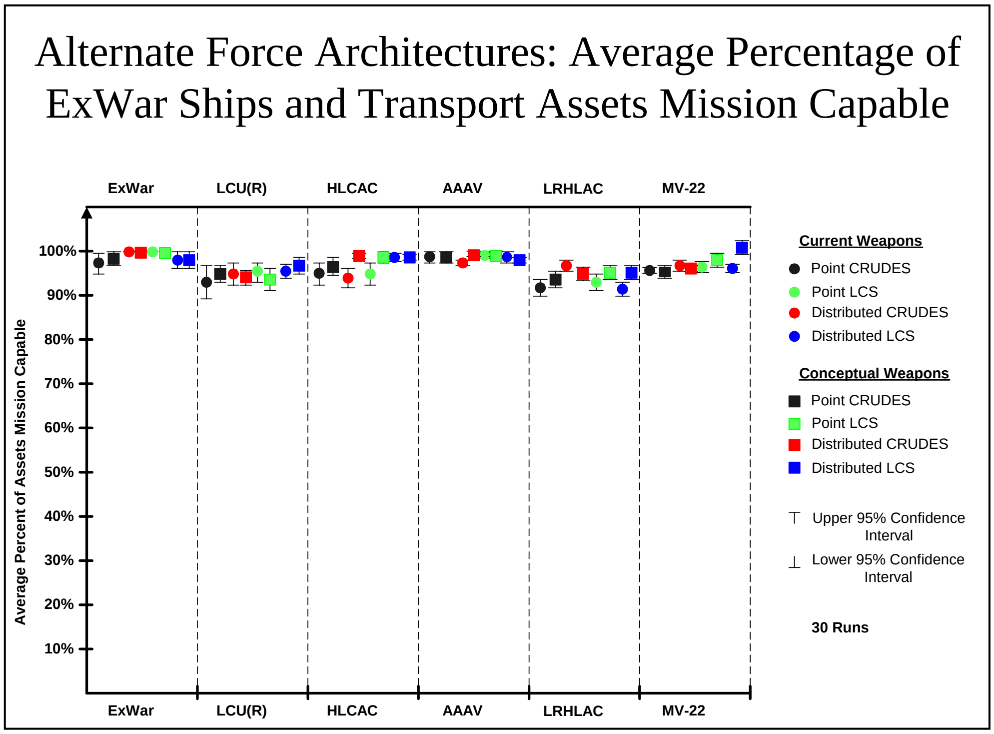


Figure VI-22 Comparison of Alternate Force Architectures with Current Weapons for ExWar Ships and Transport Assets

All architectures defend the Sea Base at 94% or better. In the case of the ExWar ship, we would expect that the distributed architecture would perform better than the point architecture. Although the results are very close, in the case of the LCS-based COA, the point architecture resulted in a 100% survivability for the ExWar ships, while the distributed architecture resulted in a 98.81%. The team hypothesized that the possible differences in the NSS scenario may be due to tactical considerations. The LCS, by nature of their increased numbers and their relative closeness to land act as a distributed sensor, making it difficult to distinguish between the point and distributed architectures. Furthermore, the distributed sensor has a slower scan rate than the point sensor, making the LCS more vulnerable to short notice threats when in the distributed architecture.

In addition to analyzing the survivability of the ExWar ships and transport assets, NSS provided the capability to investigate the survivability of force protection assets. Table VI-5 contains the average number of mission capable force protection assets and statistics for the CRUDES-based force (COA A).

ALTERNATE FORCE ARCHITECTURE	**STATISTICS**	**ASSET (INITIAL NUMBER)**					
		CG (3)	**DDG (3)**	**FFG (3)**	**JSF (36)**	**AH-1Z (24)**	**SSN (1)**
1	Average Mission Capable	2.79	2.39	2.79	19.75	13.68	0.96
	Standard Deviation	0.42	0.63	0.50	3.22	3.55	0.19
	Upper 95% CI	2.94	2.62	2.96	20.90	14.95	1.03
	Lower 95% CI	2.64	2.17	2.61	18.60	12.41	0.90
2	Average Mission Capable	2.79	2.90	2.76	22.41	14.00	0.86
	Standard Deviation	0.41	0.31	0.44	4.91	2.99	0.35
	Upper 95% CI	2.94	3.01	2.91	24.17	15.07	0.99
	Lower 95% CI	2.65	2.79	2.60	20.66	12.93	0.74
3	Average Mission Capable	2.93	2.93	2.82	20.61	13.93	0.93
	Standard Deviation	0.26	0.26	0.48	4.97	3.75	0.26
	Upper 95% CI	3.02	3.02	2.99	22.39	15.27	1.02
	Lower 95% CI	2.83	2.83	2.65	18.83	12.59	0.83
4	Average Mission Capable	2.93	3.00	2.82	21.29	15.64	0.82
	Standard Deviation	0.26	0.00	0.39	4.80	2.98	0.39
	Upper 95% CI	3.02	3.00	2.96	23.00	16.71	0.96
	Lower 95% CI	2.83	3.00	2.68	19.57	14.58	0.68

Table VI-5 Average Number Force Protection Assets Mission Capable in COA A

Figure VI-23 is a graphical representation of COA A ships and contains data from Table VI-5 for force protection ships and data from 0 for the ExWar ships. Figure VI-23 shows the percentage of mission-capable ships with both the point and distributed sensor and weapon architecture, along with both current and conceptual weapon types.

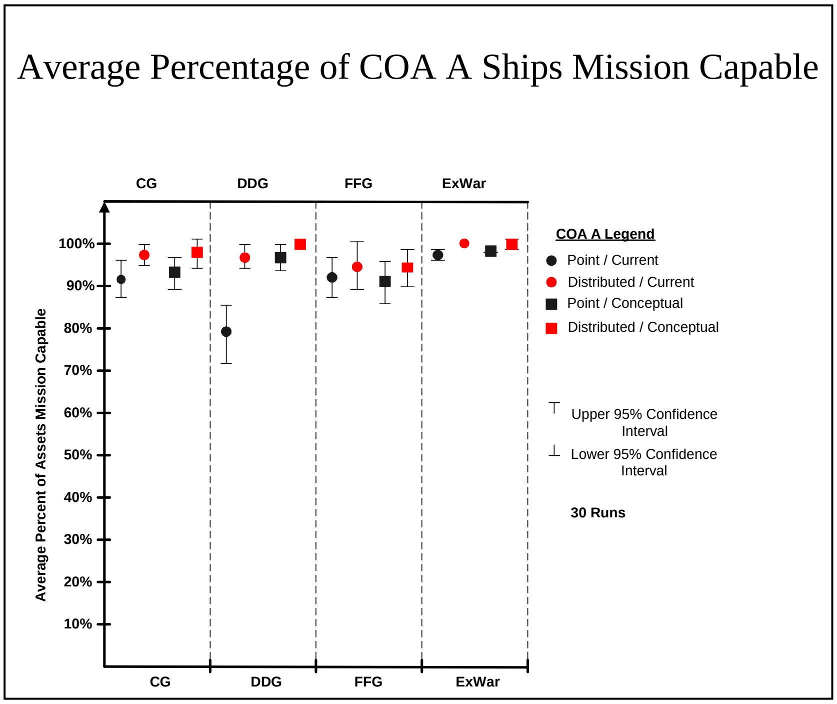


Figure VI-23 Comparison of COA A Ships Mission Capable

Table VI-6 contains the average number of mission-capable force protection assets and statistics for the Littoral Combat Ship (LCS)-based force Course of Action (COA) B.

ALTERNATE FORCE ARCHITECTURE	STATISTICS	ASSET (INITIAL NUMBER)					
		CG (1)	**DDG (1)**	**LCS (12)**	**JSF (36)**	**AH-1Z (24)**	**SSGN (1)**
5	Average Mission Capable	0.96	0.89	9.89	18.11	13.11	0.75
	Standard Deviation	0.19	0.31	1.34	3.70	3.93	0.44
	Upper 95% CI	1.03	1.01	10.37	19.43	14.51	0.91
	Lower 95% CI	0.90	0.78	9.41	16.78	11.70	0.59
6	Average Mission Capable	0.93	1.00	10.07	19.28	15.90	0.93
	Standard Deviation	0.26	0.00	1.49	4.15	2.65	0.26
	Upper 95% CI	1.02	1.00	10.60	20.76	16.84	1.02
	Lower 95% CI	0.84	1.00	9.54	17.79	14.95	0.84
7	Average Mission Capable	1.00	1.00	10.00	17.96	12.39	0.93
	Standard Deviation	0.00	0.00	1.66	3.70	3.78	0.26
	Upper 95% CI	1.00	1.00	10.59	19.29	13.75	1.02
	Lower 95% CI	1.00	1.00	9.41	16.64	11.04	0.83
8	Average Mission Capable	1.00	1.00	10.04	20.68	15.43	0.86
	Standard Deviation	0.00	0.00	1.40	4.50	2.81	0.36
	Upper 95% CI	1.00	1.00	10.54	22.29	16.43	0.98
	Lower 95% CI	1.00	1.00	9.53	19.07	14.42	0.73

Table VI-6 Average Number Force Protection Assets Mission Capable in COA B

Figure VI-24 is a graphical representation of COA B ships and contains data from Table VI-6 for force protection ships and data from Table VI-4 for the ExWar ships. Figure VI-24 shows the percentage of mission-capable ships with both the point and distributed sensor and weapon architecture, along with both current and conceptual weapon types.

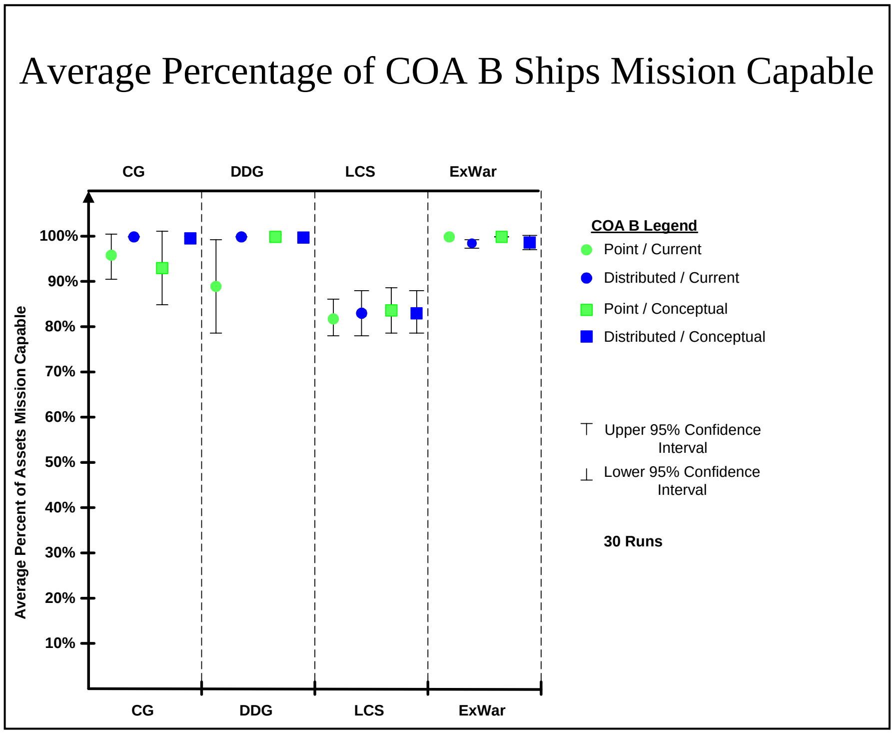


Figure VI-24 Comparison of COA B Ships Mission Capable

b. Threat Drawdown

The team explored other metrics to differentiate between point and distributed architectures. One metric used was the rate by which the threats decreased. The team hypothesized that the more rapidly the number of threats reached zero, the better the architecture. Table VI-7 shows the expected number of mission-capable SB-1s over a 24-hour period for the eight alternate force architectures. Figure VI-25 shows a graphical representation of the drawdown for the SB-1 threat in the NSS scenario. Similar graphs and tables for additional threats can be found in Appendix B.

EXPECTED NUMBER OF MISSION-CAPABLE SB-1s

	ALTERNATE FORCE ARCHITECTURES							
TIME (hrs)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
0	30.0000	30.0000	30.0000	30.0000	30.0000	30.0000	30.0000	30.0000
1	15.9286	13.6897	10.8214	2.0357	24.7143	14.1034	18.3571	4.7500
2	11.2857	10.2759	9.4643	1.6429	20.5000	9.8621	14.3571	3.2500
3	9.6786	7.6207	8.2500	0.5357	16.5714	7.0000	11.3214	1.6429
4	8.4643	7.1035	6.8929	0.4643	14.0714	5.8966	6.3571	0.7857
5	8.2857	5.7586	6.5357	0.4643	11.9643	4.8621	4.4643	0.4643
6	8.1071	5.3103	5.9286	0.4643	10.0000	3.6207	2.6071	0.1071
7	7.7500	4.2759	5.4643	0.4643	7.9286	2.8276	1.6429	0.0714
8	7.6429	3.9310	5.0357	0.4643	6.8571	2.5172	1.3214	0.0714
9	7.3214	3.7931	4.3214	0.0714	5.6429	1.9310	0.9643	0.0357
10	7.2143	3.7931	4.0357	0.0714	5.0000	1.7586	0.7500	0.0357
11	7.0000	3.7931	3.5714	0.0714	4.4286	1.5172	0.5714	0.0357
12	6.5714	3.6897	3.0357	0.0714	3.7857	1.3448	0.5357	0.0357
13	6.4643	3.4483	2.8929	0.0714	3.5000	1.1379	0.5000	0.0357
14	6.1071	3.3103	2.5714	0.0714	3.3929	1.1379	0.4643	0.0357
15	6.0000	2.7586	2.2500	0.0357	3.0357	1.0690	0.3571	0.0357
16	5.8571	2.4138	1.9643	0.0357	2.8571	0.9655	0.3571	0.0000
17	5.6786	2.4138	1.5714	0.0357	2.6429	0.8966	0.2857	0.0000
18	5.5714	2.0690	1.4643	0.0357	2.2143	0.7586	0.2857	0.0000
19	5.4286	2.0690	1.1786	0.0357	2.1429	0.7241	0.2857	0.0000
20	5.3571	2.0690	0.8929	0.0357	2.0357	0.7241	0.2857	0.0000
21	5.3214	2.0690	0.8214	0.0357	1.8929	0.6207	0.2857	0.0000
22	5.2500	2.0690	0.6429	0.0357	1.7857	0.6207	0.2500	0.0000
23	5.2143	2.0690	0.5000	0.0357	1.7857	0.5862	0.2500	0.0000
24	5.1429	2.0690	0.4286	0.0357	1.6429	0.5862	0.2143	0.0000

Table VI-7 Expected Number of Mission-Capable SB-1s

The highlighted values in Table Vi-7 indicate there are zero mission-capable SB-1s for that particular run. Therefore, Table VI-7 shows that alternate force architecture 8 was the only architecture to totally eliminate SB-1.

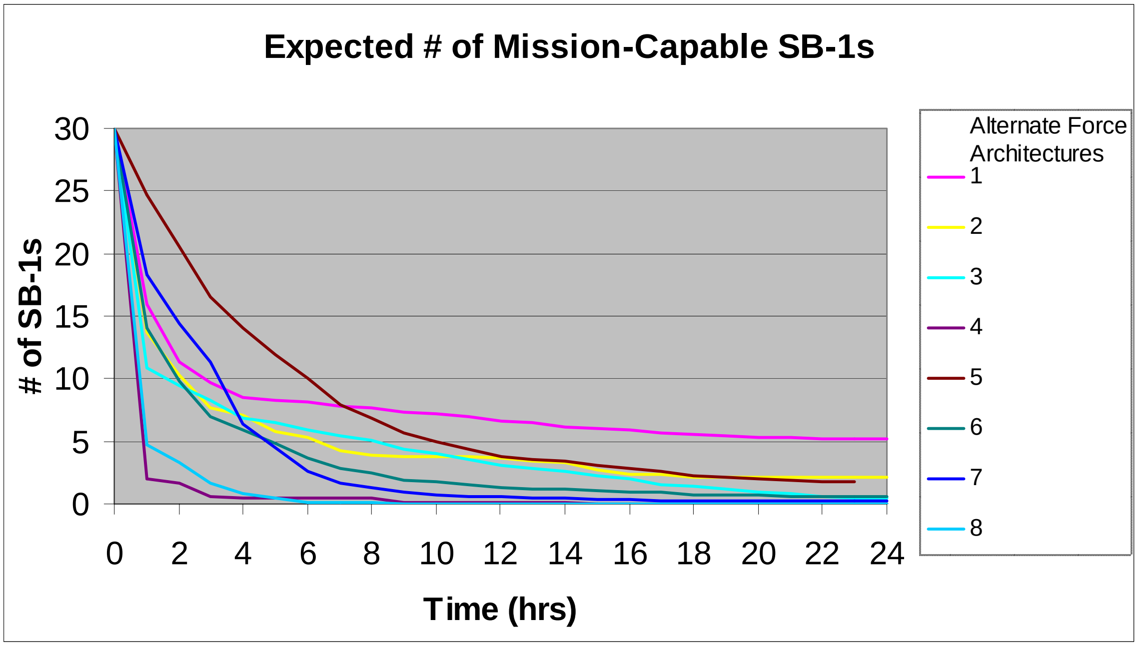


Figure VI-25 Expected Number of Mission-Capable SB-1s

As seen in Figure VI-25, the SB-1 threat is decreased the quickest in alternate force architectures 4 and 8.

b. Interceptor Launches

The metric of analyzing the expected number of threats over time produced no conclusive evidence differentiating point and distributed architectures. The team considered the number of surface-to-air interceptor launches as an additional metric to distinguish between the point and distributed architectures. The team believed that since the force was highly survivable among all alternate force architectures, the number of interceptor launches would reveal the effectiveness of the force protection assets in mitigating the threats. Figure VI-26 shows the total number of interceptor launches for the amphibious force. The total number of interceptor launches includes: surface-to-air missiles launched from ships; air-to-air missiles launched from UAVs in the distributed architecture; and free-electron laser (FEL) shots.

