NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

SYSTEMS ENGINEERING CAPSTONE REPORT

VIABILITY OF MEDIUM-SIZED UNMANNED SURFACE VEHICLES TO PROTECT SURFACE ACTION GROUPS AGAINST ANTI-SHIP CRUISE MISSILES

by

Alex J. Clark, Nathaniel E. Deascentis, Joel M. Hammen,
Jonathan P. Logan, Layna Nelson, Kimberly T. Pullen, and
Darren B. Robertson

June 2019

Advisor:	Gregory A. Miller
Co-Advisor:	John T. Dillard

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** June 2019	**3. REPORT TYPE AND DATES COVERED** Systems Engineering Capstone Report

4. TITLE AND SUBTITLE VIABILITY OF MEDIUM-SIZED UNMANNED SURFACE VEHICLES TO PROTECT SURFACE ACTION GROUPS AGAINST ANTI-SHIP CRUISE MISSILES	**5. FUNDING NUMBERS**
6. AUTHOR(S) Alex J. Clark, Nathaniel E. Deascentis, Joel M. Hammen, Jonathan P. Logan, Layna Nelson, Kimberly T. Pullen, and Darren B. Robertson	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.	**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

This report describes equipping medium-sized unmanned surface vehicles and integrating them with surface action groups to improve defense against anti-ship cruise missile threats. Requirements for air search radar, electronic warfare, soft-kill deception countermeasure, surface-to-air missile, and close-in weapons systems are generated and allocated to physical components. Requirements for supporting subsystems, such as an integrated combat system and communications, electrical power, cooling, hydraulics, positioning, navigation, and timing systems, are also identified. The unmanned surface vehicle's ability to extend sensor and weapons coverage for the surface action group is explored via modeling and simulation. The report presents quantitative analysis that employing unmanned surface vehicles equipped with systems to detect anti-ship cruise missile threats and soft-kill and hard-kill threat response options offers surface action groups a defensive advantage against those threats.

14. SUBJECT TERMS unmanned surface vehicle, sea hunter, anti-air, kill chain, ACTUV, USV, MUSV, SAG, EW, ASCM, AAW	**15. NUMBER OF PAGES** 151
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

VIABILITY OF MEDIUM-SIZED UNMANNED SURFACE VEHICLES TO PROTECT SURFACE ACTION GROUPS AGAINST ANTI-SHIP CRUISE MISSILES

LT Alex J. Clark (USN), Nathaniel E. Deascentis, LT Joel M. Hammen (USN),
Jonathan P. Logan, Layna Nelson, Kimberly T. Pullen,
and LT Darren B. Robertson (USN)

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
June 2019

Lead Editor: Joel M. Hammen

Reviewed by:	
Gregory A. Miller	John T. Dillard
Advisor	Co-Advisor

Accepted by:
Ronald E. Giachetti
Chair, Department of Systems Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

This report describes equipping medium-sized unmanned surface vehicles and integrating them with surface action groups to improve defense against anti-ship cruise missile threats. Requirements for air search radar, electronic warfare, soft-kill deception countermeasure, surface-to-air missile, and close-in weapons systems are generated and allocated to physical components. Requirements for supporting subsystems, such as an integrated combat system and communications, electrical power, cooling, hydraulics, positioning, navigation, and timing systems, are also identified. The unmanned surface vehicle's ability to extend sensor and weapons coverage for the surface action group is explored via modeling and simulation. The report presents quantitative analysis that employing unmanned surface vehicles equipped with systems to detect anti-ship cruise missile threats and soft-kill and hard-kill threat response options offers surface action groups a defensive advantage against those threats.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

ACTUV	ASW continuous trail unmanned vessel
AESOP	Afloat Electromagnetic Spectrum Operations Program
ASCM	anti-ship cruise missile
ASW	anti-submarine warfare
BLOS	beyond line of sight
CEC	Cooperative Engagement Capability
CIWS	close-in weapons system
COI	contact of interest
COLREGs	International Regulations for Preventing Collisions at Sea
CONOPS	concept of operations
COTS	commercial off-the-shelf
CSG	carrier strike group
DARPA	Defense Advanced Research Projects Agency
DRM	design reference mission
EA	electronic attack
EASR	Enterprise Air Surveillance Radar
ES	electronic support
ESSM	Evolved Sea Sparrow Missile
EW	electronic warfare
F2T2EA	find, fix, track, target, engage, assess
FSC	future surface combatant
GOTS	government off-the-shelf
HVU	high value unit
ICS	integrated combat system
ISR	intelligence, surveillance, and reconnaissance
LOS	line of sight
MCM	mine countermeasures
MDUSV	medium displacement unmanned surface vehicle

MIO	maritime interdiction operations
MS	maritime security
NM	nautical miles
ONR	Office of Naval Research
PEO	program executive office
PEO LMW	Program Executive Office for Littoral and Mine Warfare
PEO USC	Program Executive Office for Unmanned and Small Combatants
PMS 406	Program Office for Unmanned Maritime Systems
SAG	surface action group
SAM	surface-to-air missile
SCO	Strategic Capabilities Office
SEWIP	Surface Electronic Warfare Improvement Program
SRBOC	Super Rapid Bloom Offboard Countermeasures
SM	Standard Missile
SOF	special operations forces
SUW	surface warfare
SWaP	size, weight, and power
SYLVER	SYstème de Lancement VERtical
TALONS	Towed Airborne Lift of Naval Systems
TDL	tactical data link
TEWA	threat evaluation and weapon assignment
UAV	unmanned aerial vehicle
UHF	ultra-high frequency
UMS	unmanned maritime systems
UNCLOS	United Nations Convention on the Law of the Sea
USN	United States Navy
USV	unmanned surface vehicle
UUV	unmanned underwater vehicle
VHF	very-high frequency
VLS	Vertical Launch System

EXECUTIVE SUMMARY

Adversaries continue to develop anti-ship cruise missile (ASCM) threats. Medium-sized unmanned surface vessels (USVs) equipped with sensors to detect and systems to respond to ASCM threats could be used as added protection for manned surface units, including surface action groups (SAGs). This study identifies requirements for USVs defending SAGs in such a manner, selects relevant ASCM detection and response subsystems, and assesses the feasibility of medium-sized USVs in this ASCM defense role. Outputs from this study could be used to inform future medium-sized USV system designs and concepts of operation.

This study applies system engineering processes to meet the following study goals:

1. Determine functional requirements for ASCM detection and response subsystems onboard a future USV host platform
2. Identify real world subsystems that address those requirements
3. Identify required communications between USVs and SAG units in the ASCM defense scenario
4. Identify subsystems that meet communications requirements
5. Assess tactical utility of USVs employed in a SAG ASCM defense role
6. Assess effectiveness of potential USV formations within a SAG

Creation of a design reference mission describes the operational context, formalizes the concept of operations, and identifies ASCM threats that could reasonably be employed against units in a SAG. The following mission requirements define successful USV integration in the ASCM defense role:

1. USV use shall mitigate the probability of ASCM hit on SAG ships by defeating threats via kinetic or non-kinetic means.

2. USV use shall provide early warning and threat cueing to SAG ships, thereby increasing available reaction time and counter-fire opportunities of SAG ships from initial threat detection compared to a no-USV scenario.
3. ASCM detection and response subsystems on the USV host platform must not require the USV to be larger than medium sized.

The scenarios consider defense of a SAG in an open ocean environment in conditions of a sea state of four or less. Three modern missile threats, operating at supersonic and subsonic speeds, are identified as high, medium, and low threats to the SAG. The Russian 3M-54 or SS-N-27 Sizzler is the high threat, the Chinese YJ-83 or CSS-N-8 Saccade is the medium threat, and the Chinese C-704 is the low threat. Four operational scenarios are studied, two in which the USV detects and engages the threat and two in which the USV makes detection and cues the SAG to engage the threat. The ASCM launch platform is not a consideration in this study since initial detections are assumed to occur when the missile is already in flight with no prior cueing to the SAG or USV.

USV ASCM detection subsystems are air search radar and electronic support systems. Response subsystems are soft-kill deception countermeasures, surface-to-air missiles, a close-in weapons system, and electronic attack systems. An integrated combat system is required to translate and pass tactical data between the USV subsystems and units in the SAG. Requirements for the subsystems to be integrated are defined, and potential subsystems are evaluated against requirement criteria using publicly available data. Size, weight, power, interoperability, and compatibility concerns, along with additional communications requirements, are evaluated to ensure the design is feasible. The best fit subsystems are selected for inclusion into a notional prototype system.

The best fit detection subsystems selected are:

1. Enterprise Air Search Radar Variant 2
2. Surface Electronic Warfare Improvement Program Block 3

The best fit response subsystems selected are:

1. Centurion countermeasure launcher
2. Evolved Sea Sparrow Missile Block 2 launched by Mk 29 Guided Missile Launching System
3. Phalanx Close-in Weapons System
4. Surface Electronic Warfare Improvement Program Block 3

Potential communications systems include very-high frequency and ultra-high frequency radios, tactical data links, and Cooperative Engagement Capability. Line of sight methods between the USV and SAG are preferred when possible.

A Markov kill chain model uses data from the previous steps of the process to assess the tactical utility of a USV employed in the SAG ASCM defense role. This model, developed in Microsoft Excel, uses a chain of intermediate states and associated probabilities for each state transition to determine success rates for USV engagements against incoming ASCM threats. Assessments of an incoming threat flying directly overhead of the USV and a threat incoming off axis, closer to the maximum USV detection range, are performed to determine relative success of USV engagements in the scenario. Results from these two situations show that utilization of the USV as a weapon platform can significantly mitigate the probability of ASCM hits on SAG units.

The utility of the USV as an early warning sensor for cueing SAG counter-fire is explored using a time-distance analysis model created in Microsoft Excel. This model assesses variations of a single USV placed directly on the incoming missile threat axis and off axis such that the inbound threat is identified tangential to its maximum detection radius. These scenarios represent the maximum and minimum benefits for early warning detection times. Assessments for each threat missile are conducted, and the relationships between the USV and SAG detection range rings as a function of radar antenna height and USV-SAG spacing are explored. The early detection times for high, medium, and low threat missiles are then translated into SAG counter-fire shot opportunities. Results of this analysis show there is clear benefit in utilization of the USV as an early warning platform to cue SAG units to engage incoming threat missiles.

Finally, tradeoffs associated with different USV formations around the SAG are explored using a graphical tool created in Microsoft Excel from Visual Basic for Applications coding. The tool places all the SAG units in a single position and accounts for relative USV-SAG spacing, detection range rings for threat missiles derived from USV and SAG antenna heights, and inter-USV spacing. The measures of interest are degrees of coverage in terms of the USV detection screen and total linear distance between the USVs and SAG. The total linear distance correlates to early warning time available for SAG units to respond. Two basic formations are evaluated: a linear screen where USVs form a line perpendicular to a given threat access and a radial formation around the SAG, with USVs spaced evenly. The analysis shows that as the number of USVs increases, the radial formation provides the most degrees of coverage. The linear formation, however, presents an advantage in the total linear distance and corresponding early warning detection times. Tradeoffs in these measures will have to be considered when deciding on USV stationing.

This study presents quantitative analysis that employing a USV equipped with systems to detect ASCM threats and soft-kill and hard-kill response options offers a SAG a defensive advantage against those threats. The USV is able to defeat a significant portion of inbound threats as well as offer early warning to SAG units, affording those units more counter-fire opportunities when compared to a scenario without the USV.

Additional studies are recommended and could include additional analysis on USV placement and stationing respective to SAG units, organization and design of subsystems onboard the USV, kill chain analysis of multiple USVs, the potential for reduced subsystem electrical loads, and the associated determination of electrical power generation requirements onboard the USV.

ACKNOWLEDGMENTS

The authors would like to thank the following individuals and organizations, without whom this work would not have been possible to complete.

First, we would like to especially thank our thesis advisors, Greg Miller and John Dillard, for their sound advice and guidance, numerous constructive input, and incredible patience as we developed our study.

We also thank Dr. Ronald Giachetti for providing guidance and pointing us in the right direction to find related research and develop the backbone for our modeling section.

We are incredibly grateful to the following Naval Postgraduate School faculty members who provided us with subject-matter expertise and recommendations: RDML Rick Williams (Ret), CAPT Charles Good, Brian Wood, David Trask, Dr. Rama Gehris, Matthew Boensel, and Dr. Joseph Klamo.

Thank you to the following individuals for advice, perspectives, and insights into our topic selection and project execution: William Jankowski, Carmelo Fontan, and LT John Tanalega.

For being with us from start to finish and helping with everything between, we thank Heather Hahn.

For reviewing and editing our report, we truly appreciate Barbara Berlitz as well as the Thesis Processing Office, and especially our thesis processor, Janice Long.

For allowing us time to complete this effort and for their support and commitment to our education, we would like to thank our respective organizations and commands: Helicopter Training Squadron 28, Naval Undersea Warfare Center Division Newport, Afloat Training Group Western Pacific, Undersea Warfighting Development Center, Space and Naval Warfare Systems Center Atlantic, and Center for Surface Combat Systems.