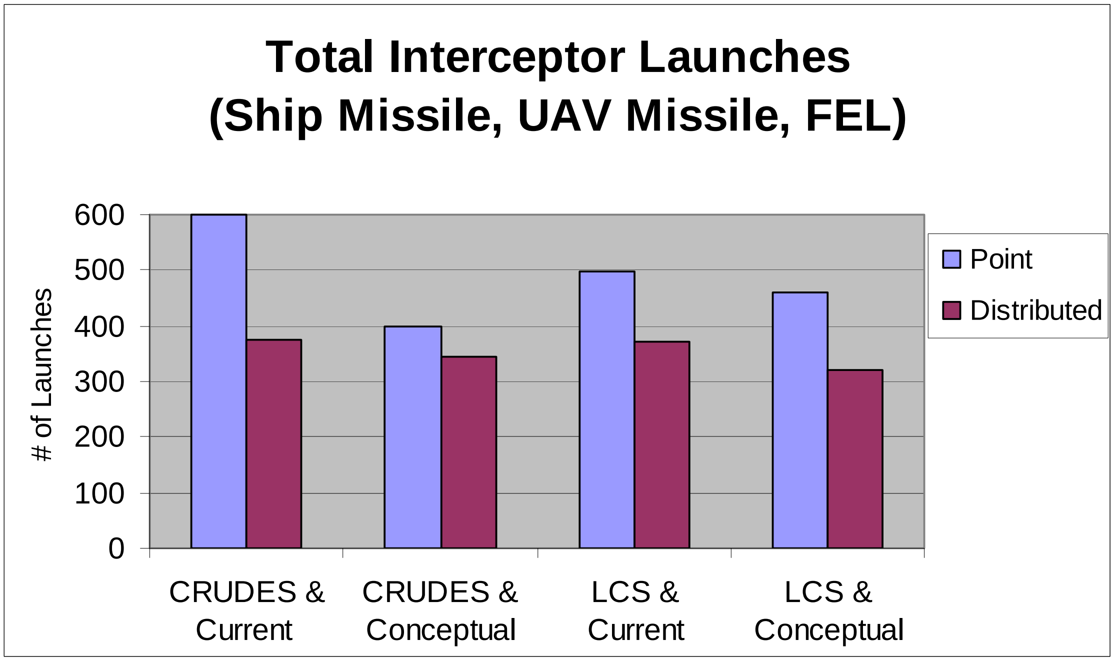


Figure VI-26 Total Number of Amphibious Force Interceptor Launches

As seen in Figure VI-26, the distributed architecture utilized considerably less interceptors than the point architecture. Further investigation into the number of interceptor launches for all of the ExWar ships reveals the same trends.

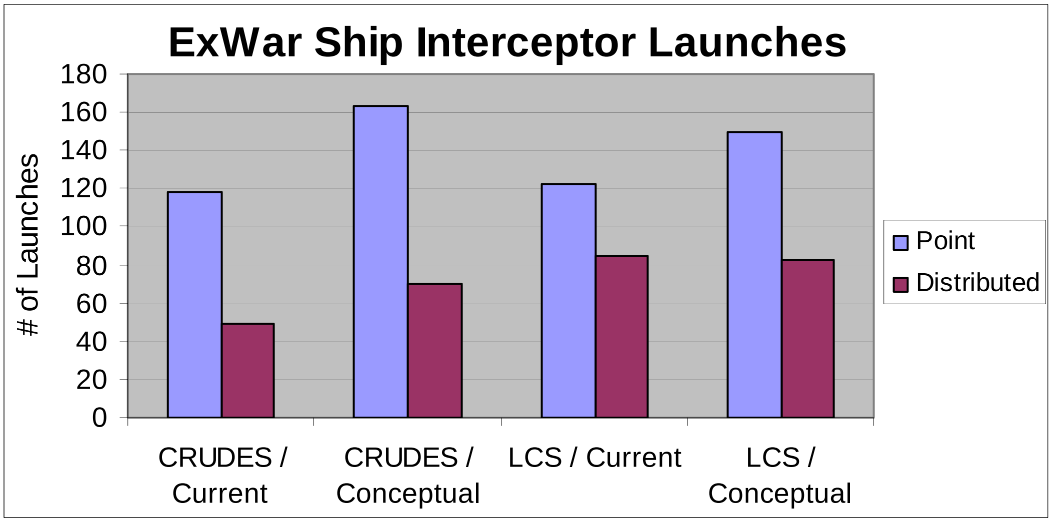


Figure VI-27 Number of Interceptors Launched by ExWar Ships

Figure VI-27 reveals that the ExWar ship launches considerably less interceptors in the distributed architecture.

c. Phase I Excursion Results

Table VI-8 contains the average number of mission capable ships, standard deviations, and upper and lower 95% confidence intervals for the missile raid excursion of alternate force architectures 5 and 7.

ALTERNATE FORCE ARCHITECTURE	**STATISTICS**	**ASSET INITIAL NUMBER**			
		CG (1)	**DDG (1)**	**LCS (12)**	**ExWar (6)**
5	Average Mission Capable	0.00	0.03	0.00	0.90
	Standard deviation	0.00	0.18	0.00	1.47
	Upper 95% CI	0.00	0.10	0.00	1.43
	Lower 95% CI	0.00	-0.03	0.00	0.37
7	Average Mission Capable	0.03	0.00	4.20	2.87
	Standard Deviation	0.18	0.00	2.19	1.33
	Upper 95% CI	0.10	0.00	4.98	3.34
	Lower 95% CI	-0.03	0.00	3.42	2.39

Table VI-8 Mission-Capable Ships in Phase I Missile Raid Excursion

Figure VI-28 is a graphical representation of data from Table VI-8.

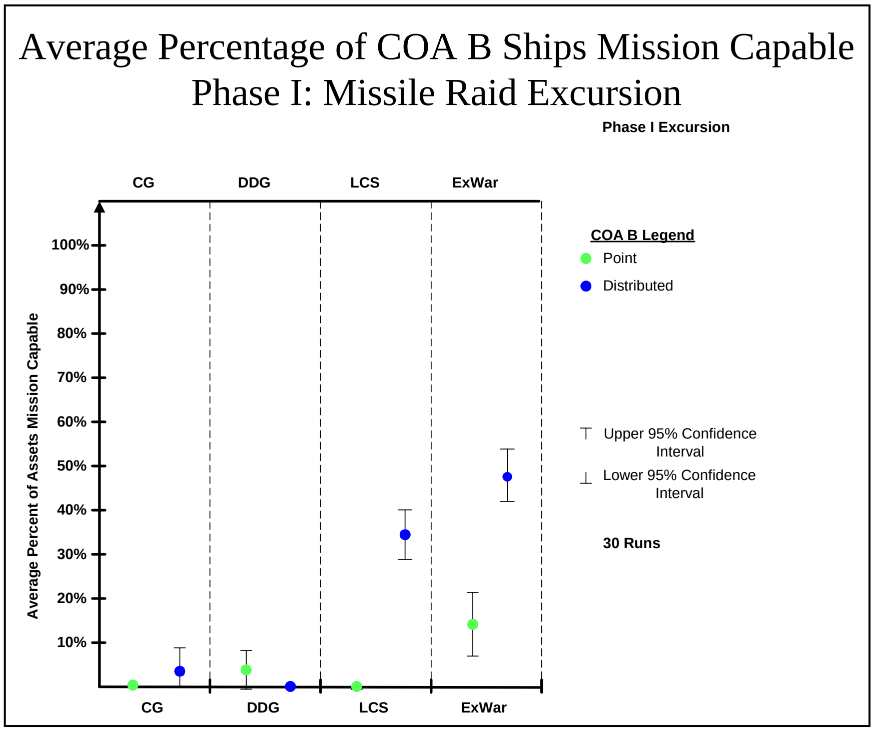


Figure VI-28 Average Percentage of COA B Ships Mission Capable in the Phase I Excursion

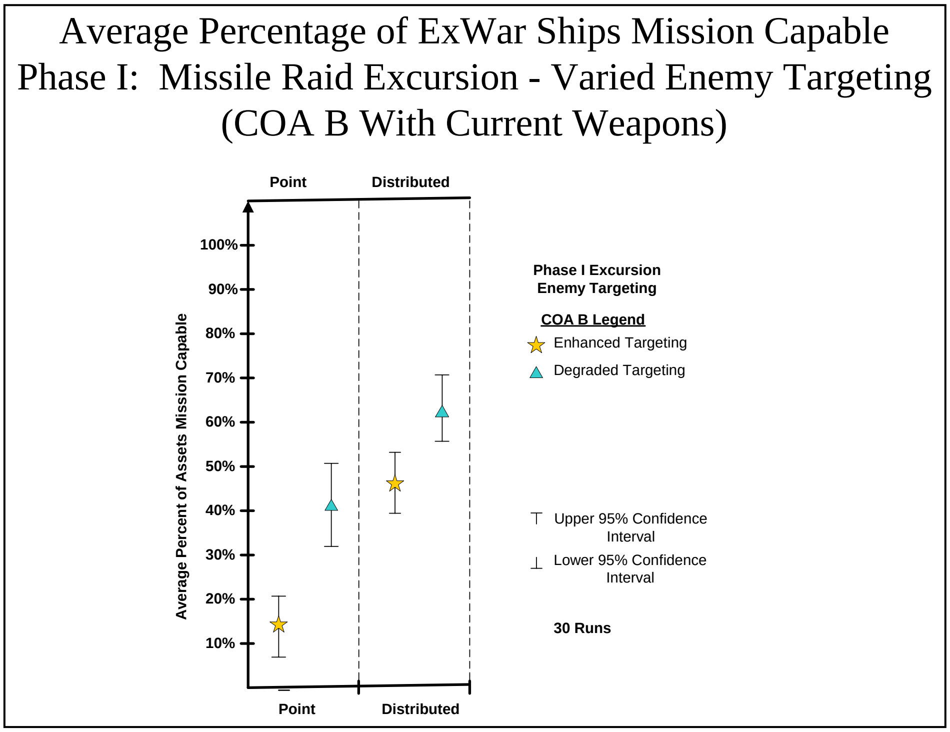
Figure VI-28 shows that the distributed architecture outperformed the point architecture when the threats originate outside the distributed architecture coverage. For the LCS and ExWar ships, there is a significant statistical difference between the point and distributed architectures. For the CG and DDG, there is no statistical difference because there were only one of each in the scenario and both of them become non-mission capable.

Table VI-9 contains the average number of mission-capable ships, standard deviations, and upper and lower 95% confidence intervals for the excursion of alternate force architectures 5 and 7 with a degraded red targeting capability. As mentioned earlier, the threat level remained the same as in the missile raid excursion. The only difference was the enemy's degraded targeting capability represented by a decrease in enemy UAVs from 10 to one.

ALTERNATE FORCE ARCHITECTURE	STATISTICS	ASSET INITIAL NUMBER			
		CG (1)	DDG (1)	LCS (12)	ExWar (6)
5	Average Mission Capable	0.00	0.07	0.31	2.55
	Standard Deviation	0.00	0.26	1.04	1.57
	Upper 95% CI	0.00	0.16	0.68	3.11
	Lower 95% CI	0.00	-0.02	-0.06	1.99
7	Average Mission Capable	0.07	0.37	5.00	3.87
	Standard Deviation	0.25	0.49	2.51	1.46
	Upper 95% CI	0.16	0.54	5.90	4.39
	Lower 95% CI	-0.02	0.19	4.10	3.35

Table VI-9 Mission-Capable Ships in COA B With Degraded Enemy Targeting

Figure VI-29 shows a comparison of ExWar ship survivability for both point and distributed architectures with both an enhanced and degraded enemy targeting capability.



Average Percentage of ExWar Ships Mission Capable
Phase I: Missile Raid Excursion - Varied Enemy Targeting
(COA B With Current Weapons)

Figure VI-29 Comparison of ExWar Ship Survivability With Varied Enemy Targeting Capability (COA B, Current Weapons, Point and Distributed Architectures)

4. Conclusions

a. Mission-Capable Assets

There was no statistical difference among alternate force architectures for the survivability of the transport assets in the NSS scenario. In other words, there was no statistical difference in survivability between force compositions, point or distributed sensor and weapon architectures, and current of conceptual weapons. However, there were confounding results in the case of the ExWar ships. In the case of the ExWar ship we would expect that the distributed architecture would perform better than the point architecture. Although the results are very close, in the case of the LCS-based COA, the point architecture resulted in 100% survivability for the ExWar ships, while the distributed architecture resulted in a 98.81%. Although this result may not be statistically significant, the team felt that the fact that one architecture had zero ExWar ship losses compared to another architecture with 0.07 ExWar ship losses was militarily significant. The team hypothesized that the possible differences in the NSS scenario may be due to tactical considerations. The LCS, by nature of their increased numbers and their relative closeness to land, act as a distributed sensor, making it difficult to distinguish between the point and distributed architectures. Furthermore, the distributed sensor has a slower scan rate than the point sensor making the LCS more vulnerable to short notice threats when in the distributed architecture.

Although there were trends reflecting an improvement in the distributed architecture with the survivability of the defending assets (CG, DDG, FFG, LCS), there was still no statistical difference. However, in the case of the DDGs in COA A, there was a statistical difference between point and distributed architectures. In the NSS scenario, two DDGs were placed between the threat and the defended ExWar ships. Therefore, the results show that in the case of defending assets placed along the threat axis, the distributed architecture provides improved survivability.

b. Threat Drawdown

All of the data regarding threat drawdown can be found in Appendix B. Trends in the data show that for the most part, the distributed architecture seems to facilitate a quicker drawdown of threats. Additionally, investigation into the force composition reveal that the

CRUDES-based force structure seems to better handle subsurface threats, while the LCS-based force structure seems to better handle small boat threats. This was possibly explained by the fact that the CRUDES ships in the scenario have more capable hull-mounted sonar than the LCS ships. The LCS-based force has an increased number of ships and therefore has an increased number of SH-60s. The same number of SH-60s played a role in USW for both force compositions. However, in the LCS-based force, the additional SH-60s were utilized in surface warfare (SUW); greatly assisting in tackling the small boat problem.

c. Interceptor Launches

The distributed architecture is more effective in its use of weapons. Figure VI-26 and Figure VI-27 show a decreased number of interceptors launched in the distributed architecture than in the point architecture. These results were related to the high survivability results from Figure VI-22, Figure VI-23, and Figure VI-24. The distributed architecture provided better targeting information and is more effective in assigning threat-weapon pairs. Furthermore, the distributed architecture was able to detect and defeat threat platforms before they were able to launch their weapons.

d. Phase I Missile Raid Excursion

Figure VI-28 shows the advantages of the distributed architecture when the threat level and distance from the force to the threat origin were increased. Furthermore, Figure VI-29 reveals that there was a statistical difference in ExWar ship survivability between an enhanced and degraded enemy targeting capability for both point and distributed architectures. In other words, the improved survivability from a degraded enemy targeting capability revealed the importance of gaining battle space superiority by sanitizing the ExWar force operating area from enemy assets capable of providing targeting information.

e. SEA-4 Evaluation of NSS

NSS had numerous advantages. The system’s flexible database allowed the team to input the characteristics of sensor and weapon systems, platforms, and generic threats used in each of the alternate force architectures. NSS’ ability to conduct analysis of numerous replications and to export metrics to Excel assisted the team in conducting statistical analysis of data. While NSS provided a means to analyze numerous replications, conducting 30 replications required approximately 15 hours. Therefore, the team was constrained in the number of replications due to processing time for each scenario. NSS also provided a means for the study to investigate tactical effects, such as ship positioning in relation to the threat axis, and at the same time, provided a look at interactions of individual assets in the scenario. However, this high-resolution capability of NSS also proved, at times, to be a disadvantage. The team found that with the numerous moving parts inherent to the scenario it was often difficult to distinguish cause and effect relationships. In some cases, NSS provided confounding results that were difficult to explain. The team assessed that utilizing NSS was not feasible without the help of an expert. NSS is a complicated system that may require a quarter's worth of instruction to learn how to create a basic scenario with few interactions. However, the fact that the team was required to work with a modeler provided a valuable learning experience with regard to Systems Engineering management. The team had to clearly express their needs and requirements, manage deadlines, and verify and validate each of the alternate force architectures. The team felt that NSS provided useful insights into the force protection problem and was therefore a viable simulation tool for this study.

VII. CONCLUSIONS

A. KEY FINDINGS

The Navy-Marine Corps Team has been executing expeditionary operations since its inception. Few of these operations have been unopposed. Future adversaries will continue to probe perceived weaknesses, and will develop plans to deny access to their regions. Conventional and asymmetric strategies will be employed to conduct attacks on the Sea Base, landing craft, and aircraft components of the expeditionary warfare force. Although sea basing reduces overall force protection requirements, it focuses those requirements on protecting the ships of the Sea Base and its airborne and seaborne transport assets.

This study analyzed the threats to the Sea Base and determined the key functions associated with the protection of the Sea Base. From functional analysis and requirements generation, survivability was determined to be the primary measure of effectiveness of force protection. Survivability was further divided into the measures of susceptibility and vulnerability. Susceptibility is the ability of the system to prevent and defeat enemy attacks or actions, while vulnerability is the ability of the system to withstand the enemy attacks or actions. This functional hierarchy was applied to the three primary mission areas of Air Warfare, Surface Warfare, and Undersea Warfare and their respective threats from the Threat Analysis.

Detecting threats is the critical first step in defending the Sea Base and its transport assets. If the force cannot "see" the enemy, it cannot defend against it. This study attempted to bound the force protection problem by taking a realistic look at threat-sensor pairings. The Systems Engineering and Analysis (SEA-4) Team modeled radar, infrared (IR), lidar, active sonar, and passive sonar against the threats. Though the Sensor Analysis itself is not all encompassing, with regard to the number of sensors available, or the tactics and techniques in which the ones mentioned above might be employed, several basic initial insights from the mathematical models developed can be drawn. First, in most cases, a sensor can detect threats at greater ranges if it is relatively positioned so the threat presents a 90^{o} (broadside) target angle. Second, the visual horizon, the environment, or both, may limit many of the sensors' performance levels. Third, several of the sensors detected the threats at greater ranges when compared to the others because of the various target properties. The key to achieving greater detection ranges is through the employment of different types of sensors that are able to take advantage of the inherent trade-offs with respect to the targets' characteristics.

In the Search Analysis, the SEA-4 Team explored the use of the various sensor types with respect to threat detection by varying the numbers, tactics, and techniques with which the sensors could be employed. The distribution of sensors was determined to offer greater detection ranges by extending the sensors' horizons and by achieving greater target aspects. The benefits of a distributed sensor network throughout the battle space are readily apparent from the results because the potential for attaining favorable target angles on future representative threats increases. By detecting the threats at greater ranges, the distributed sensor network provided the force with more time to react to the postulated threats.

An interesting sensor system relationship (see Figure VII-1) emerged from the Search Analysis. Each search system for a given sensor type is a trade-off of the number of search platforms, the search time, and the probability of detection in a defined volume. The goals of the system are to minimize the search time, minimize the number of search platforms required, and maximize the probability of detection. Any two of these goals may be satisfied to the detriment of the third. The relationship between these variables follows the probability of detection formulas identified for each sensor.

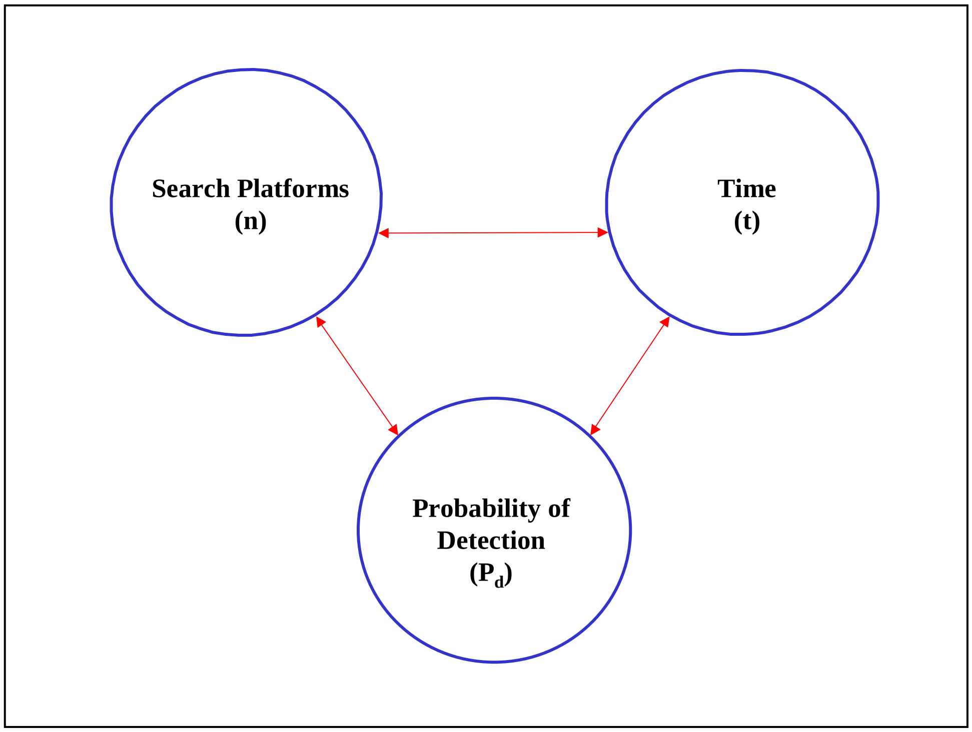


Figure VII-1 Sensor System Relationship

Another interesting insight obtained from the Search Analysis is that the point and distributed sensor configurations appear to complement each other very well. By employing a mix of point and distributed sensor systems, an effective tripwire against every threat to the Sea Base could be achieved. Furthermore, a distributed sensor network offers the benefits of greater detection ranges and more reaction time by extending the sensors' horizons and by achieving greater target cross sections against a variety of the threats. For example, the point sensor, assumed to be a ship, provides an early warning capability for the airborne assets in its vicinity against inbound surface-to-air missiles (SAMs). Likewise, the distributed sensors, assumed to be on unmanned aerial vehicles (UAVs) or unmanned underwater vehicles/unmanned surface vehicles (UUVs/USVs), provide early warning for the point assets against many of the other threats. Cued acquisition from various sensor platforms might be able to provide uninterrupted track data throughout the battle space. Even without the use of cued acquisition, a distributed sensor network could reduce the uncertainty of threat positions and narrow the scope of subsequent reacquisition searches, thus providing a more robust force protection capability to the expeditionary force. Point-only sensor systems (radar, infrared (IR), or sonar), or overhead-only sensor systems (radar or IR), display weaknesses in their inability to achieve a 0.95 probability of detection for several threat platforms prior to maximum weapons release ranges. This capability gap drives the need for a sensor system that is able to detect threat platforms at longer ranges and with ample time to counter them before they can reach their weapons' maximum effective ranges. The use of the IR and radar systems further allows the expeditionary warfare force to exploit attempted enemy trade-offs in reflectivity and emissivity. For these reasons, a mixed distributed and point sensor network system composed of IR, radar, and active sonar systems are recommended for implementation in future force structures.

A necessary next step in defeating the threat platforms is to develop weapons systems capable of destroying the targets prior to their weapons release points. From the Engagement Analysis, it is readily apparent that the ability to detect a threat at a longer range leads to a greater probability of kill for a given weapon system. The models show that a weapon's range is largely irrelevant if the sensor's range is limited in comparison. The weapon's speed, however, is a desirable attribute, particularly if longer reaction times are required; but the weapon's speed is clearly secondary to the sensor's search speed and range. This rationale is predicated on the assumption that a threat must be detected in order to be defeated. Therefore, the ability to expand the sensor coverage and improve the sensor's search speed, will allow the force to capitalize on a defensive weapon's potential speed and range advantages, which, in turn, will create more engagement opportunities, thereby increasing the probability of kill against the postulated threats.

From the EXTEND model, the team determined that distributed sensors are the factor that most affects survivability of the Sea Base. Also, the LCS-based protection force provides a level of force protection to the Sea Base statistically equivalent to that of the cruiser- and destroyer-based protection force. Furthermore, the longer range and speed of the conceptual weapons over that of the current weapons, provides no improvement to the survivability of the Sea Base. In order to gain benefits from the increase in range and speed, the sensor detection range must be improved. This is exactly what the distributed sensors do for the system.

With regard to threats to the Sea Base, the submarines and torpedoes are by far the most significant threat. In the EXTEND model, torpedoes make up roughly 10% of the total threat (anti-ship cruise missiles (ASCMs) and torpedoes (TORPs)) to the Sea Base ships, yet they account for over 95% of the mission kills. Future requirements for force protection of the Sea Base should place high emphasis on Undersea Warfare. The need for a point defense system and highly effective torpedo countermeasures is a must.

The Systems Engineering and Analysis curriculum has used EXTEND with great success in recent integration projects, as well as Joint Campaign Analysis courses. EXTEND is an extremely easy modeling and simulation tool to learn. It lends itself to the modeling of very complex processes. In most cases, it is very easy to trouble shoot, and visually represents the process being modeled. Although it may not be the right tool for every Systems Engineering problem, the team highly recommends EXTEND whenever it is applicable.

From the Naval Simulation System (NSS) model, the cruiser and destroyer (CRUDES)-based force and LCS-based force were found to be roughly equivalent in their ability to protect the force. Investigation into the force composition reveal that the CRUDES-based force structure seems to better handle subsurface threats, while the LCS-based force structure seems to better handle small boat threats.

In terms of sensor and weapon architecture, NSS results showed that the distributed architecture improves survivability. However, the benefits of the distributed architecture are more evident during Phase I (arrival and assembly), when the force is a greater distance from the threat. In Phase II (assault), it was difficult to distinguish between the point and distributed architectures. When the force is within close proximity to the threat, assets along the threat axis have a higher survivability in the distributed architecture.

The distributed architecture more effectively employs weapons and had a significantly less number of interceptor launches than the point architecture. The distributed architecture provides better targeting information and is more effective in assigning threat-weapon pairs. Additionally, the distributed architecture is able to detect and defeat threat platforms before they are able to launch their weapons.

Another key finding with NSS was that conceptual weapons required the distributed sensor architecture in order to maximize their effectiveness. Without the distributed sensor architecture, the conceptual weapons are roughly equivalent to current weapons in protecting the force. This finding revealed that the limiting factor in employing weapons is the sensor range.

NSS had numerous advantages. The system's flexible database allowed the team to input the characteristics of sensor and weapon systems, platforms, and generic threats used in each of the alternate force architectures. NSS' ability to conduct analysis of numerous replications and to export metrics to Excel assisted the team in conducting statistical analysis of data. While NSS provided a means to analyze numerous replications, conducting replications required a long period of time. Therefore, the team was constrained in the number of replications allowed due to processing time for each scenario. NSS also provided a means to investigate tactical effects, such as ship positioning in relation to the threat axis, and provided a look at interactions among individual assets in the scenario. The high-resolution capability of NSS proved to be a disadvantage in a large scenario. The team found that with the numerous moving parts inherent to the scenario it was often difficult to distinguish cause and affect relationships. In some cases, NSS provided confounding results that were difficult to explain. The team assessed that utilizing NSS was not feasible without the help of an expert. However, the fact that the team was required to work with a modeler provided a valuable learning experience with regard to systems engineering management. The team had to clearly express their needs and requirements, manage deadlines, and verify and validate each of the alternate force architectures. The team felt that NSS provided useful insights into the force protection problem and was therefore a viable simulation tool for this study.

B. RECOMMENDED ARCHITECTURES

From the models analyzed, the key factor in attaining higher survivability for the Sea Base and its transport assets was the ability of the sensor system to provide more reaction time, and therefore more engagement opportunities, to the weapons systems. For Phase I operations, it was assumed that the Sea Base would operate at extended distances from the shore. For this reason, the ability to achieve greater reaction times was accomplished through the use of the distributed sensor system and its ability to detect the threats further away. In Phases II and III, the force was placed in close proximity to the threats, and as a result, greater reaction times were provided by the point sensors' more rapid scan rates. By placing the point sensors in close proximity to the threats, the radius of the area of concern was greatly reduced when compared to Phase I. This resulted in the point sensor and point weapon architectures closely approximating that of the distributed sensor and distributed weapon architectures.

Further analysis into the two force compositions (LCS and CRUDES) revealed no significant difference with respect to survivability. Furthermore, the weapons' speed and range advantages were determined to be largely dependent on sensor performance. Therefore, no significant difference was determined to exist with respect to survivability between the current and conceptual weapons types.

As a result of these analyses, the proposed architecture can be either LCS- or CRUDES-based and possess either current or conceptual weapons. For Phase I operations, however, the proposed architecture must employ the distributed sensor system. For 360° coverage, this sensor system will require an aerostat operating at an altitude of 50 km overhead of the force center and 62 UAVs operating at an altitude of 10 km and distributed at a range of 352 km from the force center. The aerostat must possess a 20 GHz radar. The UAVs must possess 20 GHz radars and IR sensors operating in the 3-5 μm spectrum. Additionally, the distributed radar systems must use cone search geometries, while the IR systems must use hemisphere search geometries. For undersea threats, this system will require 23 USVs or UUVs, deployed at a range of 50 km from the force center, with 1 kHz active sonars. This system must use a cylinder search geometry. More specific system parameters may be obtained in the Sensor or Search Analysis sections of the Design chapter. Figure VII-2 graphically represents the distributed sensor system.

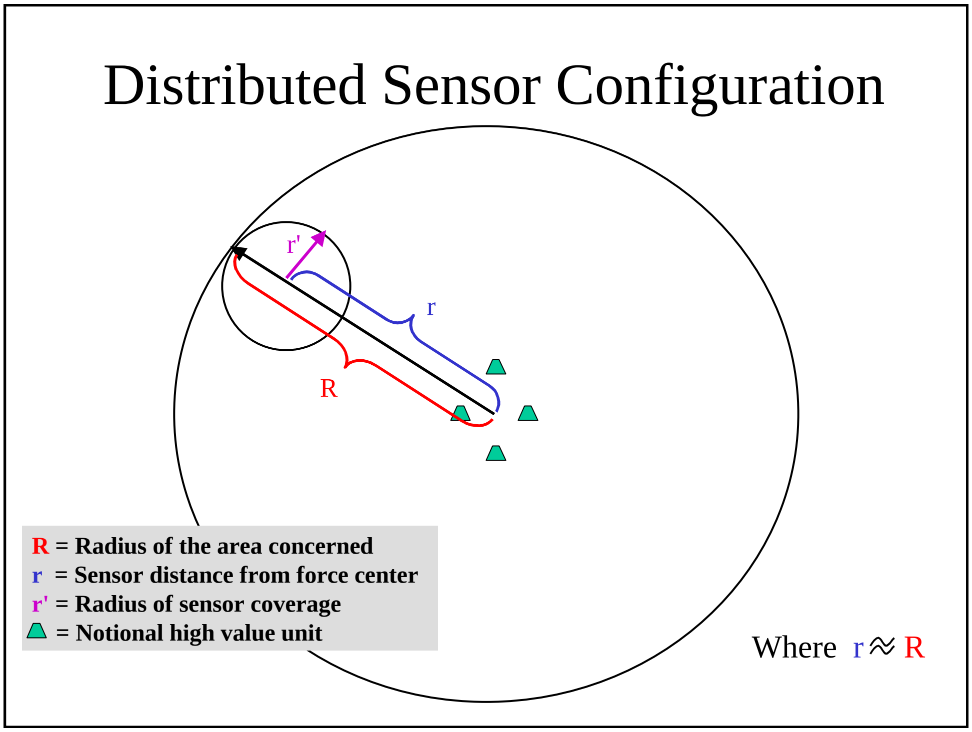


Figure VII-2 Distributed Sensor System

For Phase II and Phase III, the proposed architecture must possess the point sensor system. The point sensor system is composed of at least six platforms operating relatively close to the force center and equipped with a 3 GHz radar system using a cylinder search geometry and an IR system operating in the 3-5 μm spectrum using a hemisphere search geometry. More specific system parameters may be obtained in the Sensor or Search Analysis sections of Chapter V. Figure VII-3 graphically represents the point sensor system.

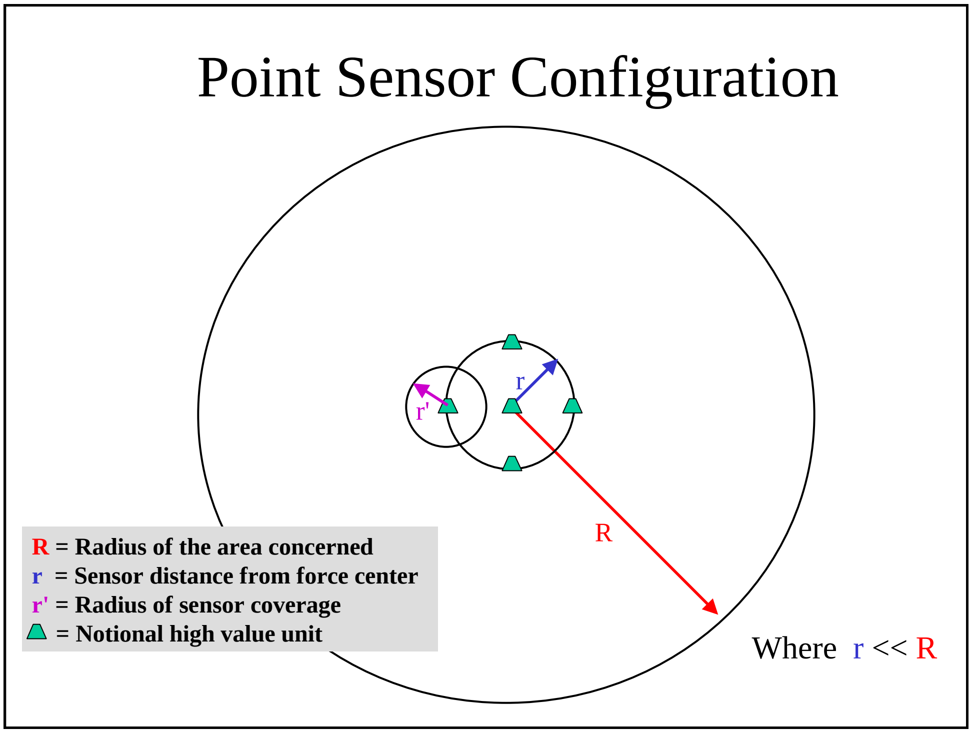


Figure VII-3 Point Sensor System

The choice of sensor architectures is driven by the phase in which the force is operating. In all cases, however, the distributed sensor architecture allows the weapons systems to take fewer shots, thereby conserving the force's fighting potential. In the final analysis, both sensor architectures are necessary for the accomplishment of expeditionary force protection. The decision of which force composition or defensive weapons to use, however, shows no significant difference when compared using survivability. Ultimately, the decision to use an LCS-based or CRUDES-based force and the decision to use the given current or conceptual weapons must be based on a measure of effectiveness other than survivability.

C. RECOMMENDATION FOR FURTHER RESEARCH

1. Introduction

The SEA-4 Team was tasked to develop a system of systems conceptual solution to provide force protection for the Sea Base and its transport assets. The team was forced to scope the project based on the available resources. As this was a broad analysis, the results are broad-based as well. In order to do a complete analysis of Sea Base force protection, many more areas would have to be covered in much more depth. The purpose of this section is to identify areas where further research will increase the understanding of force protection issues and provide a meaningful contribution to future Sea Base force protection efforts.

2. Systems Engineering and Analysis

The SEA Team was responsible for defining the problem to be solved, generating requirements, and integrating the efforts of supporting teams into a cohesive product. For future SEA Teams, further research is recommended in the following areas:

- **Distributed Sensors –** This study showed that distributed sensors were more effective than point sensors in most scenarios. Further study should include a more thorough analysis of distributed sensor requirements for the Sea Base, to include actual sensor capabilities, emerging technologies, reliability and maintainability factors, acquisition strategies, realistic timelines for deployment, and associated trade-off analyses.
- **Distributed Weapons –** This study showed that distributed weapons are an ideal complement to distributed sensors. Further study should include a more thorough analysis of distributed weapon requirements for the Sea Base, to include actual weapon capabilities, emerging technologies, reliability, maintainability, and availability factors, acquisition strategies, realistic timelines for deployment, and associated trade-off analyses.
- **Mine Warfare –** This study and the previous study showed the need for the Sea Base to have a robust mine warfare capability. Further study should include requirements and prospective designs for specific search sensors, search methods, and search platforms, in addition to countermeasures, neutralization equipment and techniques, and weapons needed for breaching. This should also include analysis of current and planned systems and acquisition strategies and the development of acquisition strategies for conceptual systems.
- **Enhanced Network Sea Basing –** The Information Assurance supporting study provided an outstanding analysis of threats to this kind of network. Further study should provide a detailed definition of Enhanced Network, analyze its strengths and weaknesses in regards to force protection, and determine the requirements needed to make it an integral part of the Sea Base force protection system.
- **Multiple Objectives –** The models used for this study were limited to a single objective. Further study should consider the effects of multiple objectives with varied spacing. The existence of widely spaced objectives will complicate the force protection problem and additional systems requirements may surface. Further study should consider aircraft survivability studies, distributed weapons and sensors, asset placement, platform capabilities, and associated trade-off analyses.
- **Anti-Submarine Warfare –** This study demonstrated the need for an undersea layered defense concept and the need for effective torpedo countermeasures.

Further study should include a detailed analysis of the undersea threat and the generation of requirements for a layered undersea defense system. Requirements should be developed for a complete undersea defense system, to include sensor system performance, weapon system performance, countermeasures, and communications architecture.

- **Emerging and/or Classified Technology** – This study was limited to open source information. Electronic warfare systems, space systems, and emerging technologies in weapon and sensor systems were not considered due to their classification. Further study should include classified research and analysis into force protection issues and the identification and incorporation of sensor and weapon technologies that will enhance Sea Base force protection efforts.
- **Non-Lethal Weapons Technology** – This study showed that unconventional vessels were a direct threat to the Sea Base. The biggest challenge with these vessels is determining their intent. Warfare commanders need an option of stopping or slowing any suspect vessel by non-lethal means to help determine its intent. Further study should include research into non-lethal systems and their applicability to Sea Base force protection. This should include identification of candidate technologies, proposed systems, and their incorporation into the force protection system. This technology should also be explored to determine its role in protecting ships in port and in areas where maneuverability is restricted.

3. Total Ship Systems Engineering (TSSE)

The 2003 TSSE Team was responsible for designing a LCS with force protection of the Sea Base as a primary mission. The ship was designed to meet requirements provided by the SEA Team. For future projects, the TSSE Teams will likely continue to design vessels based on requirements provided by the SEA Teams. For future TSSE Teams, further research is recommended in the following areas:

- **USV Design** – This study proposed using USVs as part of the force protection system. Further study should focus on specific USV design, to include hull, propulsion systems, power systems, control systems, sensor systems, weapon systems, and defensive systems. Classified research can also be done to incorporate emerging technologies into the USV design.
- **UUV Design** – This study proposed using UUVs as part of the force protection system. Further study should focus on specific UUV design, to include hull, propulsion systems, power systems, control systems, sensor systems, weapon systems, and defensive systems. Classified research can also be done to incorporate emerging technologies into the UUV design.