Lastly, we would like to thank our families for their love, support, encouragement, and understanding throughout this endeavor.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

A. UNMANNED SYSTEMS BACKGROUND

1. Unmanned Vehicles in the Military

Unmanned aerial, underwater, and surface vehicles allow the military to perform tasks that manned vehicles can accomplish with less risk to military personnel, provide force multiplication in order to accomplish assigned missions, and reduce costs relative to manned methods. Keane and Carr (2013) describe how current technologies—including GPS and live video feed—enable pilots to remotely control unmanned aerial vehicles (UAVs) like the Predator and Global Hawk from thousands of miles away to perform advanced operations. Blidberg (2001) asserts that unmanned underwater vehicles (UUVs) have taken a large role in the United States Navy (USN) and are now considered primary workhorses of mine hunting and clearing operations as well as bathymetry and sediment sampling operations. In 2007, the USN released the Unmanned Surface Vehicle (USV) Master Plan to guide "USV development to effectively meet the Navy's strategic planning and Fleet objectives and the force transformation goals of the Department of Defense to the year 2020" (Department of the Navy 2007, x). This document defined the following seven USV mission areas in prioritized order:

1. "Mine countermeasures (MCM)
2. Anti-submarine warfare (ASW)
3. Maritime security (MS)
4. Surface warfare (SUW)
5. Special operations forces (SOF) support
6. Electronic warfare (EW)
7. Maritime interdiction operations (MIO) support" (Department of the Navy 2007, xi).

2. Recent Unmanned Surface Vehicle Efforts

The USN collectively designates UUVs and USVs as unmanned maritime systems (UMS). The Navy's UMS efforts are led by the UMS Program Office—PMS 406—within the Program Executive Office for Unmanned and Small Combatants (PEO USC), formerly PEO for Littoral and Mine Warfare (PEO LMW). PMS 406 is chartered to "develop, acquire, deliver, and support operationally effective, integrated" UMS and to "direct UMS experimentation and technology maturation efforts to meet the Fleet's capability needs" (PEO LMW 2011, 1). To that end, PMS 406 maintains the USV system vision as presented in Figure 1. The vision shows the current Sea Hunter and Ghost Fleet USV efforts building into the mid-term to long-term goal of the Future Surface Combatant (FSC) USV. The stakeholder entities are shown across the bottom.

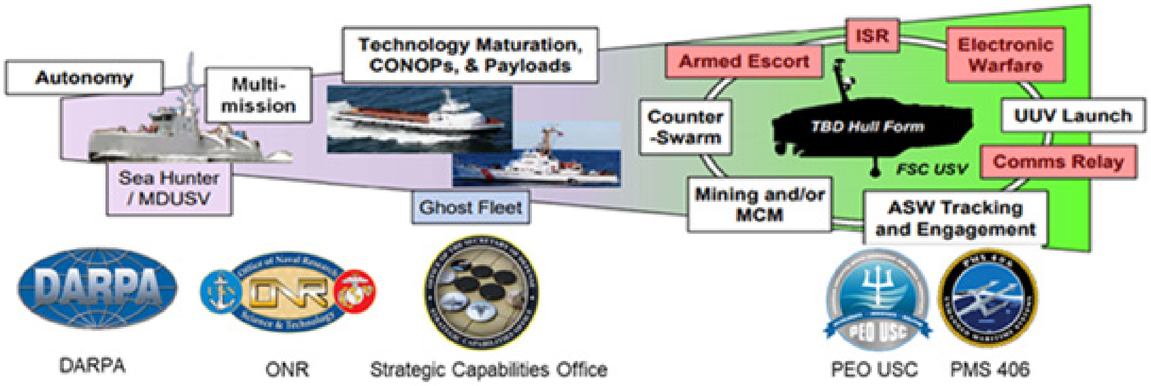


Figure 1. USV System Vision. Adapted from Rucker (2018).

In 2010, to address the 2007 USV Master Plan's ASW mission area, the Defense Advanced Research Projects Agency (DARPA) initiated the ASW Continuous Trail Unmanned Vessel (ACTUV) effort, which later became Sea Hunter and the medium displacement USV (MDUSV) when the program transitioned to the Office of Naval Research (ONR) in 2018 (DARPA 2018). It utilizes a trimaran hull and implements an autonomous navigation system that conforms to the International Regulations for Preventing Collisions at Sea (COLREGs) as well as the United Nations Convention on the Law of the Sea (UNCLOS). Additionally, autonomous ASW sensors and systems are onboard. Additional systems including DARPA's Towed Airborne Lift of Naval Systems (TALONS) project and various MCM payloads have been tested in conjunction with ACTUV sea trials, and they will continue to be tested on Sea Hunter (DARPA 2018). Sea Hunter is shown in Figure 2.

Figure 2. Sea Hunter. Source: Williams (2016).

The Ghost Fleet effort was initiated by the Secretary of Defense's Strategic Capabilities Office (SCO) in 2017. Like other SCO efforts, Ghost Fleet is a rapid prototyping effort meant to demonstrate new game-changing capability within five years and serve as a risk mitigator to transition the new capability to the appropriate service branch—in this case the USN and PMS 406 (Department of Defense 2018). The surface component of this effort is referred to as Overlord, and it is working to "convert larger, existing, manned ships into USVs over the next 3 years so that they can conduct existing missions now undertaken by manned warships" (Berkoff 2018, 38).

The FSC USV effort also originated in 2017 and is led by OPNAV N96—the Navy's director for surface warfare (Eckstein 2018). An August 28, 2018, article from the U.S. Naval Institute webpage describes the FSC goal to develop a mixed ship force structure including a large combatant similar to a destroyer, a small combatant like the littoral combat ship or the next generation frigate, and a large-sized and medium-sized USV, all with “an integrated combat system that will be the common thread linking all the platforms” (Eckstein 2018, 1).

While the Sea Hunter and Ghost Fleet efforts will be of great utility in the design of the yet-undefined hull form and specific capabilities of the FSC USV, additional studies are prudent. PMS 406 has specified the following mission areas as FSC USV areas of interest: armed escort, intelligence, surveillance, and reconnaissance (ISR), EW, UUV launch, communications relay, ASW tracking and engagement, mining and MCM, and counter-swarm against threat boat or airborne swarms (Rucker 2018). This study seeks to address the armed escort, ISR, EW, and communications relay areas of interest for the future medium-sized USV.

3. Surface Ship Missile Defense

Adversaries continue to improve their anti-ship cruise missile (ASCM) designs. These missiles range in capability from subsonic to hypersonic speeds and can be launched from land, sea (surface and subsurface), or aerial platforms. They represent a high threat from an aggressive force due to their speed and ability to exploit radar blind spots. Additionally, the U.S. and near-peer forces have developed these weapons since the early 1940s, so they are ubiquitous today.

As USVs are introduced and operate with USN and partner nation naval forces, they will be expected to play a role in increasing situational awareness for commanders. This would involve increasing the detection range of threats—such as ASCMs—from manned units beyond those units’ organic capabilities. USVs could also defend both manned units and themselves from inbound ASCMs.

B. PROBLEM STATEMENT

Adversary ASCM threats continue to evolve and present new dangers to USN ships and sailors. Methods of ASCM detection and response must evolve in parallel to pace and overcome the threat. One area for exploration is the use of USVs to augment and complement the defense of a surface action group (SAG) against ASCM threats.

C. PROJECT OBJECTIVES

The focus of this study is two-fold. First, it seeks to provide notional medium-sized USV host platform system engineering level requirements for ASCM detection and response subsystems. Medium-sized USVs are defined by the USN as having a length between 12 and 50 meters (LaGrone 2019). Focusing on the higher end of the length range, it is expected a medium-sized USV will have a maximum displacement 300 long tons, a maximum width of approximately 7.5 meters, a draft of two meters, and a maximum height above the waterline of approximately 15 meters. These values were determined by comparison against the Cyclone class patrol craft measurements, whose overall length is 51.8 meters (Pike 2011b).

Detection subsystems in this study are defined as those that perform find, fix, and track functions against ASCM threats in the find, fix, track, target, engage, and assess (F2T2EA) kill chain. This study focuses on air search radar and electronic support (ES) detection systems. Response systems are those that can target and engage via either kinetic or non-kinetic means such as counter-fire, soft-kill deception countermeasures, or electronic attack (EA).

The second focus of this study is to assess whether a notional medium-sized USV equipped with the prescribed real-world systems could be effective in the defense of a SAG against ASCM threats. This part of the study leverages operational analysis approaches to determine utility of the USV in given scenarios and involves analysis of communications paths and corresponding communications systems.

The ideas are investigated by simulating the use of USVs to increase detection range of inbound ASCM threats relative to the protected units and employ both soft-kill and hard-kill defensive countermeasures. Concepts studied would be applicable in high value unit (HVU) defense as well.

D. KEY ASSUMPTIONS

This analysis relies on three key assumptions. The first assumption—and perhaps the most critical—is that the USVs will be able to maintain station with the SAG, meaning all support needs like fuel and maintenance are met by ships in company or exceeded by the performance parameters of the USV itself and will therefore not be considered in this analysis. Second, it is assumed any Afloat Electromagnetic Spectrum Operations Program (AESOP) issues will be effectively de-conflicted. Effective management of the electromagnetic spectrum is important to prevent mutual interference, which would inhibit or restrict performance of sensors and equipment. Finally, safe recovery of the USV is assumed to be achievable in case of loss of control. Normally, the SAG commander would control the USVs remotely to coordinate changes in station and tactical responses to enemy actions. The third assumption is that in the event control of the USV cannot be maintained, communications will be reestablished quickly, or another unit will be able to tow the USV to an intermediate maintenance facility for repair.

E. SYSTEMS ENGINEERING APPROACH

1. Overview of Approach

The systems engineering process used in this study begins with an operational analysis. After threats and mission scenarios are identified via a design reference mission (DRM), system requirements are generated. The system design phase then identifies recommended ASCM detection and response subsystems and associated size, weight, and power (SWaP) requirements. Additional communications requirements are then evaluated based on selected subsystem and operational requirements. These are used to finalize the proposed USV configuration and required communications pathways. Finally, this configuration is used in simulations of the threat scenarios to evaluate the utility for using USVs to aid in ASCM defense of the manned units. The complete systems engineering process is depicted in Figure 3.

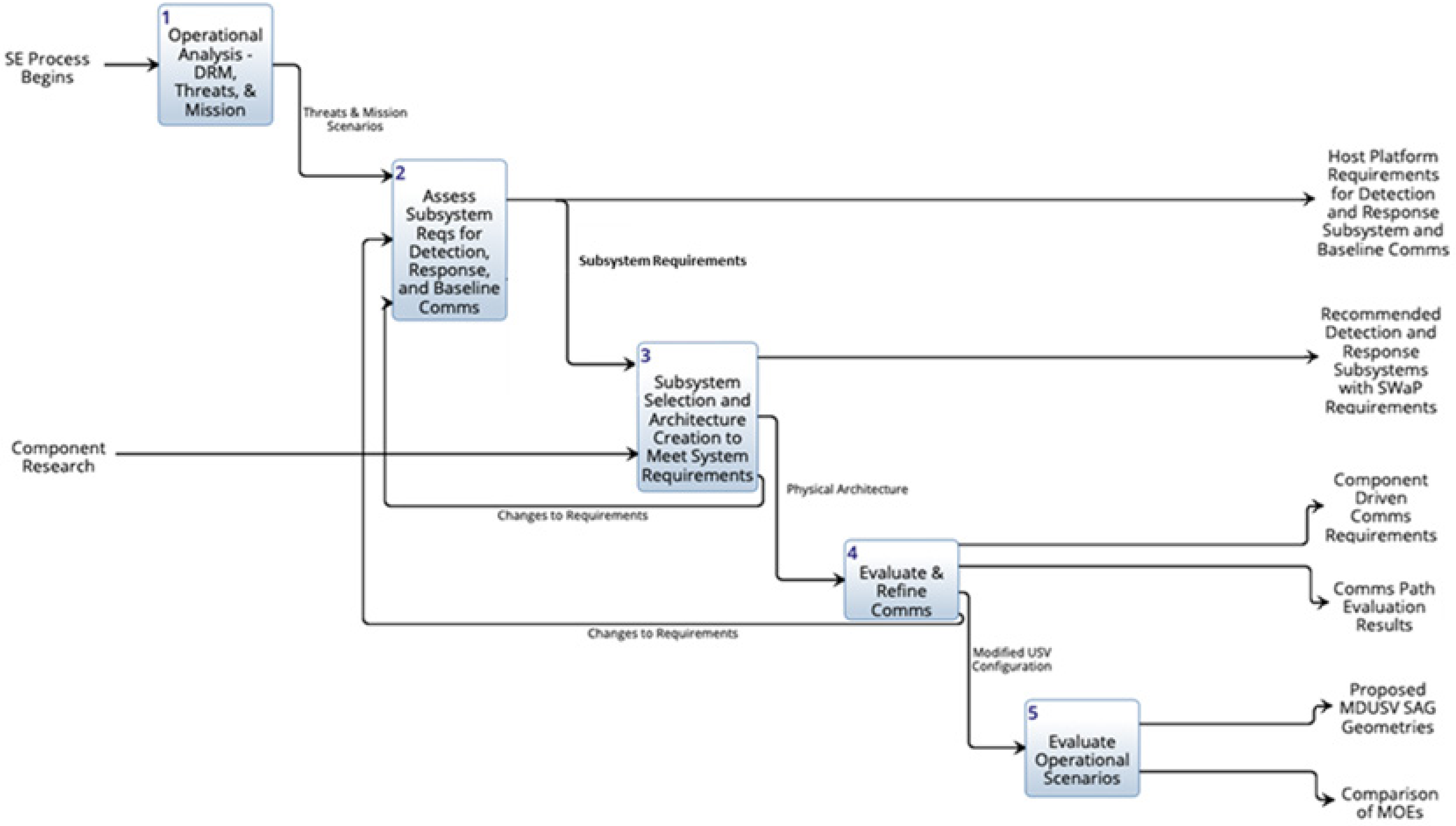


Figure 3. System Engineering Process for the Study

2. Detailed Description of Approach

During the operational analysis phase, a DRM is developed to produce multiple scenarios where the USV is positioned differently relative to the rest of the SAG, projected operating environments, mission definitions, threats, and measures. Enemy threats identified in this phase help determine required countermeasures. Threats and mission definitions are used for requirements generation in the following phase.

In the subsystem requirements generation phase, functional system requirements and baseline communications requirements for the USV detection and response subsystems are identified based on outputs from the DRM. Response systems are those that can defeat incoming ASCM threats (via soft-kill or hard-kill means). After this process, subsystem requirements are sent to the design phase. Once the engineering process is complete, these requirements become an output of the study as proposed host platform requirements.

During the subsystem selection and architecting phase, current commercial off-the-shelf (COTS) and government off-the-shelf (GOTS) detection and response subsystems are researched and compared, to include SWaP requirements of the potential subsystems. The subsystems most appropriate for use on a medium-sized USV are selected, and system requirements are allocated to those components. A proposed physical architecture for the USV system is also identified, based on the chosen subsystems. These are collected as study deliverables for use in future USV platform design considerations. Any additional requirements identified during this phase are used as feedback to the system requirements phase. This includes ensuring selected systems are compatible with and do not interfere with each other (or interference is able to be deconflicted). The outputs of this phase are recommended detection and response subsystems with associated SWaP requirements.

The fourth step in the process is to evaluate additional communications requirements. Based on the selected detection and response subsystems, the team identifies any derived communications requirements needed beyond the baseline requirements and assesses if they are viable. If the new communications requirements are not viable, the subsystem requirements are updated, and the team proposes how they could be implemented by alternative future communications systems. The proposed USV configuration is sent to the next phase of this process. The outputs of this phase also include component driven communications requirements and the results of the communications path evaluation.

The final phase of the process is to evaluate operational scenarios. An analysis of modeled scenarios is performed to determine the utility of the USV launching and emitting counter-fire effects in the ASCM defense mission, determine the tactical utility of the USV as a cueing platform for SAG organic defense, and to inform discussion on various USV geometries around the SAG.

THIS PAGE INTENTIONALLY LEFT BLANK

II. DESIGN REFERENCE MISSION

A. DESIGN REFERENCE MISSION INTRODUCTION AND OBJECTIVE

This study utilizes the DRM process, described by Skolnick and Wilkins (2000) as characterizing the operating and threat environment in addition to defining requirements. It also serves as a baseline to support concept development, trade study analysis, design, and test and evaluation activities (Skolnick and Wilkins 2000). In this study, the DRM initial outputs are baseline operational assumptions and mission context. These initial outputs are then used to produce operational requirements and scenarios that lay the foundation for further systems analysis and systems engineering activities.

This DRM has been conducted to support analysis of the feasibility of employing USVs in the defense of a SAG from enemy ASCMs. To protect the SAG, the USV is required to independently detect and counter inbound ASCM threats and cooperatively engage with the SAG. The USV will serve as a screening vessel to mitigate the probability of ASCM hits on SAG ships. This screening tactic is intended to provide the SAG additional reaction time versus ASCM threats by way of cueing and also affords the USV the chance to engage and remove the ASCM threat while it is inbound to the SAG. To operate cooperatively with the SAG, it is assumed the USV can achieve and maintain required speed to remain on station and will not have issues with on-station endurance. Cooperative engagement with SAG includes the ability of the SAG ships to execute traditional command and control of the USVs and execute counter ASCM measures based on USV cueing in a distributed lethality context.

The DRM includes operational situations (OPSITS) that describe notional scenarios where the USV is defending a SAG from ASCM threats to serve as a basis for the analysis. The DRM highlights the importance of the USV’s detection and response subsystems in our OPSITs. Each of these subsystems must be able to interact with one another onboard the USV and pass information—including target tracks and subsystem health and status messages—back to systems and operators in the SAG. These USV subsystems must also be responsive to SAG command signals and remote control.

B. MISSION BACKGROUND

Technological advancements in ASCMs make detecting and defeating them increasingly challenging. Advanced guidance systems enable ASCMs to hit targets with excellent accuracy, and various stealth methods are employed to limit detectability. ASCMs can be launched from surface ships, submarines, aircraft, and land-based platforms. Due to the diversity of the threat, ASCM defense options for friendly surface units must be continuously developed and improved.

Analysis of ASCM effectiveness and corresponding ASCM defense effectiveness and methodologies is readily available. This study leverages and builds upon the kill-chain analysis framework of Smith (2010) because his research deals specifically with surface ship defense against ASCMs and the "formidable layered defense of a target ship to include hard kill and soft kill measures" (Smith 2010, v).

Ship defense against ASCMs involves using EW or kinetic means to distract, jam, and destroy the threat. Specifically, countermeasures to ASCMs include both long-range and short-range surface-to-air missiles (SAMs), close-in weapons systems (CIWS), radio frequency jamming, electro-optical/infrared jamming, and use of deception such as decoys, flares, and chaff to seduce the missile away from its intended target (Smith 2010).

C. OPERATIONAL CONTEXT AND PROJECTED ENVIRONMENT

1. Scenario Overview

This scenario encompasses a blue SAG supported by forward positioned USVs. The ships are operating in an open ocean environment with no impediments to maneuvering. Should an ASCM be launched at friendly units, maneuvering for unit self-defense and self-preservation will be the priority over any territorial waters or politically sensitive area restrictions, so those are not a concern in the simulations. The ships will be steaming under a condition III watchbill, with no prior threat indications from intelligence sources. There are no environmental threat conditions, such as excessive winds or sea state. The environment is assumed to be communications permissive (communications are not degraded or denied). The SAG and USVs can communicate via line of sight (LOS) or beyond line of sight (BLOS) communications systems. Friendly forces are equipped with both soft-kill and hard-kill countermeasures.

Concentrating on an open ocean environment, an air or surface launched ASCM is most likely going to be utilizing over the horizon targeting. The ASCM threats are therefore assumed to have been launched from sanctuary and beyond SAG detection capabilities. Friendly forces will first identify threats on organic sensors onboard the USVs or the SAG ships. Given the short decision space and response times required in this scenario, the USV operations must be under control of the SAG and not dependent on outside operational control.

Ideally, the USV will increase the range at which the threat ASCM is detected relative to the SAG, allowing the SAG to have more decision time and space to react from initial threat detection when compared to a scenario without the USV. The USV and SAG would be communicating as described above by LOS communications or BLOS communication via a communications relay. Both the SAG and USV will be able to respond to the threat with soft-kill and hard-kill options. This notional operational picture is shown in Figure 4.

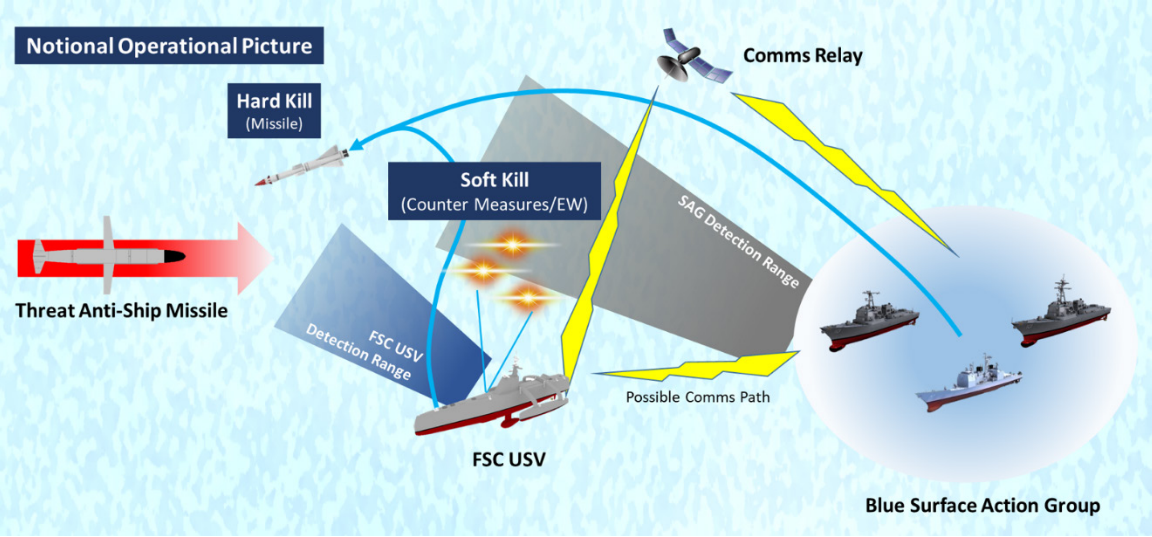


Figure 4. Notional Operational Picture

The specific scenario developed for use in the simulation for the low and medium threat ASCMs is as follows: a conflict over territorial rights in the South China Sea between naval forces from the People's Republic of China and a U.S. ally has resulted in open conflict. A SAG and three medium-sized USVs have been sent from Yokosuka, Japan to the area of conflict. The SAG consists of one Ticonderoga class cruiser and two Arleigh Burke class destroyers. While in transit in unrestricted waters, at 0815 local time, the American units are intercepted by Chinese strike aircraft equipped with ASCMs.

For the high threat ASCM, the scenario is as follows: a conflict over territorial rights in the Pacific Ocean between naval forces from the Russian Federation and a U.S. ally has resulted in open conflict. A SAG and three medium-sized USVs have been sent from Yokosuka, Japan to the area of conflict. The SAG consists of one Ticonderoga class cruiser and two Arleigh Burke class destroyers. While in transit in unrestricted waters, at 0815 local time, the American units are intercepted by Russian strike aircraft equipped with ASCMs.

2. Environmental Conditions

For this study, attacks will be limited to the following environmental conditions, which were derived based on the normal operating conditions and operational limitations of shipboard equipment and personnel:

1. Daytime
2. Air temperature from 0–50 degrees C
3. Water temperature from 2–35 degrees C
4. No ice or snow
5. Light or no precipitation
6. Winds less than 30 knots
7. Sea state correlating to no greater than 4 on the Beaufort Wind Force Scale (wave heights of 1–2 meters with occasional white caps)

8. Effects of currents and set and drift neglected (no significant effect on ship's performance in a tactical situation, given the described scenario and environment)

9. No excessive haze or dust that could limit communications capabilities

10. No other communications limitations (all pathways available)

3. Threat Details

Three adversary ASCMs have been selected for this analysis and categorized into threat levels of low, medium, and high. Threat baselines were determined by analyzing missile speed, payload, and range. The threats were selected based on missile operational history, capabilities, and operators (these weapons could also be launched from a different country given weapons proliferation).

The Chinese C-704 is identified as the low threat. It is subsonic and can be launched from ships or aircraft (Jane's by IHS Markit 2018c, 2018d). The Chinese YJ-83 (also known as the CSS-N-8 Saccade) is identified as the medium threat. It is subsonic and can be launched from ships, ground units, or aircraft (Jane's by IHS Markit 2018f, 2018h). The Russian 3M-54 (also known as the SS-N-27 Sizzler) is identified as the high threat. It can be launched from submarines, ships, or aircraft, depending on the variant (Jane's by IHS Markit 2018e). This missile is subsonic while in the cruise phase, and then deploys a terminal supersonic missile to attack its target (Jane's by IHS Markit 2018a). Figures 5 through 7 display the selected ASCMs. The threat missiles have a wide variety of maximum ranges, from 38 to 660 kilometers, and the warheads range from 130 to 400 kilograms of high explosive (Jane's by IHS Markit 2018a, 2018c, 2018d, 2018e, 2018f, 2018h). Table 1 displays the characteristics of the ASCMs.

Figure 5. Low Threat: C-704. Source: Hewson (2010).