4. Supporting Studies

Supporting Studies from the Temasek Defense Systems Institute (TDSI) Teams were responsible for contributing information in their specific areas of study. Other NPS theses were identified and used as parts of the integrated study. The SEA-4 Team used these studies to meet requirements generated for protection of the Sea Base. Future TDSI Teams and students in other curricula can contribute further studies in the following areas:

- **Aerospace Engineering** – This study used an aerostat and UAVs as part of the force protection system. Further study should focus on specific UAV and aerostat design in addition to availability and reliability analyses. Also, more in-depth aircraft survivability studies should be included to optimize survivability of Sea Base air transport assets.
- **Sensors** – As sensors are an integral component of the force protection system, further study on sensor systems needed to protect the Sea Base should focus on specific sensor systems design. Efforts should also include availability and reliability studies and proposed acquisition strategies.
- **Weapons** – As weapons are an integral component of the force protection system, further study on weapon systems should include specific design for missiles, guns, artillery rounds, lasers, torpedoes, countermeasures, and other weapon systems needed for the protection of the Sea Base. Efforts should also include availability and reliability studies and proposed acquisition strategies.
- **Space Systems** – This study did not research or analyze any space systems that could contribute to force protection of the Sea Base. Further study efforts should identify and/or propose space systems that would enhance Sea Base force protection efforts. This should also include integration into the force protection system and detailed analysis of availability and reliability.
- **Command, Control, Communications, Computers, Information, Surveillance, and Reconnaissance (C4ISR) Systems** – Sea Base force protection efforts will rely heavily on C4ISR systems. Further study should include hardware design, software requirements, and built-in growth capability for both. The study should also include a detailed analysis of availability and reliability.
- **Electronic Warfare (EW) –** This study identified the need for soft kill systems to work in conjunction with hard kill systems to achieve the desired level of force protection. Detailed, classified analyses should be done in this area in addition to specific proposals for EW threat warning systems, jamming systems, countermeasures, deception systems, and other self-protection systems. The study should also include a detailed analysis of availability and reliability.
- **Operations Research** – SEA students performed most of the analysis for this study. Future efforts with a dedicated operations research team should focus on detailed campaign-level and high-resolution modeling of various force protection

scenarios. Modeling efforts can analyze different force compositions, disposition of distributed sensors and weapons, asset placement for operations with multiple objectives, and a logistics analysis of the force protection system. The study should also examine various modeling tools and determine or design a tool most appropriate for continued research of Sea Base force protection.

- **Chemical, Biological, Radiological, and Nuclear Effects (CBRNE)** – This study identified the need for CBRNE defense, but did not research or analyze any specific systems that could contribute to this component force protection of the Sea Base. Further study efforts should identify and/or propose systems that would effectively sense, identify, and protect the Sea Base from these threats. This should also include integration into the overall force protection system and detailed analysis of availability and reliability of proposed systems.

5. Conclusion

The recommendations for further study were based on resources that are expected to be available at NPS in the future. Larger SEA classes will be able to complete more thorough analyses and provide in-depth research into all of the components of their selected system. The SEA-4 Team scoped the project and elected to focus on a macro-view of force protection. These recommendations for further studies are intended to identify areas beyond this macro-view where NPS students can conduct meaningful research to fill in gaps that this team identified, but did not have the resources to cover adequately. Having identified those areas, it is recommended that any further study into force protection of the Sea Base strongly consider one of these recommendations.

D. PROMISING SYSTEMS TECHNOLOGIES

1. Overview

Due to the unclassified nature of this study, research was limited to open source information. Additionally, resource constraints did not allow the exploration and research of some emerging lethal and non-lethal technology areas. Several emerging technologies exist that have the potential to enhance Sea Base force protection. Available resources, limited information, modeling complexity, and classification issues did not allow in-depth analysis of these technologies. Sensor technologies that exploit environmental disturbances (e.g., internal waves) or emissions (e.g., exhaust or magnetic fields) were not explored. Open source information on the capabilities of these systems warranted their mention as weapon and sensor systems that may be available in the future as applications to protect the Sea Base. Additionally, improvements to existing sensors and weapons or those conceptualized in other studies also have the potential to enhance Sea Base force protection.

2. Capabilities Needed

To facilitate recommendation of specific systems to aid in the defense of the Sea Base, data from the needs analysis and system requirements was used to develop a list of capabilities needed. These capabilities were addressed by warfare area for clarity.

Anti-Air Warfare (AAW) capabilities needed:

- Quick detection and identification of high-speed threat
- Long detection ranges to facilitate increased reaction time to counter high-speed threats
- Neutralize threat *platform* at standoff distances
- Improved aircraft countermeasures against air-to-air and surface-to-air missiles

Anti-Surface Warfare (ASUW) capabilities needed:

- Quick detection and identification of hostile surface craft
- Long detection ranges to facilitate increased reaction time against high-speed surface craft
- Non-lethal means of slowing or stopping suspect craft to determine their intentions
- Neutralize threat *platform* at stand-off distance
- Increase probability of kill of existing weapons against small boat threat
- Quickly and economically field more effective weapons to engage asymmetric ASUW threats

Anti-Submarine Warfare (ASW) capabilities needed:

- Alternative ASW sensors and weapons that exploit emerging technologies (distributed systems, deployable arrays, etc.)
- Improved shallow water ASW capabilities for existing ships and aircraft
- Improved sonar-processing capabilities
- Improved non-acoustic sensors
- Radar systems with automatic periscope detection capability
- More effective ASW weapons (torpedoes, depth bombs, mines)
- Torpedo countermeasures

Mine Warfare (MIW) capabilities needed:

- Mine avoidance capability for combatants
- Improved and eventually automated electro-optical (EO)/IR/radar detection and classification of surface mine-like objects
- Improved and eventually automated sonar detection and classification of mine-like objects in the water volume
- Improved and eventually automated detection and classification of bottom and buried mine-like objects
- Countermeasures for acoustic and magnetic influence mines
- Improved mine-clearing capabilities in all zones

a. Candidate Systems

Several candidate sensor and weapon systems—either existing, planned, or conceptual—may be available for force protection of the Sea Base in the 2015-2020 timeframe. Several systems were identified, but resource constraints did not allow in-depth research or modeling of these candidate systems. For future studies, consideration should be given to including these or similar systems in any system of systems design to protect the Sea Base.

b. Lidar Systems

Lidar sensors work on the same principles as radar, except that they use laser light in place of radio waves. Several lidar sensors have been evaluated for use as USW search sensors. Existing research and development programs and advancements in technology may eventually yield effective and reliable lidar search sensors to detect submarines and mines in the littorals.

Magic Lantern® is an airborne lidar mine countermeasures system designed to provide rapid reconnaissance of moored and floating mines. Electronic shutters in Magic Lantern®'s receivers are set to open at different depths, therefore providing coverage in multiple zones. The receivers image the reflected laser light to detect and classify mine reflections and shadows.

A lidar sensor system adapted from Magic Lantern® could be used in the future to provide the capability of improved and eventually automated detection and classification of all types of mines in shallow water, surf zone, and beach areas. The Magic Lantern® concept of operations is shown in Figure VII-4.

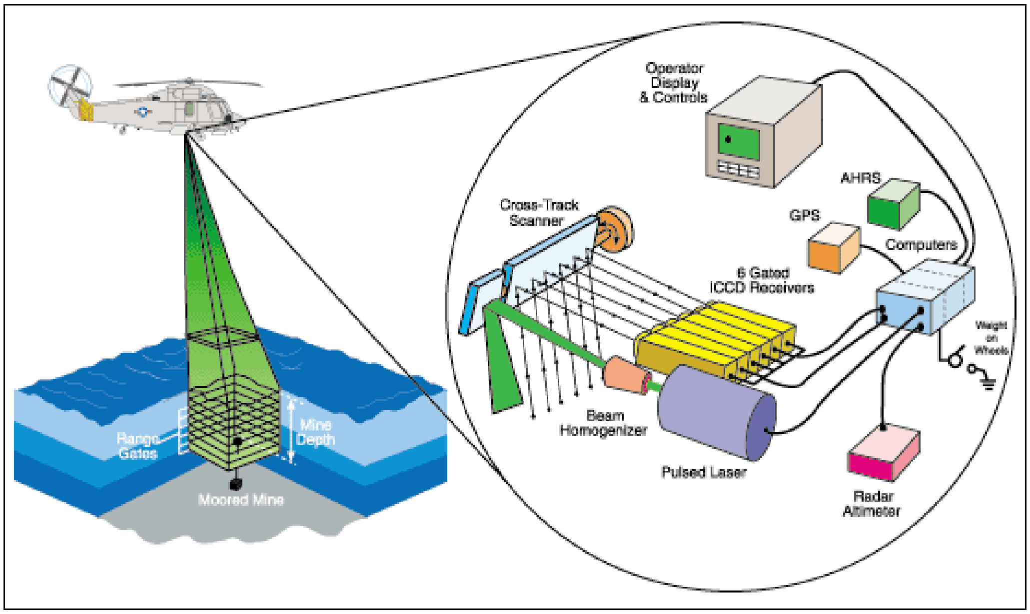


Figure VII-4 Magic Lantern® MIW Concept of Operations

Systems developed using Magic Lantern® technology could also be used as a non-acoustic ASW sensor. A representative concept of operations for this sensor is shown in Figure VII-5.

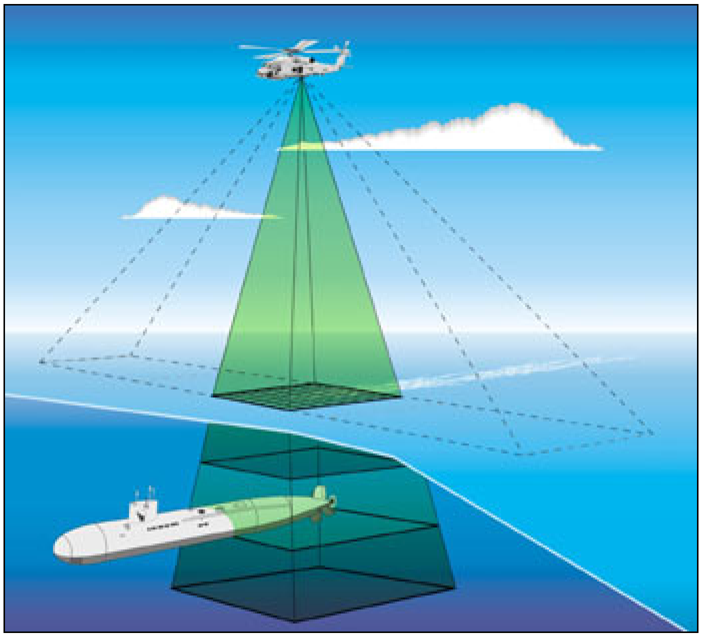


Figure VII-5 Lidar System ASW Concept of Operations

Other Lidar systems in development are the Rapid Airborne Mine Clearance System (RAMICS) sensor and the Airborne Laser Mine Detection System (ALMDS). RAMICS is a helicopter-mounted mine countermeasures system that uses lidar to locate and target mines in shallow water. Targeting information is provided to a 30mm rapid-fire gun system that fires a super cavitating, armor-piercing projectile designed to enter the water and strike the targeted mine at high velocity. The projectile is designed to penetrate the mine casing and destroy and/or sink the mine. RAMICS components and concept of operations are shown in Figure VII-6.

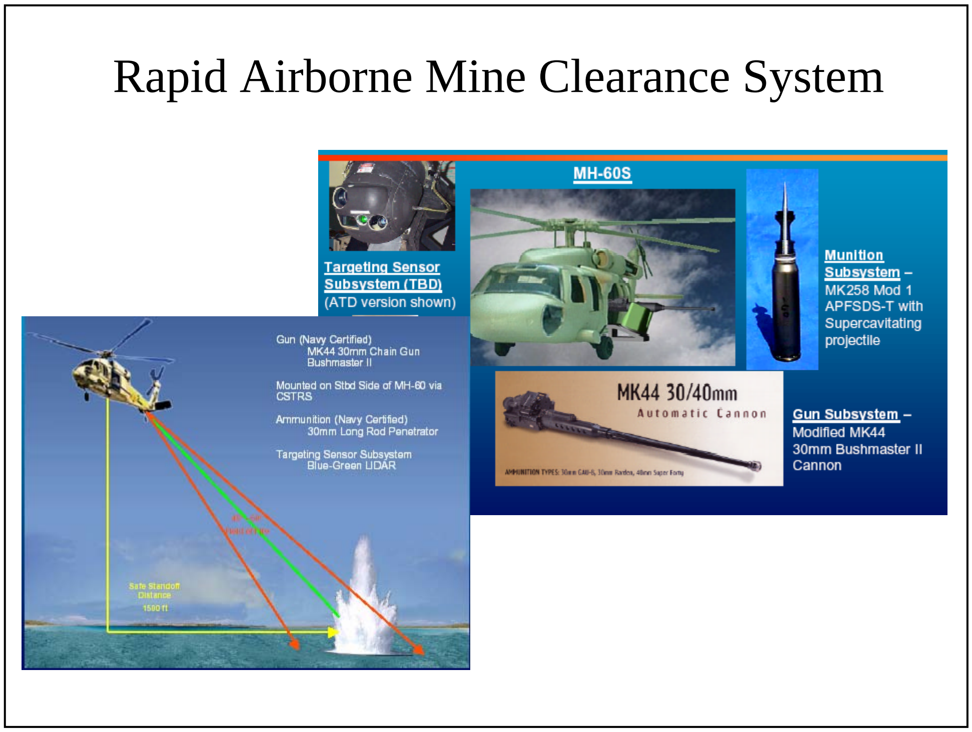


Figure VII-6 RAMICS Concept of Operations and Components

ALMDS is a helicopter-mounted lidar sensor system designed to detect mines in shallow water. The lidar scans a wide path of the ocean while the helicopter flies at high speed. The system generates computer-enhanced image of the shapes, sizes, and locations of mine-like objects. The sensor is designed to locate and identify mines in a single pass over the target area, which minimizes threats to the helicopter.

The abundance of planned lidar sensors proves its potential as a viable undersea warfare system. In the future, lidar sensors, such as those described, can be used to enhance force protection of the Sea Base from underwater threats.

c. Hyperspectral Sensors

Spectral imaging uses specialized sensors to capture and interpret color images. These imaging systems can "see" multiple colors from the ultraviolet through the far infrared. Hyperspectral sensors collect color images in many contiguous color bands. Information collected from these sensors is used to determine the nature of the material, object, or condition being viewed. This enables these systems to detect, classify, and identify these various materials, objects, or conditions. Systems such as the Littoral Airborne Sensor-Hyperspectral (LASH) and the Littoral Mine Countermeasures Rapid Reconnaissance System (L-MCM RRS) have been designed and are in the early stages of testing.

Hyperspectral sensors can be used to detect submarines and mines in the littoral environment where the Sea Base and its transport assets will be operating. Future applications of these systems on aircraft and/or UAVs could provide additional force protection for the fleet. Use of these or similar systems will provide the capability to support mine detection in the surf zone and beach zone. These systems could also provide additional capability as improved low-cost, non-expendable, non-acoustic sensors. Notional designs for a helicopter-mounted LASH sensor pod and a UAV-based L-MCS RRS are shown in Figure VII-7.

Hyperspectral Sensors

Prototype LASH system pod-mounted on SH-60.

Prototype L-MCM RRS mounted on Vertical Takeoff UAV.

Figure VII-7 Hyperspectral Sensors

d. Magnetic Anomaly Detection (MAD) Systems

MAD systems sense disturbances in the earth's magnetic field caused by the movement of large ferrous metal objects, such as submarines. Navy ASW aircraft have been using these sensors for years, but recent advances in technology have increased their range and will eventually aid on classification of targets. In the future, these systems may be mounted on helicopters and/or UAVs and used to search the littoral area for the presence of enemy submarines. These passive, non-acoustic sensors would provide improved shallow water ASW capabilities to help protect the Sea Base.

e. Automatic Target Recognition (ATR)

ATR systems augment existing sensor systems by detecting, tracking, and identifying threats without operator action. For example, the Automatic Radar Periscope Detection and Discrimination (ARPDD) uses ATR to discriminate periscopes from clutter, debris, and small objects on the ocean surface in the littoral environment over a large area in a short time period. Due to the complexity of the littoral battle space, sensor operators will need a reliable means to interpret a vast amount of data and reliably identify potential threats. In the future, ATR can be applied to lidar, radar, sonar, MAD, and other systems to facilitate immediate identification of threats. A direct outgrowth of the ARPDD program could be the use of ATR to automatically identify classes of ships, aircraft, and other threats well beyond effective weapon ranges. These systems can be used to provide the capability of immediate threat identification at long range for various sensors. This capability will augment Sea Base force protection efforts.

f. Countermeasures Systems

Countermeasures systems are used to defend aircraft against radio frequency (RF) and IR surface-to-air and air-to-air missiles. Systems in development such as the Directional Infrared Countermeasures System (DIRCM) and the Integrated Defensive Electronics Countermeasures System (IDECM) are examples of systems that could provide the needed self-protection and survivability for future Sea Base air transport assets.

DIRCM is an integrated system designed to provide threat IR missile identification and warning, and automatically activate the appropriate IR countermeasure needed to defeat the incoming threat missile. It was designed to counter the threat of new generation, highly proliferated IR threat missiles. As with all modern systems, it was designed with growth capability that would make it an ideal candidate aircraft force protection system in the 2015-2020 timeframe.

IDECM is designed to provide self-protection and increased survivability for tactical aircraft against RF and IR surface-to-air and air-to-air threat missiles. The system consists of threat warning receivers, processors, a transmitter, a towed decoy, and expendable decoys. This system is designed to integrate all EW functions, such as radar warning, self-protection jamming, chaff/flare dispersers, and towed decoys into a single system. Eventually, this could be used as a model to fully integrate shipboard EW functions as well.

The Sea Base of the future depends on aircraft for execution of Ship-to-Objective Manuever (STOM). Aircraft survivability will be critical if the force is to accomplish the intended mission. Aircraft will need protection from air-to-air and surface-to-air missiles and these or similar systems would be ideal candidate systems to perform that task. The battlefield of the future will require automated, effective, affordable, and reliable self-protection systems that will free crews to concentrate on executing their assigned mission and ensure a high rate of survivability for Sea Base aircraft.

g. Effective Low-Cost Weapons

Existing weapons systems are complex and costly. Some of these complex systems are marginally effective against threats such as small boats. Additionally, the cost of these weapons is many times the cost of the threat against which it is being used. For example, an expensive Harpoon missile would not normally be employed against a small boat. For this reason, Sea Base ships need a low-cost, effective weapon to use against this type of threat.