Figure 6. Medium Threat: YJ-83 and Export Variant. Source: Carlson (2013).

Figure 7. High Threat: 3M-54. Source: Kopp (2012).

Table 1. Threat Missile Characteristics. Adapted from Jane's by IHS Markit (2018a, 2018c, 2018d, 2018e, 2018f, 2018h).

Missile	**C-704**	**CSS-N-8 Saccade; YJ-83**	**SS-N-27 Sizzler; 3M-54**
Threat	Low	Medium	High
Country of Origin	China	China	Russia
Launch Vehicle	Ship, Air(C-704KD)	Ground, Ship, Air(YJ-83K)	Submarine, Ground, Ship, Air(3M-54AE)
Range	38km; 50km (air-launch)	180km; 200km (air-launch)	220-275km; 300km (air-launch); 660 km(submarine launch)
Speed	Subsonic; Mach 0.875	Subsonic; Mach 0.9	Supersonic; Mach 0.8 (cruise); Mach 2.9 (terminal)
Seeker Type	NATO K band active homing; dual band IR (air launch)	NATO I band active homing	active homing (band not specified)
Warhead	130 kg high explosive	165 kg high explosive	200 or 400 kg high explosive (depending on variant)

Note: Data displayed in this table was gathered from various pages on https://janes.ihs.com as accessed through the Naval Postgraduate School login (https://janes.ihs.com.libproxy.nps.edu).

D. MISSION AND MEASURES

1. Mission Success Requirements

Three high level operational and host platform design requirements that form the basis for the detection and response subsystem requirements were identified:

1. USV use shall mitigate the probability of ASCM hit on SAG ships by defeating threats via kinetic or non-kinetic means.

2. USV use shall provide early warning and threat cueing to SAG ships, thereby increasing available reaction time and counter-fire opportunities of SAG ships from initial threat detection compared to a no-USV scenario.

3. ASCM detection and response subsystems on the USV host platform must not require the USV to be larger than medium sized.

Based on these mission requirements, three scenarios were identified where USV integration with SAGs would be considered successful: all three requirements met, requirements 1 and 3 met, or requirements 2 and 3 met. Thus, the USV must remain medium sized in all scenarios. Further, the USV must defeat inbound ASCM threats or provide early warning and threat cueing to the SAG, or both.

2. OPSIT Definitions

The OPSITs describe notional scenarios where the USV is defending a SAG from ASCM threats. For the low and medium threat scenarios, the Chinese strike force consisting of eight aircraft armed with C-704s and YJ-83s approaches the SAG and launches their missiles. For the high threat scenario, the Russian strike force consisting of eight aircraft armed with 3M-54s approaches the SAG and launches their missiles. In all scenarios, the SAG is on course 225° true with the USV positions varying depending on OPSIT. Seas are calm at a sea state of two. Ambient air temperature is 22° Celsius with 50% humidity, producing a small evaporative duct height of two meters. This slightly increases the maximum detection range of air search radars when compared to an environment without evaporative ducting.

a. OPSIT 1 – USVs Fire on Inbound ASCMs

In OPSIT 1, the USVs are steaming in formation with the SAG, positioned between the SAG and the inbound missiles. The USVs either detect the threat or are cued where to search from the ships. The USVs deploy response options.

(1) Sub OPSIT 1A – USV Off the Threat Axis

In this sub OPSIT, the USVs are not directly between the threat and the SAG and are positioned to detect threats near their maximum detection range.

(2) Sub OPSIT 1B – USV On the Threat Axis

In this sub OPSIT, the USVs lie directly between the threat and the SAG such that the threat missiles pass directly overhead of the USV.

b. OPSIT 2 – Untargeted USV Detects Inbound ASCM and Cues SAG

In OPSIT 2, the SAG ships are targeted, and the USVs remain undetected or untargeted. The USVs are positioned between the SAG and the inbound missiles and are able to pass track data to the SAG ships to increase the available response time from initial threat detection for the SAG ships to deploy their own response options.

(1) Sub OPSIT 2A – USV Off the Threat Axis

In this scenario, the USVs are not directly between the threat and the SAG and are positioned to detect threats tangential to their maximum detection range. The USVs receive the initial indications of threat missiles via their onboard air search radar or ES systems, gain track of the ASCM(s) quickly, and pass the track data to the SAG, cueing the SAG's self-defense responses.

(2) Sub OPSIT 2B – USV On the Threat Axis

In this scenario, the USVs lie directly between the threat and the SAG. The USVs receive the initial indications of threat missiles via their onboard air search radar or ES systems, gain track of the ASCM(s) quickly, and pass the track data to the SAG, cueing the SAG's self-defense responses.

3. Mission Execution

a. OPSIT 1 – USVs Fire on Inbound ASCMs

1. USV or other ships in company make initial detection of inbound ASCM through active air search radar or passive ES means (if

passive detection occurs first, active radar search focuses on bearing obtained from electronic sources).

2. If initial detection is not made by USV, USV air search radars are cued to conduct focused search or the track data is passed to USVs.
3. USV's combat systems suite determines precise location and assigns track numbers to ASCMs.
4. Tracks are shared and deconflicted by use of Tactical Data Links (TDLs) and Cooperative Engagement Capability (CEC).
5. ASCM tracks are designated a high priority and updated at the combat systems' fastest rate.
6. USV's combat system calculates expected track of ASCMs and missile interceptors along with the amount of time the USV has available to conduct a successful intercept.
7. USVs launch missile interceptors and deploy electronic countermeasures.
8. USV radar systems and operators on manned ships in company conduct detailed search of intercept location to make assessment.
9. If inbound ASCMs survived engagement, USVs reengage if there is enough time to consummate the engagement or point defense systems are cued to engage.

b. OPSIT 2 – Untargeted USV Detects Inbound ASCM and Cues SAG

1. USVs make initial detection of inbound ASCM through active air search radar or passive ES means (if passive detection occurs first, active radar search focuses on bearing obtained from electronic sources).

2. USVs transmit track data to other ships in company.
3. Ship’s combat systems suite determines precise location and assigns track numbers to ASCMs.
4. Tracks are shared and deconflicted by use of TDLs and CEC.
5. ASCM tracks are designated a high priority and updated at the combat systems’ fastest rate.
6. Ships’ combat systems calculate expected track of ASCMs and missile interceptors along with the amount of time the ship has available to conduct a successful intercept.
7. Ships launch missile interceptors and deploy electronic countermeasures.
8. Ships’ radar systems and operators conduct detailed search of intercept location to make assessment.
9. If inbound ASCMs survived engagement, ships reengage if there is enough time to consummate the engagement or point defense systems are cued to engage.

4. Measures

The goal of employing the USV in this manner is to is to significantly reduce or eliminate the number of threats that reach the self-defense area of SAG units. The primary measures of interest for determining the USV’s potential to defeat ASCMs via kinetic or non-kinetic means were therefore the number of hard kills and soft kills against ASCMs across multiple iterations of a Markov kill chain model.

In the analysis of the USV as a cueing platform, the primary measure of interest was the early warning detection time in seconds. This time the time from the earliest USV detection in the scenario compared against the assessed organic SAG detection time if the

USV was not present. This time was also used to derive the potential number of additional shot opportunities, another measure of interest.

In the analysis of USV-SAG geometries, the measures of interest were degrees of coverage and linear distance. The degrees of coverage pertain to the ASCM detection screen provided by the geometric USV spacing in a given formation. The screen was measured in degrees radially from the SAG in the center of the USV formation. The linear distance pertains to the summation of the distances of each USV to the SAG. This distance relates to the potential overall early warning detection time and, correspondingly, the number of additional shot opportunities against incoming ASCM threats.

III. SYSTEM REQUIREMENTS

A. SYSTEM REQUIREMENTS INTRODUCTION

In conceptual system design activities, such as in our use case of the medium-sized USV, system needs and requirements must first be developed and understood (Blanchard and Fabrycky 2011). From the DRM, the determined operational needs are:

1. USV use shall mitigate the probability of ASCM hit on SAG ships by defeating threats via kinetic or non-kinetic means.
2. USV use shall provide early warning and threat cueing to SAG ships, thereby increasing available reaction time and counter-fire opportunities of SAG ships from initial threat detection compared to a no-USV scenario.
3. ASCM detection and response subsystems on the USV host platform must not require the USV to be larger than medium sized.

These will form the basis of the subsystem requirements necessary to implement ASCM defense capabilities on the medium-sized USV. The detection subsystems of interest in this study are the air search radar and ES subsystems. The response subsystems of interest in this study are the soft-kill deception countermeasure, SAM, CIWS, and radio frequency jamming (also known as EA) subsystems.

For each of these subsystems, requirements were generated to address the operational needs while being grounded by current technology or technology that could realistically be fielded within the next two years. Concepts of employment for each subsystem provide context to inform specific subsystem level requirements. Requirements for additional support subsystems—such as power or cooling, for example—were derived through discussion of these concepts of employment and further refined after system selection. A full list of generated requirements is available in Appendix A.

B. DETECTION SUBSYSTEM REQUIREMENTS

The detection subsystems are the air search radar and the ES system. These two systems interact with the USV via an integrated combat system (ICS) onboard the USV that also drives USV responses for an ASCM attack. By providing the necessary processed data to the SAG including target tracks, these subsystems cue the SAG ships to threats. Additionally, they provide the ability to meld their returns into a common display with the SAG ships, thereby increasing situational awareness.

Given the threat missiles have known velocities and may have correlative electromagnetic signatures, the detection subsystems can implement contact discrimination. Engagement settings and threat profiles can be established by remote SAG operators to automatically filter out items not of interest. Filtering raw data into contacts of interest (COIs) alleviates bandwidth consumption compared to transmission of all raw contact data. This discrimination logic can be edited to reflect a specific operating area or threat level. For the purpose of this paper, a COI is defined as an air contact with a velocity of greater than 400 knots travelling towards the SAG. Friendly aircraft returning to the SAG would be discounted based on positive identification (such as via Identification Friend or Foe, secure communications, and check-in procedures).

1. Air Search Radar

The air search radar must detect contacts at a range that allows for sufficient time to identify threats and deploy appropriate response measures to defeat the threat. To obtain tactically relevant detection ranges against air threats, the air search radar must be elevated to achieve detection over the horizon.

To prevent time lag and communication relay issues, the radar system shall process radar data onboard. The communication subsystem will provide this processed data in the form of target tracks to the SAG ships for threat cueing. The air search radar shall also be able to receive changes to its operating parameters (e.g., cued search areas, power levels, no transmission areas, and COI parameters) should an operator on one of the SAG ships need to adapt them to a changing operational environment or to prevent interference with other equipment, such as navigation radars.

Due to the high speed of ASCMs and large area to be searched, the radar system must have both volume search and cued search capability, as well as functionality for high-resolution tracking. This can be accomplished within one multi-function radar or the system may consist of multiple radars to fulfill the different roles. In either case, the radar(s) used need to be able to distinguish incoming threat missiles from other airborne objects.

2. Electronic Support System

The ES system must be capable of detecting threat missiles in their expected emitter operating frequency bands when they are emitting. These emitters must be detected at a range that allows for sufficient time to identify threats and deploy appropriate response measures to defeat the threat. The ES system must therefore also be elevated enough to achieve adequate detection ranges. The ES system must also provide elevation angle coverage to detect incoming threats from the surface as well as high elevation attacks.

To prevent time lag and communication relay issues, the system shall process ES data onboard the USV. This processed data will include line of bearing information and signal strength, and it will be provided locally to the ICS and to the SAG via the communication subsystem. Additionally, the ES system will be capable of isolating own ship emitters to prevent spurious detections. The ES system shall also be able to receive changes to its operating parameters (e.g., cued search bearings, search areas, and COI parameters) should an operator on one of the SAG ships need to adapt them to a changing operational environment.

C. RESPONSE SUBSYSTEM REQUIREMENTS

After obtaining track on an inbound ASCM, several subsystems may be activated to defeat the threat by either kinetic or non-kinetic means. The former seeks to destroy the ASCM in flight while the latter seeks to disrupt or deceive the flight path of the missile by using chaff, flares, and decoys or by attacking the missile’s terminal homing seeker on the electromagnetic spectrum. Subsystems considered for these applications must account for the smaller size of a medium USV relative to a standard cruiser or destroyer.

Regardless of method, all response subsystems are cued by the ICS after it has received the necessary data from the detection subsystems. The timing in which responses are activated is determined by the calculated intercept and the necessary time for personnel and systems to react. Thus, in some instances all response subsystems may be employed while in others only one will be used. To deconflict responses while defending the SAG, the ICS will communicate with the rest of the SAG through TDLs and CEC. The USV can take action either autonomously through pre-established weapons engagement settings, or it will receive engagement commands from the SAG.

1. Soft-Kill Deception Countermeasures

One method proposed to lessen the probability of an inbound ASCM hitting a SAG ship is the use of soft-kill deception countermeasures. These attempt to lure inbound ASCMs away from SAG ships by deceiving them into pursuing a decoy target. This will protect the SAG and also reduce risk of damage to the USV.