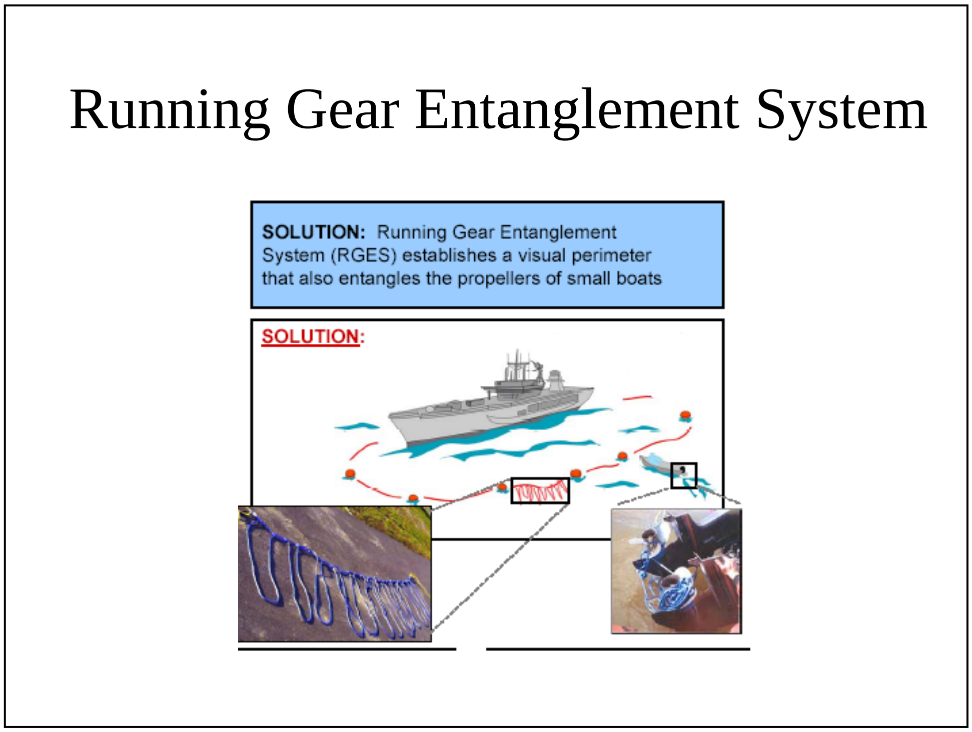
Sea Javelin is a concept developed in an NPS student thesis to provide an effective, low-cost measure of force protection against small boat attack. The Javelin Anti-armor missile is a 49.5-pound, man-portable, fire-and-forget, surface-attack, anti-tank missile originally designed to counter the current and future threat armored combat vehicles. The Sea Javelin concept uses this system in a non-traditional role aboard ships to provide force protection in restricted waters, in port, or in any situation where primary weapon systems were powered down or in an unusable state. One advantage of the Sea Javelin concept is that its stand-alone design does not require integration into the ship’s weapon and sensor systems. The weapon was also evaluated to be mechanically and tactically sound for shipboard operation. Probability of hit and probability of kill analyses showed greater than 0.90 for both. Cost effectiveness was evaluated using cost-per-kill as a measure of performance. Cost-per-kill was significantly less than any other existing or proposed missile system. Only gun systems performed better in this area; this was an expected outcome as most unguided projectiles are significantly cheaper than missiles.

This concept and other innovative concepts that use existing weapons have the potential to significantly increase force protection efforts in a cost effective manner. Systems such as this could provide specific capability to neutralize threat platforms at stand-off distances, increase probability of hit and probability of kill against small boat threats, and provide a quick, economical means of engaging asymmetric ASUW threats.

h. Non-Lethal Systems

One of the biggest challenges to the Sea Base force protection is the asymmetric threat. One method to consider would be the employment of non-lethal weapons to slow or neutralize any potential threat until its intentions can be determined. Two candidate systems currently in development are the Running Gear Entanglement System (RGES) and the Vessel Stopper System (VSS). These systems can effectively be used to stop small boats and very large ships using asymmetric tactics.

The RGES is designed to surround the ship or restricted area with a barrier and use an entanglement device to foul the propellers of unauthorized vessels that penetrate the barrier. The RGES concept is show in Figure VII-8.



Running Gear Entanglement System

SOLUTION: Running Gear Entanglement System (RGES) establishes a visual perimeter that also entangles the propellers of small boats

Figure VII-8 Running Gear Entanglement System

The VSS is designed to stop merchant ships by blocking the exhaust stack. The operational concept is to drop the device into the stack of a ship using a helicopter. Once dropped into the stack, the VSS explosively expands to completely seal the stack. Backpressure causes the engines to stall in a very short period of time. The system does not cause any permanent damage to the vessel and can later be removed to return the vessel back to normal operation.

System concepts such as these will provide additional options for commanders when they may be unsure of the intentions of a potential threat. They can also facilitate search and seizure of suspect vessels and directly provide the capability to slow or stop these vessels using non-lethal means.

3. Summary

Several emerging technologies exist that have the potential to enhance Sea Base force protection. The chapter introduced a few of those technologies and identified the capabilities that systems such as these could provide to the Sea Base. Resources, classification issues, and modeling complexity did not allow an in-depth analysis of these technologies. The existence warranted mention as these technologies will be available in the 2015-2020 timeframe and may be used as integral components in the Sea Base force protection system. Additionally, inclusion of these sensor technologies can be used as a springboard for further research opportunities. Further research is highly recommended in these areas. Future SEA classes may have significantly greater resources available and may be able to split into teams to address different topics. One team could be dedicated to research in classified areas to add that perspective to this or any other study. When resources allow, these emerging technologies should not be overlooked as an added dimension for Sea Base force protection.

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APPENDIX A

INITIAL REQUIREMENTS DOCUMENT
for
TOTAL SHIP SYSTEMS ENGINEERING (TSSE) DESIGN PROJECT
Summer and Fall Quarter 2003

17 July 2003

A. GENERAL DESCRIPTION OF OPERATIONAL CAPABILITY

1. Mission Need Statement

The top-level mission need is stated in the Project Guidance Memorandum from Professor Calvano (22 May 2003) stored on the Systems Engineering and Analysis (SEA-4) Naval Postgraduate School network share drive. This need is to "address protection of the ships of the Sea Base while at sea in the operating area, as well as the protection of the airborne transport assets moving between the Sea Base and the objective and the surface assets moving between the Sea Base and the beach or a port." The integrated teams are specifically not required to address protection of the Sea Base assets while in port. Furthermore, the tasking does not include addressing the protection of the land force itself or land transport from the beach to the objective.

The Systems Engineering and Integration (SEI-3) study paints a broad picture of expeditionary warfare as it might look like by the year 2020. The SEI-3 study embodies the capabilities of pertinent documents germane to expeditionary warfare.

2. Overall Mission Area: Expeditionary Force Protection (EFP)

SEA-4 has defined expeditionary force protection as actions taken to prevent or mitigate hostile action against the Sea Base, to include resources, facilities, and critical information. These actions conserve the force's fighting potential so it can be applied at the decisive time and place and incorporate the coordinated and synchronized offensive and defensive measures to enable the effective employment of the joint force, while degrading opportunities for the enemy.

Force protection does not include actions to defeat the enemy or protect against accidents, weather, or disease. (Adapted from the Department of Defense Dictionary definition of Force Protection.)

3. Description of Proposed System

This system is intended to be a platform, or family of platforms, that encapsulates all mission capabilities and meets system-level requirements contained in this document. The system will support the operational flexibility and rapid operational tempo required for the protection of the expeditionary warfare force (SEI-3's conceptual architecture). It will support littoral operations across the spectrum of conflict—from small-scale contingency missions as part of a forward-deployed Amphibious Ready Group (ARG), to forcible entry missions in a major theater war as part of a large naval expeditionary force. It must be able to enhance the protection of the ExWar ships and associated delivery vehicles.

This system must be capable of integration with current and future joint, combined, or interagency systems. This system must allow the Navy to fully use the capabilities of future systems such as vertical take-off and landing unmanned aerial vehicles (UAV), unmanned surface vehicles (USV), or unmanned underwater vehicles (UUV), as well as future force protection and battle management command, control, communications, computers and intelligence (BMC4I) capabilities. The system will need to be designed to accommodate growth trends and the insertion of new technologies throughout its service life to avoid built-in obsolescence.

B. SYSTEM STATES AND ASSOCIATED THREATS

Three system states have been identified for the expeditionary warfare force. The following are SEA-4 determined system states and their associated primary threats:

1. State I – Staging/Buildup (Operating Area)

- Anti-ship cruise missile (ASCM)
- Small Boats (SBs)
- Unconventional Vessels (UVs)
- Submarines/UUVs
- Mines

2. State II – Ship-to-Shore/Ship to Objective Maneuver (STOM)

- SBs
- Mines
- Surface-to-air missiles (SAMs)
- Unguided munitions
- Aircraft/UAVs

3. State III – Sustainment

- ASCM
- Mines
- UVs
- SAMs
- Aircraft/UAVs

C. WARFARE AREAS

The Sea Base will operate as an amphibious strike group. For a Marine Expeditionary Brigade (MEB)-sized force, a Carrier Strike Group (CSG) will be operating in the vicinity of the Sea Base.

1. Air Warfare (AW)

The system must detect, identify, track, and defeat air targets that have been launched without warning or have eluded AW defenses provided by other fleet units (i.e., “leakers”). The employment of these threats may vary from low density to saturation attack.

- ASCM
- Attack aircraft
- UAV
- Low, slow flyer

2. Surface Warfare (SUW)

The system must detect, identify, track, and defeat a variety of surface craft. The surface craft themselves may vary from asymmetric/unconventional boats to patrol craft. The employment of these threats may vary from low density to saturation. In the dense, cluttered, and environmentally complex littoral regions, the system must be able to:

- Detect surface threats with ownship and networked sensors
- Deconflict potentially hostile craft from friendly and neutral shipping
- Direct, support, and/or embark aircraft conducting SUW
- Engage surface threats to the expeditionary warfare force

3. Undersea Warfare (USW)

The system must support both anti-submarine operations and mine countermeasures (MCM). Furthermore, the system must be able to detect, identify, track, and defeat UUVs and no-warning torpedo attacks. The design must provide for the control and support of USW helicopters/UAVs, and the control of UUVs. The ship must also support mine warfare (MIW) assets. This includes:

- Hosting of remote mine search capability (i.e., USV/UUV and/or very shallow water (VSW) detachment operated from the ship) from deep water to surf zone
- Possess ownship capabilities to conduct MCM from deep water to VSW
- Possess an offensive mining capability

4. Information Operation/Information Warfare (IO/IW)

The Command and Control (C2) architecture must support planning, gaining, and maintaining situational awareness, decision-making, order generation, weapons direction, and ship system monitoring and control with uninterrupted voice, video, and data connectivity. The system must be able to collect, process, exploit, and disseminate an uninterrupted flow of information in support of operations. Interoperability, not just compatibility, of C2 systems across the joint/combined/interagency force is required.

The system must be capable of deploying an expeditionary sensor grid with the following characteristics:

- Communication suite allowing fully networked assets (helicopters, UAVs, USVs, UUVs)
- Deployable surface and bottom acoustic and radio frequency (RF) arrays to act as tripwire and early warning of threats

- Deployment of systems, such as aerostats and robotic airships, to extend the horizon and provide a stable sensor array versus low observable targets such as small, fast movers

The system must be capable of conducting electronic attack (EA), electronic protection (EP), and/or electronic support (ES).

D. ADDITIONAL REQUIREMENTS

1. Operational Requirements:

- Operate in deep water to VSW
- Operate as far as 200 nm offshore
- Capability to operate at a sustained speed of 35 kts at sea states three or better
- Trans-oceanic crossing capability
- Employ full capabilities in a sea state of five
- Employ full capabilities in a chemical, biological, radiological (CBR) environment
- Employ full capabilities in temperatures ranging from –18° C to 40° C (outside dry bulb)

These initial operational capabilities have been determined by SEA-4 through the use of Needs Analysis. More detailed operational capabilities will be delivered after further analysis of the force protection system. The SEA-4 Team has reviewed the Chief of Naval Operations Expeditionary Warfare (N7) Littoral Combat Ship (LCS) interim requirements document (IRD), and while the TSSE Team should take into consideration the operational characteristics identified in the N7 LCS IRD, they should not feel constrained by those requirements.

2. Environmental, Safety and Occupational Health (ESOH) and Other System Characteristics

- Must comply with Federal Environmental Protection Agency (EPA) and Naval Occupational Safety and Health (NAVOSH) regulations and international law as applicable

3. Supportability Requirements

The system must be capable of sustainment from legacy and future CLF ships, as well as from ExWar ships. Prolonged expeditionary operations will demand that the Sea Base force protection assets be able to remain on-station for the duration of the campaign. This capability will facilitate the elimination of an operational pause and permit the force to conduct STOM and Operational Maneuver From the Sea (OMFTS). By gaining and maintaining access throughout the littorals, the U.S. Navy will become the chain link that will provide the capability to conduct joint, combined, and interagency expeditionary operations. The system must have intermediate-level (I-Level) maintenance for platforms in company and by itself.

4. Human Systems Integration

- Reduced manning concepts must be employed
- Ensure crew comfort/quality of life

E. REFERENCES

- SEI-3 Expeditionary Warfare Study
- Project Guidance for AY 2003 SEA-4 Team (Professor Calvano memo dtd May 22, 2003)
- LCS Concept of Operations
  (Naval Warfare Development Center (NWDC) website
  http://www.nwdc.navy.mil/Concepts/LCSCONOPS.asp)
- The Maritime Vision
- The Naval Operational Concept
- The Maritime Concept
- Expeditionary Maneuver Warfare
- Seabased Logistics, May 1998
- MPF 2010 and Beyond
- STOM Concept of Operations (CONOPS)
- LCS Flight 0 Preliminary Design IRD (N7)

Note: All documents are located in the SEA lab or on the SEA Share Drive.

F. POINTS OF CONTACT

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APPENDIX B

A. MODELING

1. EXTEND

a. Top-Level Assumptions

The EXTEND model was built to represent the formation level interactions of the threats, sensors, and weapons. It was not intended to represent every friendly platform and its respective sensors and weapons. Therefore, it is assumed that threats arrive along a common bearing to the Sea Base and that there is a sensor and weapon along that bearing.

Threats must be detected in order for the system to defeat them through hard or soft kill means. If the threat is not detected, then only point defense systems and the threat's own inaccuracy and reliability can prevent it from hitting a friendly platform.

b. Configuration, User Inputs and Outputs

A major benefit to modeling with EXTEND is the ease of manipulating the configuration of the model. The user has the capability to change the model to represent the various alternate force architectures by simply changing inputs and rerouting within the model. This allowed the team to build one model that could be reconfigured to represent the desired force architecture.

There are two primary means by which to input data to the model—manually or automatically. Manual inputs do not change while the model is running, while automatic inputs do change during a model run depending on the process being represented. An example would be maximum radar detection range, which changes depending on the threat being detected.

With only one exception, the automatic inputs to the EXTEND model were input using a common Excel spreadsheet labeled Inputs.xls. This spreadsheet must be resident in the same folder as the EXTEND model. This spreadsheet contains the following worksheets:

- Probability of Single Hit Mission Kill
- Radar Maximum Detection Range

- IR Maximum Detection Range
- Sonar Maximum Detection Range
- Weapons Inputs

The one exception to this is the Weapon Inputs. Although there is a worksheet in the Excel file labeled Weapons Inputs, this data was exported to a text file labeled Weapon Inputs.txt. As with the Excel file, the text file must be resident in the same folder as the EXTEND model.

The specific data contained in the above input files will be discussed later in the appendix.

To ease data collection at the completion of the runs, output text files were used to capture data specific to measuring the effectiveness of the alternate force architectures. As with the input files, the output files must be resident in the same folder as the EXTEND model. The files are as follows:

- ACFT Killed.txt
- ASCM Kills.txt
- DW Kills.txt
- SAM Kills.txt
- Ships Killed.txt
- TORP Kills.txt
- Transports Killed.txt

c. Units of Measure

The units adopted for the model were metric units. Specifics are listed in Table B-1.

MEASURE	UNITS	ABBREVIATION
Distance	Meters	m
Speed	Meters per Second	m/s
Time	Seconds	s
Frequency	Hertz	Hz
Volume	Meters Cubed	m^3

Table B-1 Units of Measure Used in the Model

d. Block Descriptions

The following sections will give detailed descriptions of the various blocks in the model. The description will include the flow of the process being represented, the assumptions of the block, and inputs to block.

(1) Threat Generator

(a) Description

Threat platforms and land-based weapons are initially generated using a poisson process with exponentially distributed interarrival times. From the generator they are split into multiple entities based on raid or salvo size. Platforms are then assigned the attributes of specific type, speed, altitude, launch range, and maximum weapon range. Land-based weapons are assigned the attributes of specific type, intended target, speed, altitude, and launch range.

Platforms that are not detected by subsequent detection blocks, return to the threat generator and are converted to platform-based weapons to represent a weapon firing. These platform-based weapons are then split into multiple entities based on raid or salvo size and assigned the attributes of specific type, intended target, speed, altitude, and launch range. Because the weapon has been generated from a platform, the attribute of maximum weapon range is removed from it at this time. Also specific to platform-based weapons, the launch range attribute is set to the range of the platform at time of launch.

(b) Assumptions

In most cases, threats are generated at 80% of their maximum range. The exception to this is when the range is extremely long, in which case they are generated just outside the defined search region of the architecture (i.e., 370 km). This helps the model to run faster as processing time is wasted, decrementing the threat range until it is within maximum detection range.

(c) Inputs

Table B-2 contains the values for the intended target attribute. Table B-3 contains the values for the specific type attribute for the threats, the friendly platforms the threat can target, and the threat weapon of the threat platform. As stated in Chapter VI, due to the bounds based on the size of the team, only the threats that were deemed to have the most impact on the Sea Base were modeled to help scope the modeling effort. Details of the distributions used to determine intended target can be found later in this appendix. Table B-4 contains the other descriptive attributes of the threats.

FRIENDLY PLATFORM	INTENDED TARGET ATTRIBUTE
ExWar	1
CG	2
DDG	3
FFG/LCS*	4
LCU(R)	5
HLCAC	6
AAAV	7
LRHLAC	8
MV-22	9
JSF	10
AH-1	11

*In COA A FFG is used, and in COA B LCS is used.

Table B-2 Intended Target Attribute Values

THREATS	SPECIFIC TYPE ATTRIBUTE	POSSIBLE INTENDED TARGETS	POSSIBLE WEAPONS
WEAPONS			
ASCM-1	1	1,2,3,4	N/A*
ASCM-2	2	1,2,3,4	N/A*
ASCM-3	3	1,2,3,4	N/A*
SAM-1	4	8,9,10,11	N/A*
SAM-2	5	8,9,10,11	N/A*
DW-1	6	5,6,7	N/A*
DW-2	7	Not Currently Modeled	N/A*
DW-3	8	Not Currently Modeled	N/A*
TORP-1	9	1,2,3,4	N/A*
TORP-2	10	Not Currently Modeled	N/A*
TORP-3	11	Not Currently Modeled	N/A*
MINE-1	12	Not Currently Modeled	N/A*
MINE-2	13	Not Currently Modeled	N/A*
MINE-3	14	Not Currently Modeled	N/A*
MINE-4	15	Not Currently Modeled	N/A*
PLATFORMS			
ACFT-1	16	N/A*	Not Currently Modeled
ACFT-2	17	N/A*	ASCM-2
ACFT-3	18	N/A*	Not Currently Modeled
UAV-1	19	N/A*	Not Currently Modeled
SB-1	20	N/A*	Not Currently Modeled
SB-2	21	N/A*	Not Currently Modeled
SB-3	22	N/A*	ASCM-1
SUB-1	23	N/A*	TORP-2
SUB-2	24	N/A*	Not Currently Modeled
SUB-3	25	N/A*	Not Currently Modeled

*Not Applicable.