To counter the variety of ASCM threats, the USV will have the ability to launch chaff to protect against radar guided missiles or flares to protect against infrared guided missiles. The launcher in the chosen countermeasure system should be able to launch both types of payloads to eliminate the need for unique launchers, thereby keeping SWaP requirements to a minimum. The countermeasure system will need to be able to intercept missiles coming from any direction. This can be accomplished either by installing multiple sets of launchers with fixed firing positions to obtain 360-degree coverage or by installing dynamic launchers that can be aimed as needed. A dynamic system should be able to use data received from the detection subsystems to automatically aim the barrels. Launchers chosen for this design will fire commonly available rounds (not require custom-made chaff or flare rounds).

These countermeasure systems cannot act alone, so communication links with other systems will be required. The ICS will analyze detection data from the radar and ES systems to direct the countermeasure subsystem to release chaff or flares as appropriate against the incoming ASCM. Detection subsystems will also provide information detailing the track and speed of the ASCM. Given the threat missile velocities and relative proximity to the USV that the countermeasures are deployed, it is assumed the countermeasure system will have only one chance to neutralize the ASCM. Once a response round has launched, an event message signifying launch will be provided by the countermeasure system to the ICS and the SAG ships. The detection systems will continue to track the ASCM target. After receipt of the countermeasure launch message, indications from the detection system that the threat exists or no longer exists will serve as the battle damage assessment. This subsystem will periodically return a status message to the ICS for further dissemination to the SAG so operators know the health of the countermeasure launchers and the amount of payload available for use.

2. Surface to Air Missiles

The USV will be equipped with a SAM subsystem as a long-range response measure to engage and intercept ASCM threats. For this study, long-range is defined as more than 3.7 kilometers (two nautical miles), the threshold range for the CIWS subsystems. The SAM subsystem will consist of the SAM, the launcher, and corresponding SAM control systems integrated with the ICS. The SAM subsystem will be able to be configured to either engage threats autonomously or to require receipt of a launch order from the SAG in order to engage threats. In both scenarios, some level of automation is required for weapons launch. The ethics of a remote weapons launch and semi or full automation in weapons launch is not addressed in this paper. This study will simply attempt to address if such an employment concept is feasible and meets technical requirements.

Auto-engaging incoming threats requires a confirmed threat classification from the ICS. The ICS will receive initial configuration of threat profiles and rules of engagement settings and any configuration updates from operators in the SAG via the communication subsystem.

If operational commanders determine authority to launch SAMs must be obtained from operators in the SAG, the USV will first send a data package to the SAG detailing target information including track and threat classification as well as calculated launch parameters. Upon receipt, review, and approval by SAG operators, the USV would be enabled to launch. Provided the USV is granted authorization to fire, it will either launch

SAMs, or it will be unable to launch because the target no longer meets launch criteria for any reason, including that a firing solution may no longer exist due to proximity or geometry between the ASCM and the USV or defended assets.

Following launch, the SAMs will be able to receive updated guidance information from the USV and the SAG. The SAM subsystem will report general health and status messages and launch event reports. The SAM subsystem will use a missile capable of in-flight maneuvering and equipped with infrared seekers at a minimum to address the ASCM threat.

3. Close-in Weapons System

If the ASCM passes through long-range defenses, a short-range CIWS on the USV will be able engage the ASCMs and protect the SAG, provided the geometry between the USV and the ASCM supports the engagement. For this study, the terms "short-range" and "close-in" are interchangeable and defined as 3.7 kilometers (two nautical miles) or less. Since a CIWS is inherently a short-range system, it has short timelines in which it can prosecute targets and must leverage automation to do so.

The CIWS will need to have a maximum range of at least 3.7 kilometers (two nautical miles) to cover the area defined as close-in. It must be able to automatically detect and track incoming threats. The CIWS will automatically fire when a threat is identified in range and will cease fire when it no longer detects the threat, has detected elimination of the threat, or detects the threat is outbound or outside its engagement range, or to prevent accidental engagement of friendly forces. The CIWS must use commonly available rounds and must not require custom ammunition.

Even though the CIWS will be fully autonomous, it will require communication with the ICS so operators in the SAG can configure the CIWS including rules of engagement settings and threat profiles. Additionally, it must be able to receive handoff information from the ICS via the long-range defenses as well. This subsystem will also periodically send status messages to the ICS for further dissemination to the SAG operators will know the health of the subsystem, the amount of ammunition remaining for use, and the battle damage assessment from any engagements.

4. Radio Frequency Jamming or Electronic Attack

Besides attempting to cause the ASCM to detonate away from its intended target, another soft-kill approach is to employ active radio frequency jamming. Otherwise known as EA, this is focused on jamming the active homing seeker on the ASCM, thereby making it unable to lock onto its intended target. Such an EA capability could be combined with ES and soft-kill deception countermeasures into a single EW system, some capabilities could be combined in an EW system, or the capabilities may be split up into their own individual systems.

The range of the EA would need to be able to affect the ASCM far enough away to ensure the ASCM fails to lock on before entering its terminal phase. Furthermore, the EA system must operate on the frequency bands employed by the seekers on expected threat missiles. The EA system must also be able to receive threat parameter updates from the SAG via the ICS.

The ICS will validate the ASCM target based on information provided by the detection subsystems and threat criteria provided by SAG operators. Upon determination the threat is susceptible to jamming, the ICS will pass the ASCM track and emitter data to the EA subsystem and direct execution of EA. The ASCM threat will continue to be tracked by detection subsystems and may require additional response measures including hard-kill responses if the ICS determines the missile threat is not sufficiently addressed by jamming alone.

D. DERIVED SUBSYSTEM REQUIREMENTS

Additional subsystems will be necessary to support the detection and response subsystems. All subsystems will be required to interact with the ICS, and they will also require services from the USV such as electrical power, cooling, hydraulics, positioning, navigation, and timing services. It was therefore necessary to articulate additional requirements these support subsystems must perform in order to meet the detection and response subsystem requirements.

1. Integrated Combat System

The ICS primary functions are to manage all USV combat system interactions and to execute USV command and control functions with initial input and configuration updates from SAG operators.

The ICS will act as contact manager and track integrator. Once an ES or radar COI has been detected, the data will be compared with engagement parameters, which will be comprised of both ES and radar threat level tripwires. These parameters and thresholds must be editable via the SAG remotely. The ICS shall make determinations whether COIs meet engagement parameters and command the appropriate response subsystem reaction. It will provide relevant information including ASCM track, emitter information, and response measure type to the launchers to maximize the effectiveness of the response measures. It will also interface with all onboard subsystems in order to provide the detection and response subsystems with accurate data, such as position, navigation, and timing data or status of other systems, for instance. Response subsystems will provide the ICS general health and status messages and launch event reports.

The ICS will serve as the primary conduit for all detection and response subsystems to interface with the USV communications systems back to the SAG. Onboard the USV, it will integrate with each subsystem via a common architecture like the Common Object Request Broker Architecture. This architecture is not envisioned to be unique to our subsystems of interest and is expected to also interface with any other subsystem not covered under the scope of this study.

2. Electrical Power

The electrical power system must be able to generate and provide enough power at the correct voltage, frequency, and phase to support all onboard systems. This requires the system to generate power at 450 volts alternating current at 60 hertz in 3-phase. The power must then be able to be directly distributed in 3-phase or in a single-phase as well as transformed down to 120 volts. The 120 volts alternating current at 60 hertz will then be distributed in 3-phase or in a single-phase. Frequency converters must also be able to create 120 volts alternating current power at 400 hertz in 3-phase for further distribution.

Since the USV will not have personnel onboard to respond to emergencies at a moment's notice, the system must be capable of self-monitoring for potential and confirmed system faults. Further, the system must be able to report its status to the ICS for further transmission to the SAG as well as respond autonomously to any electrical problems by taking such actions as isolating circuits or equipment, shutting down switchboards or generators, and shifting the electrical distribution configuration.

3. Cooling

For sustainable operations, subsystem cooling will be required. Seawater cooling will be required for heat tolerant systems and chill water for heat sensitive systems. Recalling that the envisioned operating environment for the USV is in waters from 2—35 degrees Celsius, it is noted that a seawater-based cooling system's effectiveness will depend on environmental conditions. Cold seawater is more advantageous, while more tropical waters can make regular cooling more challenging.

A traditional on-board chill-water system is assumed to be a requirement for heat sensitive subsystems such as electronics. Since the USV is unmanned, it is assumed it will be heavily populated with electronics racks to address processing requirements of its various subsystems and that it will already have a robust chill-water subsystem in place. Subsystems and components like the ICS and detection and response subsystem processors will still require additional dedicated and stable cooling.

Given the SWaP requirements for cooling units and the limited space and power available onboard the USV, high heat generating items that can withstand changes in temperature are ill-suited to be incorporated in the chill-water cooling system because the chill-water system would have difficulty maintaining its cooling capability. As such, it will be necessary to incorporate and maintain a separate seawater-based cooling system.

4. Hydraulics

USV machinery parameters must be controlled precisely. Moving hydraulic oil to open and close hydraulic valves remotely from an automated control system can maintain requisite fluid pressures and move heavy parts. Applications are important for propulsion, electrical power generation, and steering systems, as well as for combat systems equipment with moving parts, such as directing the launch vector for response subsystems. The hydraulics system will need to integrate with the ICS to receive input for instantaneous response subsystem demands and respond accordingly.

5. Positioning, Navigation, and Timing

The positioning, navigation, and timing system onboard the USV must comply with accuracy standards set forth in the Chairman, Joint Chiefs of Staff Instruction 6130.01, the Department of Defense Master Positioning, Navigation, and Timing Plan. This will allow for accurate and precise determination of both the USV three-dimensional location—referenced to World Geodetic System 1984—and the Coordinated Universal Time. These measurements are critical to USV effectiveness as a maritime platform and the effectiveness of its onboard weapons systems. The system must interact with the ICS to pass positioning, navigation, and timing data to all combat systems.

Use of an inertial navigation system allows for determination of position absent GPS input in case of GPS denial. This supports the navigation goal of the system to provide for effective and safe navigation in accordance with COLREGs, UNCLOS, and other international agreements, unless overridden by the ICS. Such an override would be necessary when operational commanders determine the tactical situation warrants navigation methods not in accordance with such agreements. Normally, operators would pass navigation and stationing instructions to the USV via the ICS but would not override the normal safety and international agreement conformance programming. Either way, the system will determine and apply course and speed corrections to attain position and maintain station.

IV. SUBSYSTEM SELECTION

A. SUBSYSTEM SELECTION INTRODUCTION

Following requirements generation, the physical components and corresponding host platform SWaP requirements were identified. Potential subsystems for inclusion in this analysis were identified and compared against the subsystem requirements and the concepts of system employment. To maintain an unclassified study, all subsystems and components considered for the design were current COTS or GOTS products, and all data was collected from publicly available sources. The subsystems and components were not restricted to any particular nation or group of nations.

Consideration was also given to combinations of subsystems to assess if emergent behaviors are more favorable when systems operate coherently rather than individually. At the conclusion of this analysis, a system was selected for each detection and response subsystem of interest for inclusion in a notional medium-sized USV. For the ICS and support systems, such as electrical power, cooling, hydraulics, positioning, navigation, and timing services, and other services required for the proper function of the detection and response systems, it is assumed there is an existing equivalent on the host platform. This analysis will therefore not make specific COTS or GOTS recommendations for those systems.

B. DETECTION SUBSYSTEM COMPARISON AND SELECTION

1. Air Search Radar

Many radars were ruled out due to their large SWaP requirements. For example, the smallest AN/SPY-1 radar variant is the SPY-1F. This radar was designed for frigates (larger than a medium-sized USV), consists of four 2.44-meter wide octagonal panels mounted on the sides of the superstructure, and the entire system including below deck portions weighs over 20 metric tons (Janes by IHS Markit 2018b; Lockheed Martin 2009).

The AN/SPS-49 fulfills the requirements for an air search radar on the USV. It has a rotation clearance of 8.7 meters and is currently installed on U.S. aircraft carriers, cruisers, and amphibious ships as well as Australian, New Zealand, Spanish, Korean, and Canadian ships (Pike 1999). Due to the 8.7 meter clearance requirement, it was determined this radar could be used if it was installed high or otherwise lifted, which is something that will need to occur in order to achieve the required radar range anyways. Figure 8 shows the SPS-49 as outfitted aboard a Korean destroyer.

Figure 8. AN/SPS-49 Radar. Source: Richards (n.d.).

A more recent option not utilized by the USN is the SAMPSON, produced by BAE Systems and used by France and the United Kingdom. It consists of two array faces rotating inside a radome, has a range of 400 kilometers and weighs 4.6 metric tons (Jane's by IHS Markit 2019b). It is also assumed to fulfill the various tracking and contact generation requirements, since it is widely in use by the United Kingdom in conjunction with their Sea Viper Naval Air Defense System and would probably not be if it was unable to complete those requirements (Missile Defense Advocacy Alliance 2018). However, since it is not used in the USN, an unknown amount of effort would need to be expended integrating it into the ICS and the USN communication architecture since it likely will not be compatible off-the-shelf. The SAMPSON is shown in Figure 9 sitting atop the mainmast of HMS Daring.

Figure 9. SAMPSON Radar (Radome Atop Mast). Source: Hpeterswald (2013).

To support the next generation of USN surface combatants and replace the AN/SPY-1 radar, Raytheon developed the AN/SPY-6 and a smaller version, the Enterprise Air Surveillance Radar (EASR), which can be placed on a single face rotating array or in a three faced fixed array configuration (Raytheon Company 2019). The fixed array configuration is preferred over the rotating array due to less moving parts leading to a lower maintenance requirement and because a fixed array configuration would work well with USN integrated topside design initiatives. The two EASR variants are shown in Figure 10.

Figure 10. EASR Variant 1 (Left) and a Single Face of Variant 2 (Right). Adapted from Raytheon Company (2019).

A short-range radar will be necessary to track ASCMs close to the USV to mitigate the short-range coverage gap, or shadow zone, common to long-range radars. ASCMs will be engaged in this short-range space by CIWS. Therefore, space can be saved by ensuring the selected CIWS includes an integrated short-range air search radar. After selection of the CIWS, additional software or hardware development may be necessary to ensure the CIWS radar interfaces with the ICS to meet track generation, update, and sharing requirements.

Ultimately, the SPS-49 and SAMPSON radars are adequate but require a large footprint on the medium-sized USV, so the EASR was selected as the primary air search radar for the USV as well as ensuring the CIWS includes an integrated short-range air search radar. Variant 2, the three-faced fixed array variant, was selected over Variant 1. Weight and power requirements were approximated as a scalable function of the SPY-1A. This leads to an approximate weight of 6.7 metric tons including below-deck support systems and a power requirement of 440 volts alternating current at 60 hertz in 3-phase (Jane’s by IHS Markit 2018b). The USV superstructure will be designed of appreciable height to support the panels of the EASR and attain required radar range.

2. Electronic Support System

Two ES systems were examined as potential candidates. The USN Surface Electronic Warfare Improvement Program (SEWIP) consists of many iterative upgrades to the AN/SLQ-32 equipped on almost all USN surface combatants. The Outfit UAT is produced by Thales and is found on the United Kingdom's major surface combatants.

Legacy AN/SLQ-32 systems can detect emitters transmitting from a frequency range of 250 MHz–20 GHz, and some versions, such as those found on USN cruisers and destroyers, have an offensive jamming capability (Forecast International 1999). All versions are integrated with the Mk 36 Super Rapid Bloom Offboard Countermeasures (SRBOC), except for those equipped on aircraft carriers (Forecast International 1999). It is known the system requires cooling, especially for its electronics, but specific details are unavailable. Additionally, specific frequency ranges for emitters that can be detected by SEWIP upgraded units are classified, but they will encompass a wider range than the legacy SLQ-32 (Lockheed Martin 2016). Likewise, integration capability with SRBOC is assumed to remain in SEWIP upgraded systems. SEWIP Block 2 relies heavily on COTS components, and the Block 3 upgrade will add EA capability to the system (Cole 2015). An artist's rendering of proposed SEWIP Block 3 antennas is shown in Figure 11.

Figure 11. SEWIP Block 3 Antennas (Circled in Red). Adapted from Northrop Grumman (2019).

The Outfit UAT is able to detect signals from 2–18 GHz and can be reconfigured to cover other frequencies as well (Thales 7 Seas n.d.). Similar to the SLQ-32, identification of received emissions occurs by comparing to a library of known emitters. Furthermore, it is integrated with its associated chaff systems to allow automatic responses (Thales 7 Seas n.d.). The pyramid shaped Outfit UAT antennas are shown in Figure 12.

Figure 12. Outfit UAT (Circled in Red). Adapted from Thales 7 Seas (n.d.).

The SEWIP upgraded AN/SLQ-32 system was chosen as the ES system due to its interoperability with other USN combat systems and its wider frequency range compared to the Outfit UAT. Additionally, the planned integration of EA in the SEWIP Block 3 upgrade will allow for a single EW system, allowing for SWaP savings compared to two separate ES and EA systems. Finally, the Block 3 upgrade will also align with USN integrated topside design initiatives.

C. RESPONSE SUBSYSTEM COMPARISON AND SELECTION

1. Soft-Kill Deception Countermeasures

Available unclassified countermeasure information was weighed against system requirements to compare potential subsystems. The Mk 36 SRBOC and Centurion chaff and flare launchers were chosen for this down select process. The SRBOC is made by BAE Systems for the USN and other countries, and the Centurion is made by Chemring Countermeasures for the UK.

According to the manufacturers' websites, both subsystems can launch chaff and infrared countermeasures, meeting the requirement to be multifunctional, and both systems can fire standard Mk 36 rounds, meeting the requirement to use standard non-custom rounds (BAE Systems 2019; Chemring Countermeasures 2013a, 2013b). Both subsystems are equipped with control subsystems to receive firing inputs (Chemring Countermeasures 2013b; Ward n.d.).

Where these subsystems differ is in the dynamic versus static nature of the barrels. According to Larry Ward's data sheet from United Defense (n.d.), a single launcher in the SRBOC system contains six static barrels, and the system supports installing multiple launchers in different areas to cover the required 360-degree area around the defended unit. These barrels are aimed at fixed locations, some at 45 degrees and some at 60 degrees (Ward n.d.). The SRBOC system is shown in action in Figure 13.

Figure 13. SRBOC System. Source: BAE Systems (2019).

The Centurion launcher is specifically designed for use on smaller vessels; the barrels fold up when not in use, allowing the system to be constructed on a lighter frame and be more compact, and they will unfold when launching (Chemring Countermeasures 2013b). The system also includes a stabilizer that helps compensate for sea motion affecting the vessel, and it will rotate to point the barrels in the needed firing direction (Chemring Countermeasures 2013b). The launcher may also be installed with a cover that will minimize its radar cross-section (Chemring Countermeasures 2013b).

The Centurion launcher was determined to be a better fit for a medium-sized USV due to its versatility and lightweight, compact design for smaller vessels. The Centurion launcher is shown with the cover installed in Figure 14 and without the cover in Figure 15. Figure 16 is a screen capture of a Chemring Countermeasures promotional video depicting relative system size compared against two operators loading the launcher.

Figure 14. Centurion Launcher with Cover Installed. Source: Chemring Countermeasures (2014).

Figure 15. Centurion Launcher without Cover Installed. Source: Chemring Countermeasures (2013b).

Figure 16. Operators Loading a Centurion Launcher. Adapted from Wow Media Limited (2013).

2. Surface to Air Missiles

When considering SAMs, both the missile system and launcher system need to be selected. For the launchers, the required deck space and depth of the launchers are crucial size factors. Two primary candidates for missile defense were considered. The first was the Standard Missile (SM) family of missiles, with the addition of the Evolved Sea Sparrow Missile (ESSM), launched by the Mk 41 Vertical Launch System (VLS), commonly in use by the USN. The other was the Aster family of missiles, launched by the SYstème de Lancement VERtical (SYLVER), which is used onboard naval ships of the United Kingdom, France, Italy, and other countries.

The Standard Missiles considered were the SM-2 Medium Range and SM-6, with the addition of the ESSM since it is also VLS capable. Depending on the block of the missile, the SM-2 Medium Range has a range of 130, 165, or 170 kilometers (70.19, 89.09, or 91.79 nautical miles) and relies on semi-active terminal guidance (Jane’s by IHS Markit 2013). The SM-2 weighs 0.708 metric tons, is 4.72 meters long, and has a 0.34 meter diameter (Jane’s by IHS Markit 2013). The SM-6 has a much longer range of 370 kilometers (199.78 nautical miles) and uses both semi-active and active terminal guidance, but it is much larger, weighing 1.497 metric tons with a length of 6.55 meters and a 0.34 meter diameter (Jane’s by IHS Markit 2013). Despite the size, it is still VLS capable. The ESSM is much smaller, weighing only 0.297 metric tons with a length of 3.64 meters and a 0.25 meter diameter, and due to its small size, four ESSMs can be placed into a single Mk 41 VLS cell (Jane's by IHS Markit 2019a; Missile Threat 2018; Rogoway 2017). As a result, however, it has a nominal range of only 50 kilometers (27 nautical miles) (Missile Threat 2018).

All of these missiles require mid-course guidance through uplink and downlink messages, and they use semi-active terminal guidance, meaning a separate system is required to emit a beam of electromagnetic energy at the ASCM that is then reflected to the interceptor missile (Jane's by IHS Markit 2013, 2019a; Missile Threat 2018; Rogoway 2017). USN ships use the AN/SPG-62 radar, part of the Mk 99 Fire Control System, to perform this illumination and terminal guidance function, which requires electrical energy, auxiliary services, and deck space for the antennae (Pike 2011a). In addition to semi-active terminal guidance capability, the SM-6 and the ESSM Block 2 variant use terminal active radar homing, thereby mitigating the requirement for illumination from and reliance on an external system (Jane's by IHS Markit 2013; Rogoway 2017). The SM-2 is shown in Figure 17. The SM-6 and ESSM have similar appearance, with different sizes.

Figure 17. SM-2 Launch. Source: Royal Australian Navy (2011).

The Mk 41 VLS missile launching system produced by Lockheed Martin is used by the USN and many other navies. Its modular design allows for customization of the launching system footprint. The Mk 41 VLS is composed of the launcher and the launch control system, and the launch control system is made up of the launch control unit, remote launch enable panel, and the status panel (Kelly n.d.). The system comes in three sizes to accommodate various missiles, with the base design for each being an 8-cell module requiring 3.4 meters by 2.54 meters of deck space (Jane's by IHS Markit 2018g). The smallest size is the self-defense module with a height of 5.31 meters and weighing 12.16 metric tons empty, the next largest version is the tactical version with a height of 6.76 meters and weighing 13.5 metric tons empty, and the largest version is the strike version with a height of 7.7 meters and weighing 14.5 metric tons empty (Jane's by IHS Markit 2018g). The launch control system weighs 0.67 metric tons (Kelly n.d.). Multiple 8-cell modules can be built together, such as the case with USN destroyers, where the total system weighs 118.84 metric tons empty (Kelly n.d.). An 8-cell VLS is shown in Figure 18.

Figure 18. Mk 41 VLS. Source: Ostheim (n.d.).

The Aster family of missiles are produced by the European consortium Eurosam and were designed to counter supersonic sea-skimming ASCMs. The Aster 15 and Aster 30 are the two principle variants. Like the SM family, these missiles use a data uplink for mid-course guidance, but unlike the SMs, they use active seekers for terminal guidance (Eurosam 2019a). The primary difference between the two Aster missiles is their operational range. The Aster 15 range extends from 1.7 to over 30 kilometers (0.92 to over 16.2 nautical miles), it weighs 0.31 metric tons, it is 4.2 meters long, and it has a 180 millimeter diameter (Eurosam 2019a; MBDA Missile Systems 2016a). The Aster 30 range extends from 3.0 to over 100 kilometers (1.62 to over 54 nautical miles), it weighs 0.51 metric tons, and is 5.2 meters long, and it also has a 180 millimeter diameter (Eurosam 2019a). Figure 19 shows the Aster 30 missile. The Aster 15 has a similar appearance.

Figure 19. Aster 30 Missile. Source: MBDA Missile Systems (2016b).

Like the Mk 41, the SYLVER launching system is constructed in eight cell modules and comes in a variety of sizes to accommodate different sized missiles (Eurosam 2019b). The A-43 variant can only support the Aster 15 with a height of 5.4 meters, a weight of 7.5 metric tons, and footprint on deck of 2.6 meters by 2.3 meters, while the A-50 variant can support both the Aster 15 or 30 with a height of 6.1 meters, weight of eight metric tons, and footprint on deck of 2.6 meters by 2.3 meters (Eurosam 2019b). The SYLVER launching system is shown in Figure 20.