Table B-3 Specific Type Attribute Values and Possible Targets

THREATS	# OF RAIDS	RAID SIZE	SPEED (m/s)	LAUNCH RANGE (m)	ALTITUDE (m)	MAX WEAPON RANGE (m)
WEAPONS						
ASCM-1	#	2	300.0	*	3	N/A
ASCM-2	#	4	825.0	*	5	N/A
ASCM-3	4	5	1650.0	372000	24000	N/A
SAM-1	100	2	1852.0	160000	5000	N/A
SAM-2	20	1	824.0	8000	5000	N/A
DW-1	50	6	N/A	23705	-213.4	N/A
DW-2	Not Currently Modeled					N/A
DW-3	Not Currently Modeled					N/A
TORP-1	#	4	25.7	*		N/A
TORP-2	Not Currently Modeled					N/A
TORP-3	Not Currently Modeled					N/A
MINE-1	Not Currently Modeled					N/A
MINE-2	Not Currently Modeled					N/A
MINE-3	Not Currently Modeled					N/A
MINE-4	Not Currently Modeled					N/A
PLATFORMS						
ACFT-1	Not Currently Modeled					
ACFT-2	10	4	824.1	372000	5000	240000
ACFT-3	Not Currently Modeled					
UAV-1	Not Currently Modeled					
SB-1	Not Currently Modeled					
SB-2	Not Currently Modeled					
SB-3	8	2	20.6	372000	0	120000
SUB-1	5	1	5.1	100000	-213.4	37040
SUB-2	Not Currently Modeled					
SUB-3	Not Currently Modeled					

- Based on number of threat platforms surviving to launch.
* - Based on range of threat platform at time of launch.
N/A - Not Applicable.

Table B-4 Descriptive Attributes

(2) Radar Detection

(a) Description

When threats enter the block, they are routed initially based on the architectural setup of the model. If the model is setup for the point architecture, threats are sent to the point sensor loop. If the model is setup for the distributed architecture, threats are sent to the unmanned aerial vehicle (UAV) sensor loop.

In the UAV sensor loop, the model determines whether or not the threat is either outside the UAV footprint, or above the UAV in altitude. If the threat meets either of these criteria, it is passed to the aerostat sensor loop. If neither criterion is true, then the threat continues in the UAV sensor loop. The model then determines when the threat is within maximum detection range. If the threat is not within maximum detection range, the range is decreased until it is with in maximum detection range. While a platform is in the UAV sensor loop, the range is compared to the maximum weapon range to determine if the threat platform can launch its weapon. Once the threat is within maximum detection range, probability of detection was calculated using the first principle equations used in the search analysis. These equations were applied stochastically in the model to determine probability of detection based on search time. The threat remains in this loop until it reaches its maximum weapon range, is detected, or transitions out of the UAV footprint. If it transitions out of the UAV footprint, the threat is routed to the aerostat sensor loop.

The aerostat and point sensor loops are functionally identical. In either loop, the model determines when the threat is within maximum detection range. If the threat is not within maximum detection range, the range is decreased until it is within maximum detection range. While a platform is in the sensor loop, the range is compared to the maximum weapon range to determine if the threat platform can launch its weapon. Once the threat is within maximum detection range, the probability of detection is calculated based on the amount of time the sensor has to search for the threat. The threat remains in this loop until it reaches its maximum weapon range, the minimum engagement range of the force protection weapons, or until it is detected.

Platforms that reach their maximum weapon range return to the threat generator to represent a weapon firing. Detected threats are routed to the defeat block, and not detected threats are routed to the withstand block.

(b) Assumptions

The same assumptions and theory used in the sensor and search analysis sections were applied to the development of the radar detection block.

(c) Inputs

Table B-5 contains the maximum detection ranges for the various radar sensor architectures. This data is input into the model using the Excel Input.xls file.

	MAX DETECTION RANGE (m) - HORIZONTAL			
	Frequency	3 GHz	20 GHz	
THREAT	Search Area Type	Point / Cylinder	Aerostat / Cone	UAV / Cone
ASCM-1		14100	101338	18012
ASCM-2		17800	189206	18013
ASCM-3		18100	238544	No Detect*
SAM-1		118394	150517	9005
SAM-2		8660	21564	9005
DW-1		10206	87841	14431
DW-2		3000	No Detect*	No Detect*
DW-3		1100	No Detect*	No Detect*
ACFT-1		26100	370039	18016
ACFT-2		147215	332872	9005
ACFT-3		22200	63861	18016
UAV-1		20700	No Detect*	17901
SB-1		13000	99996	18010
SB-2		13000	370037	18010
SB-3		13000	370037	18010

*Either the sensor cannot detect the threat or it won't detect it prior to threat impact.

Table B-5 Radar Maximum Detection Ranges

(3) IR Detection

(a) Description

The IR detection block is specifically designed to detect surface-to-air missiles (SAMs) and dumb weapons (DWs). From the search analysis, it was concluded that IR would be the best detection sensor for these threats. When UAVs are based as in the distributed architecture, it is also the only sensor in close proximity to the threat. This block is also unique in the fact that the soft kill of the threat and the threat's chance of mission killing a friendly platform is processed here and not in the withstand block.

When threats enter the block, they are initially routed based on the architectural setup of the model. If the model is setup for the point architecture, threats bypass the IR sensor and are routed to the processing loop that determines soft kill of the threat and mission kill of a friendly platform. If the model is setup for the distributed architecture, threats are sent to the distributed sensor loop.

In the distributed sensor loop, the model determines when the threat is within maximum detection range. If the threat is not within maximum detection range, the range is decreased until it is with in maximum detection range. Once the threat is within maximum detection range, probability of detection was calculated using the first principle equations used in the search analysis. These equations were applied stochastically in the model to determine probability of detection based on search time. The threat remains in this loop until it is no longer in detection range, or until it is detected. Once it is detected it is routed to the processing loop that determines soft kill of the threat and mission kill of a friendly platform.

The processing loop that determines soft kill of the threat and mission kill of a friendly platform models a flaming datum type process. This is to say that once a threat has fired and is detected, the friendly platforms can avoid the area, and supporting fires can neutralize the threat.

(b) Assumptions

The assumptions for the flaming datum theory vary based on architecture. If point architecture is selected, the threat is neutralized (i.e., soft killed) linearly. If distributed architecture is selected, the threat is neutralized exponentially. The increased neutralization rate for distributed is because of the advantage of having the UAV-based IR sensor. The team felt that the cooperative nature of the distributed sensor architecture would allow for faster notification of the threats, and subsequently allow for supporting fires to neutralize the threat at a faster rate.

(c) Inputs

Table B-6 contains the maximum detection ranges for the IR sensor architectures. This data is input into the model using the Excel Input.xls file.

	MAX DETECTION RANGE (m) - HORIZONTAL	
	Frequency	3-5 micormeters
THREAT	Search Area Type	UAV/ Cone
ASCM-1		8923
ASCM-2		27968
ASCM-3		No Detect*
SAM-1		40996
SAM-2		17708
DW-1		34587
DW-2		No Detect*
DW-3		No Detect*
ACFT-1		15571
ACFT-2		19778
ACFT-3		17901
UAV-1		11851
SB-1		6633
SB-2		15445
SB-3		19371

*Either the sensor cannot detect the threat or it won't detect it prior to threat impact.

Table B-6 IR Maximum Detection Ranges

(4) Above the Water Defeat

(a) Description

As detected threats enter the block, the model determines when the threat is within maximum engagement range of the force protection weapons. If the threat is not within maximum engagement range of the force protection weapons, the range is decreased until it is within maximum engagement range of the force protection weapons. While a platform is in this loop, the range is compared to the maximum weapon range to determine if the threat platform can launch its weapon. Once the threat is within maximum engagement range of the force protection weapons, the probability of hard killing the threat is calculated. The threat remains in this loop until it reaches its maximum weapon range, the minimum engagement range of the force protection weapons, or until it is hard killed.

Platforms that reach their maximum weapon range return to the threat generator to represent a weapon firing. Hard killed threats are routed to the outputs block, and not hard killed threats are routed to the soft kill loop.

The soft kill loop represents the effects of soft kill weapons, such as EW suites, decoys, and expendables (i.e., chaff and flares).

Soft killed threats are routed to the outputs block, while not soft killed threats are routed to the withstand block.

(b) Assumptions

The team used an assumed probability of hard kill for the force protection weapons of 0.7. The team used an assumed probability of soft kill for the force protection system of 0.5.

The team assumed that the ships of the force protection force (i.e., CG, DDG, LCS) would defend the ExWar ship and themselves, but not one another. Therefore, the combined probability of hard kill of a threat targeting an ExWar ship is 0.91.

(c) Inputs

Table B-7 contains the values for maximum and minimum engagement ranges, weapon speed, and probability of hard kill for the force protection weapons. This data is input into the model using the Excel Input.xls file and Weapon Input.txt file.

	MAX ENGAGEMENT RANGE (m)	**MIN ENGAGEMENT RANGE (m)**	**WEAPON SPEED (m / s)**
Current ATW	130000	5000	825
Conceptual ATW	370000	5000	1650
Current BTW	7300	100	20.6
Conceptual BTW	11000	100	25.7
FRIENDLY PLATFORM	**PROBABILITY OF KILL**		
None	0.7		
ExWar#	0.91		
CG	0.7		
DDG	0.7		
FFG / LCS*	0.7		

#Higher Probability of Kill based on combined defense from CG and DDG.
*In COA A FFG is used, and in COA B LCS is used.
ATW = Above the Water.
BTW = Below the Water.

Table B-7 Weapon Inputs

(5) ATW Withstand

(a) Description

The withstand block models the last chance of defeating a threat through point defense type systems. If the point defense systems fail, it determines whether or not a threat hits a friendly platform, and subsequently, whether it mission kills a friendly platform.

Threats that weren't detected or weren't soft killed enter the block and are routed to the appropriate loop that determines the probability of the threat hitting its target. There are two loops: targets *with* point defense (i.e., ExWar, CG, DDG, LCS) and those *without* point defense (i.e., LCU(R), HLCAC, AAAV). If the threat misses its target, it is routed to the outputs block. If the threat hits its target, it is routed to the loop that determines if it mission kills a friendly platform.

Mission kills are computed two ways: one as a single hit mission kill (meaning the threat hits a vital part of a friendly platform) and two as an accumulation of hits. In either case, the number of mission kills is routed to the outputs block. Details of the calculation of single hit probability of mission kill can be found later in this Appendix.

(b) Assumptions

The team used an assumed probability of hit for the threats of 0.5.

(c) Inputs

Table B-8 contains the probability of single hit mission kill for the various threats and their intended targets. Table B-9 contains the number of hits to non-vital areas that equate to a mission kill.

	THREAT							
INTENDED TARGET	ASCM-1	ASCM-2	ASCM-3	SAM-1	SAM-2	DW-1	DW-2	DW-3
ExWar	0.11	0.11	0.11					
CG	0.20	0.20	0.20					
DDG	0.20	0.20	0.20					
FFG / LCS*	0.20	0.20	0.20					
LCUR	1.00	1.00	1.00			0.31	0.16	
HLCAC	1.00	1.00	1.00			1.00	0.50	
AAAV	1.00	1.00	1.00			0.45	0.23	
LRHLAC				1.00	1.00	1.00		
MV-22				1.00	1.00	1.00		

*In COA A FFG is used, and in COA B LCS is used.

Table B-8 Probability of Single Hit Mission Kill

INTENDED TARGET	NUMBER OF HITS TO MISSION KILL
ExWar	5
CG	3
DDG	3
FFG / LCS*	2

*In COA A FFG is used, and in COA B LCS is used.

Table B-9 Number of Hits Above the Water to Mission Kill

(6) Sonar Detection

(a) Description

When threats enter the block, they are routed initially based on the architecture setup of the model. If the model is setup for the point architecture, threats are sent to the point sensor loop. If the model is setup for the distributed architecture, threats are sent to the distributed sensor loop.

In the distributed sensor loop, the model determines whether or not the threat is within the distributed sensor's detection area. If the threat is inside of the distributed sensor's detection area, it is passed to the point sensor loop. If the threat is outside of the distributed sensor's detection area, then the threat continues in the distributed sensor loop. The model then determines when the threat is within maximum detection range. If the threat is not within maximum detection range, the range is decreased until it is within maximum detection range. While a platform is in the distributed sensor loop, the range is compared to the maximum weapon range to determine if the threat platform can launch its weapon. Once the threat is within maximum detection range, the probability of detection is calculated based on the amount of time the sensor has to search for the threat. The threat remains in this loop until it reaches its maximum weapon range, the minimum engagement range of the force protection weapons, or is detected.

Platforms that reach their maximum weapon range return to the threat generator to represent a weapon firing. Detected threats are routed to the defeat block, and not detected threats are routed to the withstand block.

The point sensor loops is functionally identical to the distributed sensor loop. The model then determines when the threat is within maximum detection range. If the threat is not within maximum detection range, the range is decreased until it is within maximum detection range. While a platform is in the distributed sensor loop, the range is compared to the maximum weapon range to determine if the threat platform can launch its weapon. Once the threat is within maximum detection range, the probability of detection is calculated based on the amount of time the sensor has to search for the threat. The threat remains in this loop until it reaches its maximum weapon range, the minimum engagement range of the force protection weapons, or is detected.

(b) Assumptions

The same assumptions and theory used in the sensor and search analysis sections were applied to the development of the sonar detection block.

(c) Inputs

Table B-10 contains the maximum detection ranges for the various sonar sensor architectures. This data is input into the model using the Excel Input.xls file.

	MAX DETECTION RANGE (m) - HORIZONTAL		
	Frequency	1 kHz Sonar - Point	1 kHz Sonar - Distributed
THREAT	Search Area Type	Cylinder	Cylinder
TORP-1		800	3200
TORP-2		800	3200
TORP-3		500	1800
MINE-1		1000	900
MINE-2		800	1500
MINE-3		1200	1500
MINE-4		700	1600
SUB-1		3200	7000
SUB-2		3500	7000
SUB-3		1500	7000

Table B-10 Sonar Maximum Detection Ranges

(7) Below the Water Defeat

(a) Description

As detected threats enter the block, the model routes them based on type. Submarine threats (SUBs) are routed to a loop that represents hard kill, and torpedo threats (TORPs) are routed to a loop that represents soft kill. This is because there is not currently, nor is there envisioned, a hard kill force protection system against torpedoes.

Within the hard kill loop, the model determines when the threat is within maximum engagement range of the force protection weapons. If the threat is not within maximum engagement range of the force protection weapons, the range is decreased until it is within maximum engagement range of the force protection weapons. While a platform is in this loop, the range is compared to the maximum weapon range to determine if the threat platform can launch its weapon. Once the threat is within maximum engagement range of the force protection weapons, the probability of hard killing the threat is calculated. The threat remains in this loop until it reaches its maximum weapon range, the minimum engagement range of the force protection weapons, or until it is hard killed.

Platforms that reach their maximum weapon range return to the threat generator to represent a weapon firing. Hard killed threats are routed to the outputs block, and not hard killed threats are routed to the soft kill loop.

The soft kill loop represents the effects of soft kill weapons such as acoustic countermeasure suites, and decoys.

Soft killed threats are routed to the outputs block, while not soft killed threats are routed to the withstand block.

(b) Assumptions

The team used an assumed probability of hard kill for the force protection weapons of 0.7. The team used an assumed probability of soft kill for the force protection system of 0.5.

(c) Inputs

Table B-7, previously discussed, contains the values for maximum and minimum engagement ranges, weapon speed, and probability of hard kill for the force protection weapons. This data is input into the model using the Excel Input.xls file and Weapon Input.txt file.

(8) BTW Withstand

(a) Description

The withstand block models the last chance that a threat hits a friendly platform, and subsequently, whether it mission kills a friendly platform.

Mission kills are computed two ways: one as a single hit mission kill (meaning the threat hits a vital part of a friendly platform) and two as an accumulation of hits. In either case, the number of kills is routed to the outputs block. Details of the calculation of single hit probability of mission kill can be found later in this Appendix.

(b) Assumptions

The team used an assumed probability of hit for the threats of 0.5.

(c) Inputs

Table B-11 contains the probability of single hit mission kill for the various threats and their intended targets. Table B-12 contains the number of hits to non-vital areas that equate to a mission kill.

	THREAT						
INTENDED TARGET	TORP-1	TORP-2	TORP-3	MINE-1	MINE-2	MINE-3	MINE-4
ExWar	0.31	0.31	0.31	0.31	0.31	0.31	0.31
CG	0.35	0.35	0.35	0.35	0.35	0.35	0.35
DDG	0.35	0.35	0.35	0.35	0.35	0.35	0.35
FFG / LCS*	0.45	0.45	0.45	0.45	0.45	0.45	0.45
LCU R	1.00	1.00	1.00	1.00	1.00	1.00	1.00
HLCAC	1.00	1.00	1.00	1.00	1.00	1.00	1.00
AAAV	1.00	1.00	1.00	1.00	1.00	1.00	1.00

*In COA A FFG is used, and in COA B LCS is used.

Table B-11 Probability of Single Hit Mission Kill

INTENDED TARGET	**NUMBER OF HITS TO MISSION KILL**
ExWar	5
CG	2
DDG	2
FFG / LCS*	2

*In COA A FFG is used, and in COA B LCS is used.

Table B-12 Number of Hits Below the Water to Mission Kill

(9) Outputs

(a) Description

The outputs block accumulates the data required to evaluate the proposed system architectures. It accumulates the data from both the above the water and the below the water blocks.

The outputs compiled are the number of each type of friendly platforms mission killed and the number of mission kills attributed to each type of threat weapon. These outputs are then exported to the previously mentioned text files at the end of each run.

(b) Assumptions

There are no specific assumptions for this block.

(c) Inputs

There are no inputs required for this block.

2. Naval Simulation System (NSS)

The NSS was utilized to provide the team with a means to investigate detailed interactions among entities. In order to build the Palawan scenario, the team had to provide numerous inputs to the NSS modeler. Many of the inputs were already discussed in the Analysis Chapter of this study. This Appendix covers more detailed inputs required to build the scenario. Additionally, this section contains miscellaneous results from the enemy drawdown.

a. Scenario Inputs

(1) Landing Plan

In order to properly simulate Phase II in the NSS model, landing plan information had to be developed for the NSS modeler. The landing plan information provided to the modeler included a drawing of the Palawan Littoral Penetration Zone (LPZ) seen in Figure B-1. The LPZ contains two littoral penetration sites (LPS A AND B) that supported the landing of Heavy Lift Landing Craft Air Cushioned (HLCAC), Landing Craft Utility (Replacement) (LCU(R)), and

Advanced Amphibious Assault Vehicle (AAAV). Two landing zones (LZ Hawk and Eagle) were designed to support the landing of the Long Range Heavy Lift Aircraft (LRHLAC) and the MV-22.