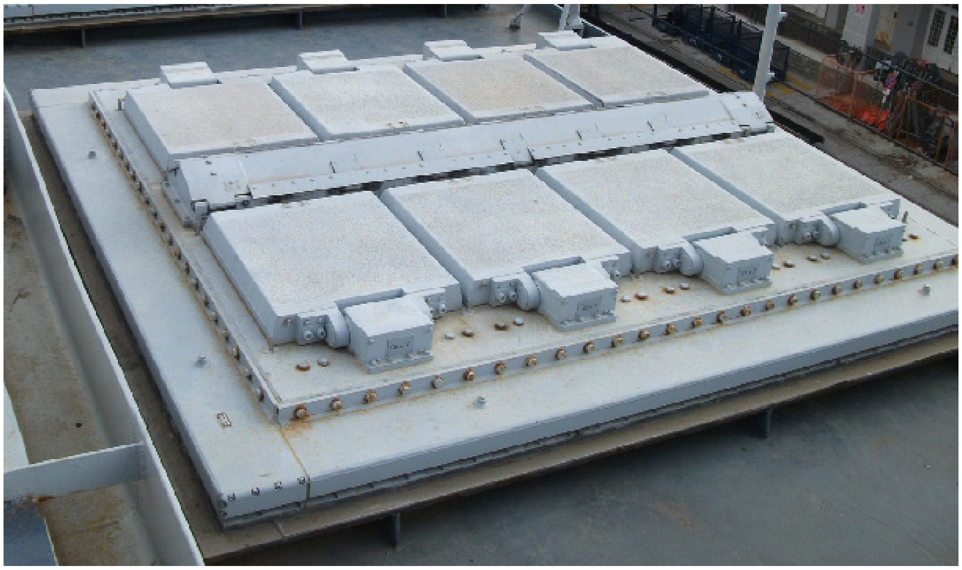


Figure 20. SYLVER Launching System. Source: Seaforces Naval Information (n.d.).

In consideration of the best fit missile, nominal USV detection range must first be assessed. Missiles with ranges that exceed the organic detection radius of the USV provide no practical advantage in this study. Equation 1 is Robinson's (2019) simplified radar horizon equation against a target at elevation in metric units, adapted for use where the surface unit is the detection platform against an inbound ASCM. Therefore, R_H is the radar horizon range in kilometers, $h_{Antenna}$ is the height of the USV (or ship) radar antenna in meters, and h_{ASCM} is the height of the ASCM in meters.

$$R_H = 4.124 \times (\sqrt{h_{Antenna}} + \sqrt{h_{ASCM}}) \tag{1}$$

Assuming the USV radar height is 12 meters and given the nominal cruise missile altitude for each of the three missile threats from Jane's by IHS Markit (2018a, 2018c, 2018d, 2018e, 2018f, 2018h) of approximately 20 meters, the equation results in the USV's maximum detection range of 32.72 kilometers (17.67 nautical miles).

The ESSM Block 2 was therefore selected as the USV SAM due to its range being sufficient to cover the USV maximum detection range and because it presents the smallest footprint of the evaluated missiles. Also, the ESSM Block 2 has the added benefit of not requiring an additional fire control system for terminal guidance, since it is equipped with an active seeker.

Both the Mk 41 VLS and the SYLVER were determined not to be adequate launch systems because of their SWaP requirements. Specifically, the height of the USV from the keel to the main deck is not tall enough to fully contain the launcher. The amount of deck space required by the launchers as well as the overall system weight was also significant.

A deck-mounted launcher was therefore favored to mitigate below deck impacts and allow more space for support systems. With selection of the ESSM as the missile, the Mk 29 Guided Missile Launching System, already compatible with the ESSM, was investigated. At 6.38 metric tons empty, the MK 29 weighs about three-fourths that of the SYLVER launching system and about half that of the MK 41 VLS (Raytheon Company 2007). The Mk 29 was therefore selected as the SAM launching system due to SWaP considerations given the selection of the ESSM as the missile. Use of a fixed, non-rotating Mk 29 launcher is likely feasible and could be investigated for the benefit of reduced maintenance and increased reliability and evaluated against cost and performance tradeoffs. A Mk 29 launching an ESSM is depicted in Figure 21.

Figure 21. ESSM Launch from Mk 29 Launching System. Source: Rogoway (2017).

3. Close-in Weapons System

Two CIWS components were chosen for this down select process due to their autonomous capability and ability to fire commonly available rounds. The first was the Phalanx originally created by General Dynamics and equipped on almost all USN surface ships and used by many foreign militaries (General Dynamics 2003b). This system was purchased by Raytheon who is the current manufacturer (Department of the Navy 2019). The second CIWS system was the Goalkeeper made by Thales Defense in conjunction with General Dynamics, currently in use by several foreign militaries (General Dynamics 2003a). Range information on these systems is classified.

According to General Dynamics (2003b), the Phalanx CIWS uses a Gatling gun that fires 20 millimeter rounds at a speed up to 4,500 rounds per minute. The magazine of this weapon holds 1,550 rounds, and the system is autonomous, using a Ku-band search and track radar at 12 to 18 GHz (General Dynamics 2003b). This CIWS weighs 6.17 metric tons and has an internal seawater cooling system (General Dynamics 2003b). The Phalanx is shown in Figure 22.

Figure 22. The Phalanx CIWS. Source: Raytheon Company (2018).

The Goalkeeper uses a seven-barrel Gatling gun that fires 30 millimeter rounds at a speed of 4,200 rounds per minute, and the magazine of this weapon holds 1,200 rounds (Thales Group n.d.). This system is also autonomous, using I-band radar at 8—10 GHz to search for threats and dual frequency I and K-band radar at 8—10 GHz and 20—40 GHz to track threats (Thales Group n.d.). Weighing 9.9 metric tons, it is heavier than the Phalanx (General Dynamics 2003a). The Goalkeeper is shown in Figure 23.

Figure 23. The Goalkeeper CIWS. Source: Thales Group (n.d.).

All systems are effective against missiles and are valid choices for the CIWS component when functionality is considered. However, the Phalanx was selected over the Goalkeeper due to the larger size and weight of the Goalkeeper.

4. Radio Frequency Jamming or Electronic Attack

Since all the ES systems analyzed included an EA capability as a single EW system, there was no need to select additional EA systems.

D. DERIVED SIZE, WEIGHT, AND POWER REQUIREMENTS

Based on the chosen subsystems, SWaP requirements have been identified for the medium-sized USV. The air search radar system will be mounted to a superstructure and will add a weight of 6.7 metric tons. The EW system requires two separate spaces of approximately three by two meters each, within the superstructure to support integrated topside design initiatives, and will add a weight of 2.5 metric tons. The countermeasure launcher will require a circular space approximately two meters in diameter and will add a weight of approximately 1.2 metric tons (Think Defence 2013). The SAM system will require a space of approximately 4.7 by 2.0 meters for one launcher holding eight missiles and will add a weight of approximately 8.75 metric tons, including the SAMs and the SAM launch control unit. The chosen CIWS will require approximately three by three meters of deck space for one unit and will add a weight of 6.17 metric tons.

These subsystems add a total weight of approximately 25.5 metric tons. This total subsystem weight is within the rule of thumb that “a modern warship’s mission payload makes up 10–15% of its total displacement” (Kelley 2002, 42). For a vessel with a 300 long ton displacement, that maximum is 30 to 45 long tons. This leaves available weight for required support systems and any additional payloads. This heuristic was developed for manned vessels; with no requirement for crew considerations, the percentage of mission payload displacement is expected to be even greater.

Standard ship power is three phase 450 volts at 60 hertz along with the ability to convert it to 400 hertz or transform it to 120 volts. Many of the chosen subsystems will draw from standard ship power, so consideration will be needed during USV integration to ensure it can handle the power draw of the newly added subsystems. The largest power requirement for the selected subsystems will be those of the EASR and SEWIP. Power consumption data could not be obtained for EASR or SEWIP, but peak power consumption is expected to be on the order of tens of megawatts. The Phalanx product specification sheets indicate a 70 kilowatt peak power consumption, and the Mk 29 Guided Missile Launching System specification sheets present a 55 kilowatt peak value (General Dynamics 2003b; Raytheon Company 2007). The Centurion power consumption could not be obtained but is expected to also be on the order of kilowatts. Future study areas for ship power include identification of total maximum load for all subsystems.

THIS PAGE INTENTIONALLY LEFT BLANK

V. DERIVED COMMUNICATION REQUIREMENTS

On the USV, many systems need to seamlessly send and receive information to and from other systems to properly execute the mission. This includes external communications from the USV to the SAG and internal communications amongst the USV subsystems. This chapter discusses requirements and considerations for the communications subsystem.

Areas outside the scope of this project involving communications are an enemy's ability to misdirect the USV, causing defensive gaps, and specific communication system selection. Enemy misdirection of the USV is not within the realm of the DRM, and it would be difficult to maintain an unclassified study if specific communication systems' capabilities were discussed in detail. Both areas would be good candidates for future study.

A. OVERVIEW

The USV must be able to receive and execute tactical commands from the SAG via the ICS. Additionally, the USV needs to indicate receipt of and compliance with these directions so operational commanders can account for USV use or plan accordingly if the USV is not in receipt of tasking or unable to comply. All directives received from an external source must be disseminated to the respective USV subsystems via the ICS, and those subsystems must be able to send response messages back to the ICS for compilation and dispatch to the SAG.

The USV subsystems also all use information from each other. Therefore, either all subsystems shall be able to communicate with each other in a mutually understandable language, or the ICS must be able to communicate with all subsystems in their specific language.

B. COMMUNICATION REQUIREMENTS

In addition to tactical direction, operators on the SAG will send configuration updates to the ICS to set operating parameters of the autonomous subsystems. Such parameters include threat profiles, rules of engagement, and COI criteria. The SAG and USV need to send tactical data to each other to ensure they share a common operating picture. Initial operating picture data will be sent to the ICS on the USV, and tracks sent from the USV back to the SAG will then update the common operating picture. LOS communications will be primary, with BLOS methods used if the distance between the USV and SAG is greater than that supported by LOS communications. Methods available for USV to SAG communications include very-high frequency (VHF) radio, ultra-high frequency (UHF) radio, satellite communications, and direct datalink systems.

To detect and appropriately respond to threats, internal communications are required between the subsystems located on the USV, facilitated by the ICS. These internal communications can be sent over a local area network cable using Ethernet or other standard network protocols. Local area network speeds are assumed to be fast enough to carry all internal communications in a timely manner.

Detection subsystems (air search radar and ES portion of the EW system) will receive search orders to initiate threat searches. Response subsystems will receive arm and disarm orders as well as configuration updates from the ICS. The countermeasure and SAM subsystems will need to know the location, type, and speed of the threat to know what measure to launch and where. The EW system will need to know where to direct EA. This information will be provided by the ICS via launch or EA orders developed using track data received from the air search radar and EW subsystems. The ICS will receive status reports from the response subsystems and forward them to the SAG for monitoring. Figure 24 shows the communications that are required internal to the USV and between the USV and the SAG as described above.

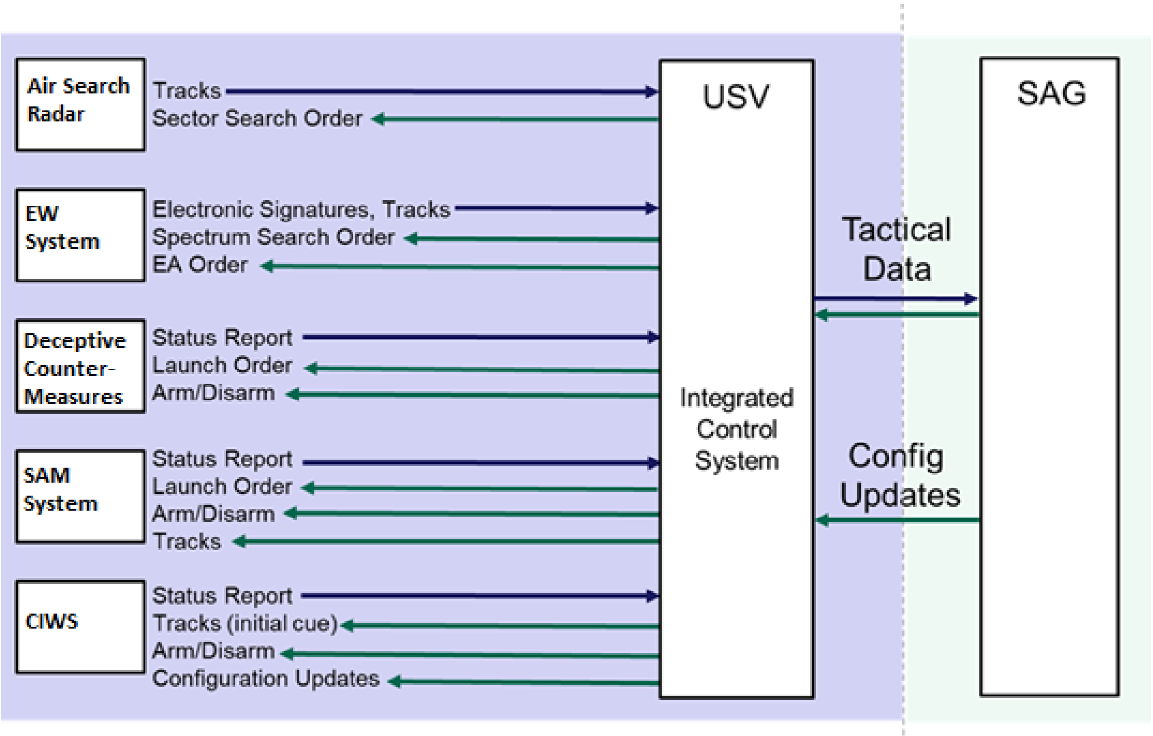


Figure 24. Required Internal and External USV Communications

The following requirements are therefore derived for the USV communications:

1. External communications shall be accomplished using VHF or UHF radios, satellite links, or a direct datalink system.
2. External communications shall use LOS methods if within range and BLOS if beyond the range of LOS methods.
3. Internal communications shall be accomplished using local area network cable connections.
4. Communication systems shall utilize standard network protocols.
5. Latency of external communication systems shall be within specifications for all equipment and networks used. For example, Satellite Link 16 requires a latency of no more than 12 seconds (Northrop Grumman 2014).