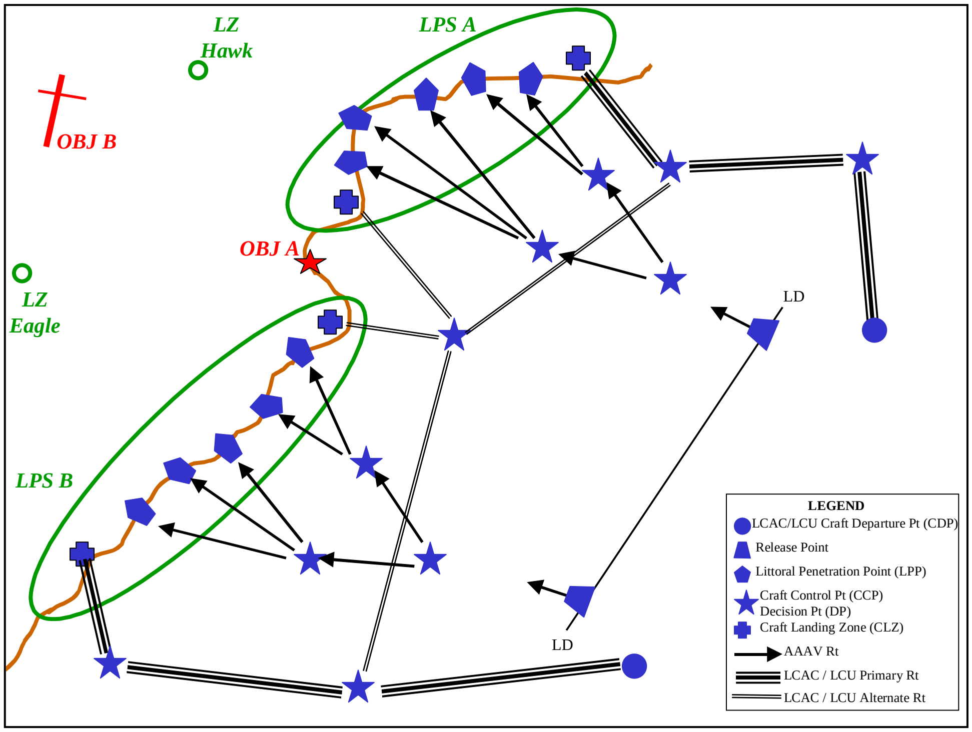

Figure B-1 Palawan LPZ

A line of departure, craft routes, craft control points, and landing penetration points are all included in the littoral penetration zone. In addition to the LPZ diagram, the team provided planning factors for the ship to shore movement. The planning factors are listed in Table B-13.

ASSET	SPEED (kts)		DELAY (min)		SURGE SORTIE
	AVG	MAX	SHIP	OBJ	
LCU(R)	15	18	20	10	4
HLCAC	30	40	15	7	9
AAAV	20	25	N/A*	N/A*	N/A*
LRHLAC	225	250	30	25	3
MV-22	250	275	20	15	4

*Not Applicable.

Table B-13 NSS Planning Factors

The delay columns represent the loading and offloading times for the various surface and aircraft onboard the ship and at the objective. The surge sortie column represents the amount of sorties required in a 24-hour period at a surge rate during Phase II. The surge sortie rates were defined in the SEI-3 Expeditionary Warfare Project. For the scenario, it is assumed that once the AAAV reaches the LPS it would conduct its land mission and therefore required no associated objective delay or sortie rate.

The landing schedule for the air and surface assaults are shown in Table B-14 and Table B-15. L-HOUR represents the LZ touchdown time for the first wave of air assets and H-HOUR represents the LPS touchdown time for the surface craft.

ASSAULT WAVES (AIR)			**L-HOUR**	**0500**
Wave Number	**Landing Time (+ min)**	**LZ Destination**	**A/C Type**	**Craft Qty**
1	L-HOUR	EAGLE	MV-22	7
		EAGLE	LRHLAC	3
		HAWK	MV-22	7
		HAWK	LRHLAC	3
2	L+5	EAGLE	MV-22	7
		EAGLE	LRHLAC	3
		HAWK	MV-22	7
		HAWK	LRHLAC	3
3	L+25	EAGLE	MV-22	7
		EAGLE	LRHLAC	3
		HAWK	MV-22	7
		HAWK	LRHLAC	3
4	L+30	EAGLE	MV-22	7
		EAGLE	LRHLAC	3
		HAWK	MV-22	7
		HAWK	LRHLAC	3
5	L+50	EAGLE	MV-22	7
		EAGLE	LRHLAC	3
		HAWK	MV-22	7
		HAWK	LRHLAC	3
6	L+55	EAGLE	MV-22	7
		EAGLE	LRHLAC	3
		HAWK	MV-22	7
		HAWK	LRHLAC	3

Table B-14 Air Landing Schedule

ASSAULT WAVES (SURFACE)			**H-HOUR**	**0500**
Wave Number	**Landing Time (+ min)**	**Destination**	**Craft Type**	**Craft Qty**
1	H-Hour	LPS A	AAAV	36
		LPS B	AAAV	36
2	H+3	LPS A	HLCAC	9
		LPS B	HLCAC	9
3	H+6	LPS A	LCU(R)	6
		LPS B	LCU(R)	6

Table B-15 Surface Landing Schedule

(2) Enemy Order of Battle

The team utilized all of the generic threats developed in the Threat Analysis. Through careful research, the team equated the enemy order of battle defined in the Joint Campaign Analysis South China Sea Scenario to this study’s threats for the NSS model. The list of threats and how they were employed in the NSS scenario is summarized in Table B-16.

Threats	Quantity	Weapons	Weapon Qty	Employment
SUB-1	5	TORP-1	12	Patrolling Sulu Sea
		TORP-2	2	
		ASCM-1	2	
		ASCM-2	2	
		SAM-2	8	
SUB-2	2	TORP-1	16	Patrolling Sulu Sea
		TORP-2	2	
		ASCM-1	4	
		ASCM-2	4	
		SAM-2	8	
SUB-3	10	TORP-1	2	Originate from Palawan
SB-1	30	DW-2	2	Originate from Palawan and attack in 3 swarms of 10
		DW-3	2 / 200 rnds	
		SAM-2	2	
SB-2	15	TORP-3	4	Originate from Palawan and conduct a multi-axis attack in 3 swarms of 5
		SAM-2	4	
		DW-2	2 / 500 rnds	
		DW-3	2	
SB-3	8	TORP-3	4	Patrolling Sulu Sea and conduct a multi-axis attack in 4 groups of 2
		ASCM-1	4	
		ASCM-2	2	
		SAM-2	4	
UnconVes A	1	ASCM-1	10	Randomly appear in the Sea Echelon Area and launches all of its cruise missiles
		ASCM-2	10	
UnconVes B	30	Mine-1	2	Randomly appear in the Sulu Sea
		Mine-2	2	
		DW-2	2 / 500 rnds	
		DW-3	3 / 1000 rnds	
ACFT-1	20	ASCM-1	4	Originate from Palawan and conduct a multi-axis attack in 5 swarms of 4
		TORP-3	2	
		DW-2	2 / 500 rnds	
		DW-3	1 / 1000 rnds	
ACFT-2	40	ASCM-1	2	Originate from Palawan and conduct random multi-axis attacks in 20 groups of 2
		ASCM-2	4	
		TORP-3	2	
		DW-2	2	
		DW-3	1	
ACFT-3	10	ASCM-1	2	Originate from somewhere in South China Sea (assumed from Spratly Islands or from a carrier) and conduct random attacks
		TORP-3	1	
		DW-2	1 / 500 rnds	
UAV / UCAV	10	ASCM-1	2	Randomly patrolling Sulu Sea
		TORP-3	1	
		DW-2	1	
DW-1 Launcher	50	DW-1	6 rockets each	Randomly appear near landing sites
ASCM-1 Launcher	5	ASCM-1	3 missiles each	Randomly appear on Palawan
ASCM-2 Launcher	5	ASCM-2	2 missiles each	Randomly appear on Palawan
ASCM-3 Launcher	20	ASCM-3	1 missile each	Fired from Spratly Islands
SAM-1 Launcher	10	SAM-1	4 missiles each	Randomly appear on Palawan
SAM-2 Launcher	100	SAM-2	1 missile each	Randomly appear on Palawan

Table B-16 NSS Enemy Order of Battle and Employment

b. Enemy Drawdown Results

Table B-17 through Table B-27 reflect the drawdown of enemy assets. The tables show the number of mission-capable threats over time for each of the alternate force architectures. The shaded threat blocks represent the time period when the threat was eliminated for each alternate force architecture. The highlighted alternate force architectures represent architectures that facilitated the quickest defeat of threats.

	ALTERNATE FORCE ARCHITECTURES							
TIME (HRS)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
0	30.0000	30.0000	30.0000	30.0000	30.0000	30.0000	30.0000	30.0000
1	15.9286	13.6897	10.8214	2.0357	24.7143	14.1034	18.3571	4.7500
2	11.2857	10.2759	9.4643	1.6429	20.5000	9.8621	14.3571	3.2500
3	9.6786	7.6207	8.2500	0.5357	16.5714	7.0000	11.3214	1.6429
4	8.4643	7.1035	6.8929	0.4643	14.0714	5.8966	6.3571	0.7857
5	8.2857	5.7586	6.5357	0.4643	11.9643	4.8621	4.4643	0.4643
6	8.1071	5.3103	5.9286	0.4643	10.0000	3.6207	2.6071	0.1071
7	7.7500	4.2759	5.4643	0.4643	7.9286	2.8276	1.6429	0.0714
8	7.6429	3.9310	5.0357	0.4643	6.8571	2.5172	1.3214	0.0714
9	7.3214	3.7931	4.3214	0.0714	5.6429	1.9310	0.9643	0.0357
10	7.2143	3.7931	4.0357	0.0714	5.0000	1.7586	0.7500	0.0357
11	7.0000	3.7931	3.5714	0.0714	4.4286	1.5172	0.5714	0.0357
12	6.5714	3.6897	3.0357	0.0714	3.7857	1.3448	0.5357	0.0357
13	6.4643	3.4483	2.8929	0.0714	3.5000	1.1379	0.5000	0.0357
14	6.1071	3.3103	2.5714	0.0714	3.3929	1.1379	0.4643	0.0357
15	6.0000	2.7586	2.2500	0.0357	3.0357	1.0690	0.3571	0.0357
16	5.8571	2.4138	1.9643	0.0357	2.8571	0.9655	0.3571	0.0000
17	5.6786	2.4138	1.5714	0.0357	2.6429	0.8966	0.2857	0.0000
18	5.5714	2.0690	1.4643	0.0357	2.2143	0.7586	0.2857	0.0000
19	5.4286	2.0690	1.1786	0.0357	2.1429	0.7241	0.2857	0.0000
20	5.3571	2.0690	0.8929	0.0357	2.0357	0.7241	0.2857	0.0000
21	5.3214	2.0690	0.8214	0.0357	1.8929	0.6207	0.2857	0.0000
22	5.2500	2.0690	0.6429	0.0357	1.7857	0.6207	0.2500	0.0000
23	5.2143	2.0690	0.5000	0.0357	1.7857	0.5862	0.2500	0.0000
24	5.1429	2.0690	0.4286	0.0357	1.6429	0.5862	0.2143	0.0000

Table B-17 Expected Number of SB-1 Mission Capable

	ALTERNATE FORCE ARCHITECTURES							
TIME (HRS)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
0	15.0000	15.0000	15.0000	15.0000	15.0000	15.0000	15.0000	15.0000
1	0.0714	0.0000	0.5000	0.0000	0.4286	0.0800	2.2143	0.5357
2	0.0357	0.0000	0.0000	0.0000	0.0357	0.0000	0.4643	0.0357
3	0.0000	0.0000	0.0000	0.0000	0.0357	0.0000	0.1071	0.0000
4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table B-18 Expected Number of SB-2 Mission Capable

	ALTERNATE FORCE ACHITECTURES							
TIME (HRS)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
0	8.0000	8.0000	8.0000	8.0000	8.0000	8.0000	8.0000	8.0000
1	4.8214	4.9310	1.6429	0.1429	5.2500	4.1724	3.3214	1.3571
2	2.9286	1.5517	1.0714	0.0357	1.7143	0.7241	1.5357	0.1429
3	1.7857	0.1379	0.5000	0.0000	0.3214	0.0345	0.2857	0.0357
4	0.5000	0.0000	0.1786	0.0000	0.0357	0.0000	0.0000	0.0000
5	0.1429	0.0000	0.0357	0.0000	0.0000	0.0000	0.0000	0.0000
6	0.0000	0.0000	0.0357	0.0000	0.0000	0.0000	0.0000	0.0000
7	0.0000	0.0000	0.0357	0.0000	0.0000	0.0000	0.0000	0.0000
8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table B-19 Expected Number of SB-3 Mission Capable

	ALTERNATE FORCE ARCHITECTURES							
TIME (HRS)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
0	5.0000	5.0000	5.0000	5.0000	5.0000	5.0000	5.0000	5.0000
1	4.3571	3.9310	4.0357	4.1071	4.0714	3.9655	4.4286	4.5357
2	4.0714	3.4483	3.5357	3.5714	3.7143	3.5862	4.0714	4.0000
3	3.7500	3.0345	2.8929	3.1071	3.3214	3.2759	3.7857	3.7500
4	3.3571	2.6552	2.6429	2.8214	3.1071	3.0345	3.5357	3.4286
5	2.8214	2.0690	2.3571	2.3571	2.5714	2.4483	3.3214	3.1071
6	2.2143	1.8966	2.1071	2.0714	2.3214	2.2759	2.8929	2.6429
7	1.8214	1.6207	1.6786	1.8214	2.0357	1.8966	2.5000	2.3929
8	1.3929	1.1379	1.3929	1.3214	1.4643	1.3103	1.7500	1.8571
9	0.9286	0.8276	1.0357	0.8929	1.1071	0.8621	1.1786	1.3929
10	0.6786	0.6897	0.8929	0.7857	1.0000	0.6897	0.9286	1.0357
11	0.5714	0.6552	0.8214	0.7143	0.7143	0.6207	0.7500	0.7857
12	0.3929	0.4828	0.6786	0.4643	0.5714	0.4483	0.5714	0.5000
13	0.1071	0.2069	0.3214	0.3929	0.3571	0.2069	0.4286	0.4286
14	0.0000	0.0690	0.2857	0.2143	0.2500	0.1724	0.2857	0.3214
15	0.0000	0.0690	0.2143	0.2143	0.2143	0.1034	0.1786	0.2500
16	0.0000	0.0345	0.1429	0.1071	0.1071	0.0690	0.0714	0.0357
17	0.0000	0.0345	0.0714	0.0357	0.1071	0.0345	0.0000	0.0000
18	0.0000	0.0000	0.0000	0.0000	0.0714	0.0000	0.0000	0.0000
19	0.0000	0.0000	0.0000	0.0000	0.0357	0.0000	0.0000	0.0000
20	0.0000	0.0000	0.0000	0.0000	0.0357	0.0000	0.0000	0.0000
21	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table B-20 Expected Number of SUB-1 Mission Capable

	ALTERNATE FORCE ARCHITECTURES							
TIME (HRS)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
0	2.0000	2.0000	2.0000	2.0000	2.0000	2.0000	2.0000	2.0000
1	1.7500	1.5517	1.4286	1.4643	1.5000	1.5862	1.6786	1.6786
2	1.5714	1.3793	1.1786	1.1786	1.3214	1.3793	1.4286	1.4286
3	1.3929	1.2069	1.0714	1.1071	1.2143	1.3103	1.3571	1.3571
4	1.2143	1.1379	0.9643	1.0357	1.1786	1.2414	1.2500	1.2857
5	1.1429	1.0000	0.8929	0.8571	1.1429	1.1724	1.1786	1.1786
6	0.9286	0.9655	0.7857	0.7500	1.0714	1.0690	0.8214	0.9643
7	0.8214	0.7931	0.6071	0.6786	0.9286	0.8276	0.6786	0.7857
8	0.7500	0.6552	0.5357	0.6071	0.7143	0.6552	0.6071	0.6429
9	0.6786	0.4828	0.3571	0.3571	0.6786	0.6207	0.5357	0.5000
10	0.5000	0.3448	0.2857	0.2857	0.4286	0.4828	0.3929	0.4286
11	0.4286	0.3448	0.1429	0.1786	0.3214	0.3793	0.3929	0.3929
12	0.2143	0.2069	0.1071	0.1429	0.2500	0.2759	0.2857	0.2500
13	0.1071	0.1379	0.0357	0.0714	0.1071	0.1379	0.1429	0.1429
14	0.0000	0.1034	0.0000	0.0000	0.0000	0.0345	0.0714	0.0714
15	0.0000	0.0345	0.0000	0.0000	0.0000	0.0345	0.0714	0.0714
16	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0357	0.0357
17	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0357
18	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0357
19	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0357
20	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table B-21 Expected Number of SUB-2 Mission Capable

	ALTERNATE FORCE ARCHITECTURES							
TIME (HRS)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
0	10.0000	10.0000	10.0000	10.0000	10.0000	10.0000	10.0000	10.0000
1	3.3571	3.3793	3.6429	3.7857	3.9286	3.7931	4.5000	4.2143
2	1.4643	1.8621	2.0357	1.9643	1.6429	1.6552	2.3571	2.0714
3	0.6071	0.8276	0.7143	0.7500	0.6071	0.6207	1.2857	1.0357
4	0.2857	0.3448	0.4643	0.3929	0.5357	0.3793	0.7857	0.8571
5	0.2143	0.3103	0.3571	0.3571	0.3571	0.3103	0.5714	0.3929
6	0.1429	0.1379	0.1429	0.1071	0.2143	0.1724	0.1429	0.2500
7	0.0714	0.0000	0.0357	0.0000	0.0357	0.1379	0.1071	0.0357
8	0.0714	0.0000	0.0357	0.0000	0.0357	0.1034	0.0357	0.0357
9	0.0714	0.0000	0.0000	0.0000	0.0000	0.0690	0.0000	0.0000
10	0.0714	0.0000	0.0000	0.0000	0.0000	0.0690	0.0000	0.0000
11	0.0000	0.0000	0.0000	0.0000	0.0000	0.0690	0.0000	0.0000
12	0.0000	0.0000	0.0000	0.0000	0.0000	0.0345	0.0000	0.0000
13	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table B-22 Expected Number of SUB-3 Mission Capable

	ALTERNATE FORCE ARCHITECTURES							
TIME (HRS)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
0	50.0000	50.0000	50.0000	50.0000	50.0000	50.0000	50.0000	50.0000
1	22.0714	20.2414	20.7857	19.8571	22.0357	20.7241	22.7500	22.2500
2	13.3929	12.1724	12.3929	11.8214	13.1429	12.0345	13.8571	13.2143
3	8.1429	7.2069	7.0357	7.1429	7.3571	7.3103	7.2857	6.7857
4	5.5357	4.7586	4.3214	4.6429	4.8929	4.7931	5.1786	4.1071
5	3.8929	3.1035	2.7857	2.8929	3.1071	2.9310	3.3929	2.4286
6	2.6429	1.8621	1.6786	2.0357	2.1429	2.0345	2.1786	1.6786
7	2.0000	1.4138	1.1429	1.5000	1.7143	1.5172	1.5357	1.2143
8	1.4643	0.7931	0.8571	1.0357	1.0357	1.0690	1.2143	1.0357
9	0.9286	0.4828	0.6786	0.7500	0.8929	0.9655	0.8929	0.9286
10	0.6786	0.4138	0.4643	0.6071	0.6429	0.7586	0.7143	0.7500
11	0.2500	0.3103	0.2857	0.4286	0.5357	0.5172	0.5357	0.4286
12	0.2500	0.2759	0.2500	0.3571	0.3214	0.3793	0.3929	0.1786
13	0.1786	0.2069	0.2500	0.2857	0.2143	0.2414	0.3214	0.1786
14	0.1429	0.1379	0.1429	0.1786	0.1786	0.2069	0.2500	0.1786
15	0.1071	0.1034	0.1429	0.1786	0.0714	0.1724	0.0000	0.1071
16	0.0714	0.0690	0.1429	0.1786	0.0714	0.1724	0.0000	0.1071
17	0.0714	0.0690	0.1429	0.1786	0.0000	0.1379	0.0000	0.1071
18	0.0357	0.0690	0.1429	0.1071	0.0000	0.1379	0.0000	0.1071
19	0.0357	0.0690	0.1429	0.1071	0.0000	0.1034	0.0000	0.0714
20	0.0357	0.0345	0.1071	0.0714	0.0000	0.1034	0.0000	0.0714
21	0.0000	0.0345	0.1071	0.0714	0.0000	0.1034	0.0000	0.0714
22	0.0000	0.0345	0.1071	0.0714	0.0000	0.1034	0.0000	0.0714
23	0.0000	0.0345	0.0714	0.0714	0.0000	0.1034	0.0000	0.0714
24	0.0000	0.0000	0.0357	0.0357	0.0000	0.0690	0.0000	0.0714

Table B-23 Expected Number of Combined DW-1 and SAM-2 Launcher Mission Capable

	ALTERNATE FORCE ARCHITECTURES							
TIME (HRS)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
0	10.0000	10.0000	10.0000	10.0000	10.0000	10.0000	10.0000	10.0000
1	5.6786	5.3793	5.6786	5.6786	5.2500	4.6207	5.3214	4.7857
2	3.5714	3.8621	3.9286	3.8214	3.8929	3.2759	3.7857	3.6071
3	2.3571	2.5517	2.3571	2.4286	2.3214	2.1379	2.2857	2.1786
4	1.5714	1.8276	1.7500	1.7143	1.6429	1.4828	1.7143	1.6071
5	1.0714	1.4828	1.2857	1.2857	1.2500	1.0690	1.4643	1.3214
6	0.7857	0.9655	0.9286	0.8929	0.9643	0.7931	1.2500	1.2143
7	0.5357	0.8276	0.7857	0.6429	0.7143	0.6552	1.0357	1.0000
8	0.3929	0.7241	0.5714	0.4286	0.3929	0.3793	0.6786	0.8571
9	0.3214	0.5517	0.3929	0.3214	0.3571	0.3103	0.4643	0.6786
10	0.2500	0.4828	0.2857	0.2500	0.1786	0.1724	0.2143	0.4643
11	0.2500	0.3793	0.2500	0.2143	0.1429	0.1034	0.1429	0.3571
12	0.1786	0.3103	0.1786	0.1786	0.0357	0.0690	0.1071	0.3571
13	0.1429	0.2414	0.1786	0.1786	0.0357	0.0345	0.0714	0.3214
14	0.1429	0.2069	0.1071	0.1429	0.0357	0.0345	0.0714	0.2857
15	0.1429	0.2069	0.1071	0.1429	0.0357	0.0345	0.0357	0.2857
16	0.1071	0.2069	0.1071	0.1071	0.0000	0.0000	0.0000	0.2500
17	0.1071	0.2069	0.1071	0.1071	0.0000	0.0000	0.0000	0.2143
18	0.1071	0.2069	0.1071	0.1071	0.0000	0.0000	0.0000	0.2143
19	0.1071	0.2069	0.1071	0.1071	0.0000	0.0000	0.0000	0.2143
20	0.1071	0.1724	0.1071	0.1071	0.0000	0.0000	0.0000	0.2143
21	0.1071	0.1724	0.1071	0.1071	0.0000	0.0000	0.0000	0.2143
22	0.1071	0.1724	0.1071	0.1071	0.0000	0.0000	0.0000	0.2143
23	0.1071	0.1724	0.1071	0.1071	0.0000	0.0000	0.0000	0.2143
24	0.1071	0.1724	0.1071	0.1071	0.0000	0.0000	0.0000	0.2143

Table B-24 Expected Number of SAM-1 Launchers Mission Capable

	ALTERNATE FORCE ARCHITECTURES							
TIME (HRS)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
0	20	20	20	20	20	20	20	20
1	1.5714	1.1724	0.0000	0.0000	2.1071	2.1379	0.0000	0.0000
2	0.1071	0.0345	0.0000	0.0000	0.3928	0.2069	0.0000	0.0000
3	0.0000	0.0000	0.0000	0.0000	0.0357	0.0345	0.0000	0.0000
4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table B-25 Expected Number of ACFT-1 Mission Capable

	ALTERNATE FORCE ARCHITECTURES							
TIME (HRS)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
0	40	40	40	40	40	40	40	40
1	19.1786	18.7241	18.1429	18.6071	19.7500	18.2414	19.1429	17.2143
2	6.9286	6.9655	6.9286	6.9285	6.9286	6.8966	7.0000	6.8929
3	0.0000	0.0000	0.0000	0.0000	0.0357	0.0000	0.0000	0.0000
4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table B-26 Expected Number of ACFT-2 Mission Capable

	ALTERNATE FORCE ARCHITECTURES							
TIME (HRS)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
0	10	10	10	10	10	10	10	10
1	7.0000	7.0345	7.0000	7.0000	7.0000	7.0000	7.0000	7.0357
2	5.0357	5.0345	5.0000	5.0000	5.0000	5.0345	5.0000	5.0000
3	2.4286	2.4483	2.3571	2.3929	2.5357	2.3448	2.2143	2.2143
4	0.0357	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table B-27 Expected Number of ACFT-3 Mission Capable

3. Miscellaneous Analysis

d. Targeting Distributions

In order to determine the probability of a given friendly platform being targeted by a specific threat, the team had to determine which threats would be a factor to which friendly platforms. This also helped to scope and bound the EXTEND modeling effort. Through subject matter expert inputs it was determined that the following assumptions applied with respect to targeting:

- ASCMs are a threat to the ships that make up the Sea Base and Sea Base protection force
- DWs are a threat to the surface-based transport assets of the Sea Base, specifically when they in the vicinity of the beach
- SAMs are a threat to the air transport assets of the Sea Base, specifically when they are in the vicinity of the objective

The team then determined what was the defining characteristic of the targeted platform that would determine the targeting distribution. Using the work completed by the Summer Quarter 2003 Joint Campaign Analysis course, OA4602, relative size and number of platforms would be the best predictor of the targeting distribution.

(1) ASCM Targeting

For the ships of the Sea Base, the applicable measure of relative size was determined to be displacement. In order to normalize the size, a relative size factor was computed for each class of ship by comparing it to the smallest ship class in the force. This relative size factor was then multiplied by the number ships by class to determine a density. This density was divided by the sum of the densities to determine the probability of being targeted by an ASCM.

Because the team developed two force compositions for the force protection force, the calculations had to be computed for both COA A and COA B. COA A is a CG, DDG, and FFG-based protection force, while COA B is a LCS-based protection force.

After determining the probabilities of being targeted by an ASCM, the team realized that the probability was artificially high for the ExWar ship due to its size. Subject matter expert opinion was again applied that accounted for the proximity to the threat. These new corrected probabilities of being targeted were then used in the EXTEND model.

Table B-28 and Table B-29 contain the targeting distribution data for COA A and COA B, respectively.

COA A	**Displacement (tons)**					
Class		**Relative Size**	**Number of Units**	**Number Multiple**	**Probability of Target**	**Corrected Probability of Target**
ExWar	86000	21.0	6	125.9	0.883	0.5
CG	9600	2.3	3	7.0	0.049	0.175
DDG	9200	2.2	3	6.7	0.047	0.175
FFG	4100	1.0	3	3.0	0.021	0.15
SUM	108900			142.6	1	1
Min	4100					

Table B-28 ASCM Targeting Distribution for COA A

COA B	**Displacement (tons)**					
Class		**Relative Size**	**Number of Units**	**Number Multiple**	**Probability of Target**	**Corrected Probability of Target**
ExWar	86000	26.1	6	156.4	0.898	0.5
CG	9600	2.9	1	2.9	0.017	0.06
DDG	9200	2.8	1	2.8	0.016	0.06
LCS	3300	1.0	12	12.0	0.069	0.38
SUM	108100			174.1	1	1
Min	3300					

Table B-29 ASCM Targeting Distribution for COA B

(2) DW Targeting

For the surface transport assets of the Sea Base, the applicable measure of relative size was determined to be displacement. In order to normalize the size, a relative size factor was computed for each type of transport by comparing it to the smallest transport in the force. This relative size factor was then multiplied by the number transports expected to be in the vicinity of the beach at any one time to determine a density. This density was divided by the sum of the densities to determine the probability of being targeted by a DW.

Table B-30 contains the targeting distribution data for DWs.

					Number Multiple	**Probability of Target**
Type	**Displacement (tons)**	**Relative Size**	**Number of Units**	**Max Number on the Beach**	**Max Number on the Beach**	**Max Number on the Beach**
LCU R	1078	28.9	12	6	173.6	0.535
HLCAC	300	8.1	18	12	96.6	0.298
AAAV	37.25	1.0	108	54	54.0	0.167
SUM	1415.25				324.3	1
Min	37.25					

Table B-30 DW Targeting Distribution

(3) SAM Targeting

For the aircraft of the Sea Base, the applicable measure of relative size was determined to be plan form area. In order to normalize the size, a relative size factor was computed for each type of aircraft by comparing it to the smallest aircraft in the force. This relative size factor was then multiplied by the number transports expected to be in the vicinity of the objective or LZ at any one time to determine a density. This density was divided by the sum of the densities to determine the probability of being targeted by a SAM.

Table B-31 contains the targeting distribution data for SAMs.

	Plan Form Area (ft^2)				**Number Multiple**	**Probability of Target**
Type		**Relative Size**	**Number of Units**	**Max Number at LZ**	**Max Number at LZ**	**Max Number at LZ**
LRHLAC	10780.2	6.7	36	6	39.9	0.401
MV-22	4777.3	2.9	84	14	41.3	0.415
JSF	1620.0	1.0	36	8	8.0	0.080
AH-1	2784.0	1.7	24	6	10.3	0.104
SUM	17177.5				99.5	1
Min	1620.0					

Table B-31 SAM Targeting Distribution

b. Probability of Single Hit Mission Kill

In order to determine the probability of a single hit mission kill of a given friendly platform, expert opinion was used to divide the platforms up by vital and non-vital areas. Ships and surface based transport assets were further divided by above the water line and below the line. Examples of this work are shown in Figure B-2 and Figure B-3. A percentage was determined by dividing the vital area by the overall area of the platform.

After the percentages of vital area were determined, expert opinion was applied to each platform and its possible threats to determine an overall probability of single hit mission kill. In some cases, the probability of single hit mission kill was determined to be the same as the percentage of vital area, and in other cases it was determined that a single hit from a given threat would result in a mission kill. This data was previously presented in Table B-8 and Table B-11.

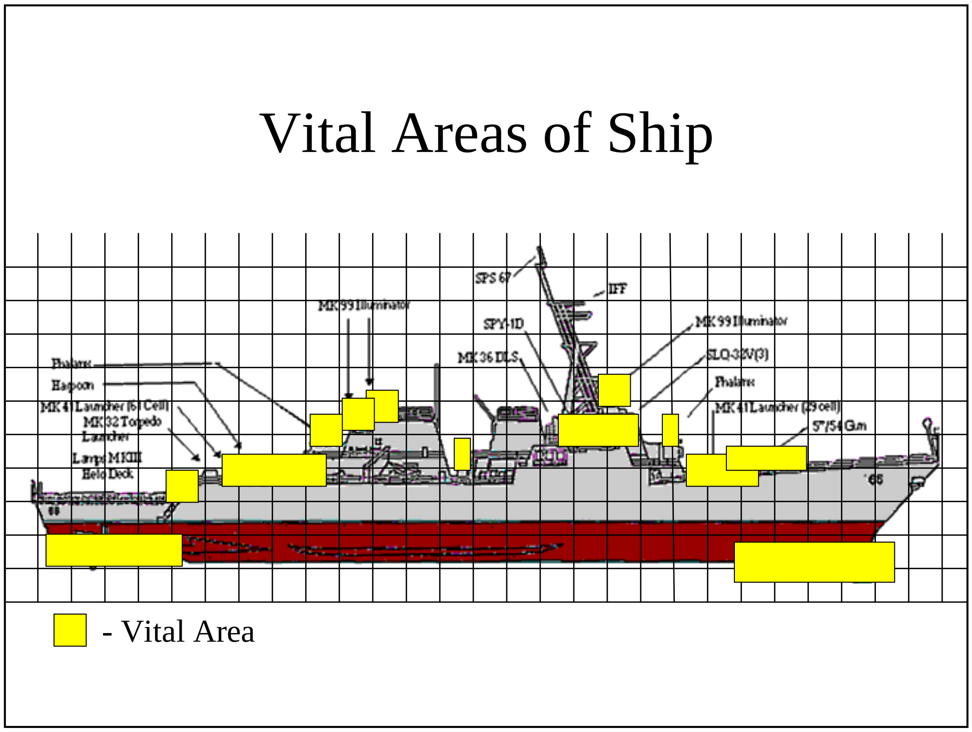

Figure B-2 Example Vital Area Distribution of a Ship

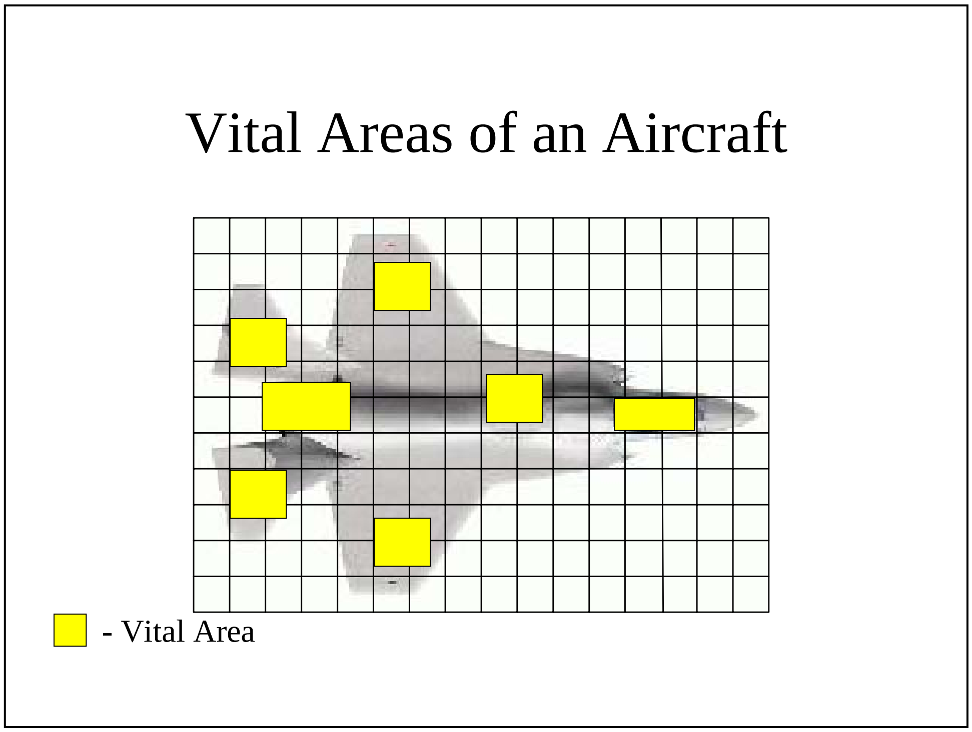

Figure B-3 Example Vital Area Distribution of an Aircraft

LIST OF ACRONYMS AND ABBREVIATIONS

AAA	Anti-Aircraft Artillery
AAAV	Advanced Amphibious Assault Vehicle
AAW	Anti-Air Warfare
ACFT	Aircraft
ARG	Amphibious Ready Group
ASCM	Anti-Ship Cruise Missile
ASM	Anti-Ship Missile
AW	Air Warfare
C4I	Command, Control, Communications, Computers, and Intelligence
CBRNE	Chemical, Biological, Radiological, and Nuclear Effects
CES	Cooperative Engagement Strategy
CNO	Chief of Naval Operations
COA	Course of Action
CONUS	Continental United States
COP	Common Operational Picture
COTS	Commercial Over The Shelf
CRANK	Cooperative Radar Network
CSG	Carrier Strike Group
DOD	Department of Defense
DW	Dumb Weapon
EA	Electronic Attack
ECE	Electrical Computer Engineering
EINSTein	Enhanced ISAAC Neural Simulation Toolkit
EMW	Expeditionary Maneuver Warfare
ERG	Electromagnetic Rail Gun

ERGM	Extended Range Guided Munitions
EW	Electronic Warfare
FEL	Free-Electron Laser
GCE	Ground Combat Element
HDT	High Density Threat
HETF	High Explosive Timed Fuse
HLAC	Heavy Lift Aircraft
HLCAC	Heavy Lift Landing Craft Air Cushioned
HQ	Headquarters
HSB	High Speed Boat
HSV	High Speed Vessel
HVU	High Value Unit
IA	Information Assurance
IAAM	Information Assurance Analysis Model
IOC	Impact on Operational Capability
IPT	Integrated Project Team
IR	Infrared
IRC	Impact on Resource Costs
IRDM	Infrared Dual Mode Enable
IS	Information Systems
ISAAC	Irreducible Semi-Autonomous Adaptive Combat
JANUS	Joint Army Navy Uniform Simulation
JSF	Joint Strike Fighter
JTLS	Joint Theater Level Simulation
KETF	Kinetic Explosive Timed Fuse
LAV	Light armored vehicles
LCAC	Landing Craft Air Cushion

LCS	Littoral Combat Ship
LCU(R)	Landing Craft Utility (Replacement)
LMSR	Large Medium-Speed Roll-on/Roll-off
LRHLAC	Long Range Heavy Lift Aircraft
MAGTF	Marine Air Ground Task Force
MAV	Micro-Air Vehicle
MEB	Marine Expeditionary Brigade
MEU	Marine Expeditionary Unit
MOE	Measure of Effectiveness
MSSE	Master of Science in Systems Engineering
NESG	Naval Expeditionary Strike Group
NGFS	Naval Gun Fire Support
NM	Nautical Miles
NPS	Naval Postgraduate School
NSS	Naval Simulation System
OMFTS	Operational Maneuver From the Sea
OPNAV N7	Office of the Deputy Chief of Naval Operations
OR	Operations Research
OTH	Over-the-Horizon
POA&M	Plan of Action and Milestones
RF	Radio Frequency
SAM	Surface-to-Air Missile
SB	Small Boat
SEA	Systems Engineering and Analysis
SEAD	Suppression of Enemy Air Defenses
SEI	Systems Engineering and Integration
SEMP	Systems Engineering and Management Process

STAMRA	Single Transmitter Multiple Receiver Arrangement
STOM	Ship to Objective Maneuver
STOVL	Short Take-Off and Vertical Landing
SUB	Submarine
SUW	Surface Warfare
TBMD	Theater Ballistic Missile Defense
TF	Task Force
TORP	Torpedo
TSSE	Total Ships System Engineering
UAV	Unmanned Aerial Vehicle
UCAV	Unmanned Combat Aerial Vehicle
UN	United Nations
USMC	United States Marine Corps
USV	Unmanned Surface Vehicle
USW	Undersea Warfare
UUV	Unmanned Underwater Vehicle
UV	Unconventional Vessel
VTOL	Vertical Takeoff and Landing
WC	Water Camouflage

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