C. DATA SHARING SYSTEMS

Data must be able to be shared between the USV and the SAG on compatible systems. This is to allow for tracks and engagement information—such as orders, reports, and battle damage assessments—to be reported from the USV to the SAG and vice versa with minimal delay. Common TDLs and CEC will therefore be used.

The most common TDLs found aboard USN vessels are Link 11, Link 16, and Link 22. Link 11 is the oldest data link still in use. It creates a network between users for mutual exchange of tactical data and operates on both the HF (2—30 MHz) and UHF (225—400 MHz) portions of the radio spectrum (Northrop Grumman 2014). Two primary disadvantages of Link 11 compared to other TDLs are that it is not jam resistant, and it relies on a specific unit as a central node (Northrop Grumman 2014). In this construct, if the node is lost, the network will go down (Northrop Grumman 2014).

Link 16 is a secure data link installed on nearly all operational cruisers, destroyers, aircraft carriers, airborne early warning aircraft, and fighters. It is transmitted over UHF for LOS applications and also has BLOS capability via satellites (Northrop Grumman 2014). According to the Tactical Data Link Guide by Northrop Grumman (2014), Link 16 data is formatted in J-Series messages, point-to-point messages or networks of users are supported, and it uses the time division multiple access principle to allocate transmission and receive timeframes across all units in the network. Link 16 is therefore node-less. It also employs frequency hopping to be jam resistant (Northrop Grumman 2014).

Link 22 is the replacement for Link 11. One of the biggest improvements is that it is much more secure and resistant to jamming than Link 11 in part by also employing frequency hopping and formatting information it transmits in J-Series messages, allowing it to integrate with Link 16 (Northrop Grumman 2014). According to the Tactical Data Link Guide by Northrop Grumman (2014), up to eight networks can be integrated into a super network consisting of up to 125 units, and it has a built-in automatic relay setting that will pass on received data to the rest of the network without any operator actions. It has a transmission range of 300 nautical miles (Northrop Grumman 2014).

CEC is a method of sharing fire control quality track data between platforms by combining radar measurement data from each platform with an organic track on the target into one composite track, resulting in each unit having the same air picture (Department of the Navy 2017). The Department of the Navy CEC Fact File (2017) also states that platforms that do not have an organic radar track on a target can engage the target anyway by using the composite track data, which is a significant advantage.

THIS PAGE INTENTIONALLY LEFT BLANK

VI. EVALUATION OF OPERATIONAL SCENARIOS

To evaluate the operational scenarios described in the DRM, two analysis methods were applied: a Markov kill chain and a time series analysis. These analyses use Microsoft Excel, Visual Basic for Applications, and Real Options Valuation's Risk Simulator to determine the effectiveness of the USV. The Markov chain model addresses the study goal of determining utility of USV responses to ASCM threats. The time series analysis is a separate unrelated analysis and determines if the USV provides additional reaction time and counter-fire opportunities in the event an incoming ASCM is targeted at the SAG. Finally, two basic USV-SAG geometric formations are explored, and their potential benefits are compared.

A. KILL CHAIN MODEL

1. Kill Chain Model Description

The first model for this project determines the capability of the USV to defeat incoming ASCMs, providing the SAG a defensive advantage as in OPSITs 1A and 1B. The model uses a Markov kill chain analysis and was based on Giachetti's (2015) "System of Systems Capability Needs Analysis via a Stochastic Network Model." A Markov chain model is a stochastic model that describes event states and the probability based potential transitions between states.

a. State Transition Diagram

This model uses the state transition diagram presented in Figure 25. The states are either transitional or final. Transitional states are intermediate states used to determine probabilities for and times until reaching the final states. States 1 through 5 constitute the Find, Fix, and Track components of the traditional F2T2EA kill chain. States 6, 7, and 8 correspond to the Target component of the kill chain. State 6 is for threat evaluation and weapons assignment (TEWA), where the determination is made to either employ USV or SAG ship subsystems to engage the threat, and states 7 and 8 reflect targeting with the appropriate response subsystem onboard the SAG and USV. State 7 also includes Engage and Assess portions of the kill chain for the SAG and was not used in this study. This is because the model was developed to incorporate the option for SAG responses in addition to USV responses, but only the USV defensive measures were explored to meet the study goals.

States 9, 11, 13, 15, and 17 comprise the USV's Engage component of the F2T2EA kill chain. Three different range rings centered around the USV are used for this part of the model. These range rings are labeled as "RR" in Figure 25 as well as in following tables. When the threat missile is only inside Range Ring 1, SAMs are used to engage the threat. When the threat closes to be within Range Ring 2, electronic attack is employed, and range ring 3 comprises CIWS and soft-kill deception countermeasure engagements.

States 10, 12, 14, and 16 constitute the assess component of the F2T2EA kill chain. In states 2, 3, or 4, the target can be lost, requiring a transition back to state 1 "Search" for the USV to reacquire the threat. In states, 10, 12, 14, or 16, the battle damage assessment can indicate the target has not been destroyed, requiring a transition back to state 1 for the USV to begin another kill chain sequence. States 18, 19, and 20 are the model's three final states: Hard Kill, Soft Kill, or No Kill. The model completes when a final state is reached.

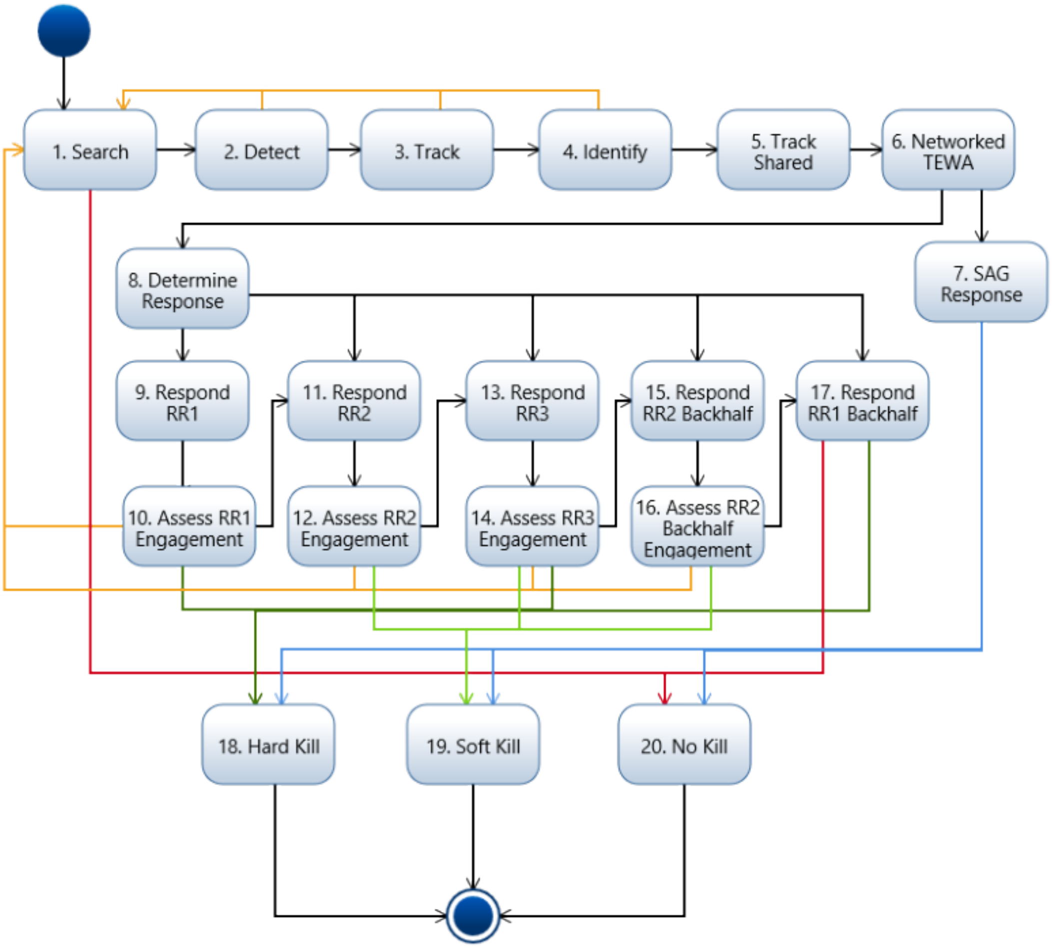


Figure 25. State Transition Diagram

b. *Scenarios Used in Kill Chain Analysis*

The kill chain analysis evaluates four different scenarios:

1. The medium threat ASCM traveling at cruise speed in OPSIT 1A
2. The medium threat ASCM traveling at cruise speed in OPSIT 1B
3. The high threat ASCM traveling at terminal speed in OPSIT 1B
4. The medium threat ASCM traveling at cruise speed in OPSIT 1B only engaged with SAMs (i.e., without Range Ring 2 or Range Ring 3)

The low threat ASCM was not used for this model due to having both a lower cruise speed and a lower terminal speed than the other two threat levels. It is assumed the USV will perform equally or better against this lower level threat. The medium threat was chosen for the majority of the modeling due to the threat having the highest cruise speed, and the high threat was chosen in order to represent the worst-case scenario where the incoming ASCM is already at terminal speed when detected. In all scenarios for this model, if an incoming threat is detected by the USV, the SAG must provide authorization for the USV to employ countermeasures during the Networked TEWA state.

Each range ring in the model represents specific response options the USV will employ. The range rings are time-based, commensurate with the ASCM's position along its threat axis as it continues inbound. The times associated with how long it takes an incoming threat to reach the SAG are calculated based on a time-speed-distance analysis using the cruise speed of Mach 0.9 for the medium threat and the high threat terminal speed of Mach 2.9, with the maximum USV detection range in each case as the starting distance. This range was determined from Equation 1, using a USV antenna height of 12 meters and an ASCM height of 20 meters for the medium threat and five meters for the high threat, based on ASCM cruise and terminal heights.

Figure 26 displays Scenario 1, which is based on OPSIT 1A where the USV is offset from the incoming threat missile. In this scenario, the USV is only able to engage the ASCM once within Range Ring 1.

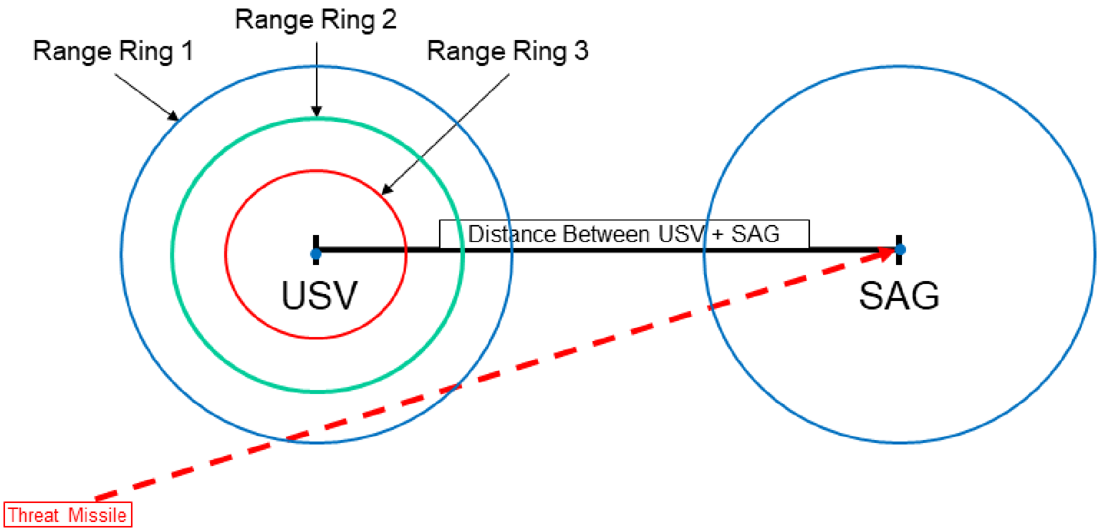


Figure 26. Scenario 1—Based on OPSIT 1A

Figure 27 displays Scenario 2 and Scenario 3, which are based on OPSIT 1B where an ASCM is passing overhead the USV on its way to the SAG. The ASCM passes through each of the three range rings, which are split into the front half and back half. The front half encompasses the situation where the USV is between the ASCM and the SAG and the ASCM is within the range rings. The back half refers to the situation where the ASCM has passed the USV and is within the range rings between the USV and the SAG.

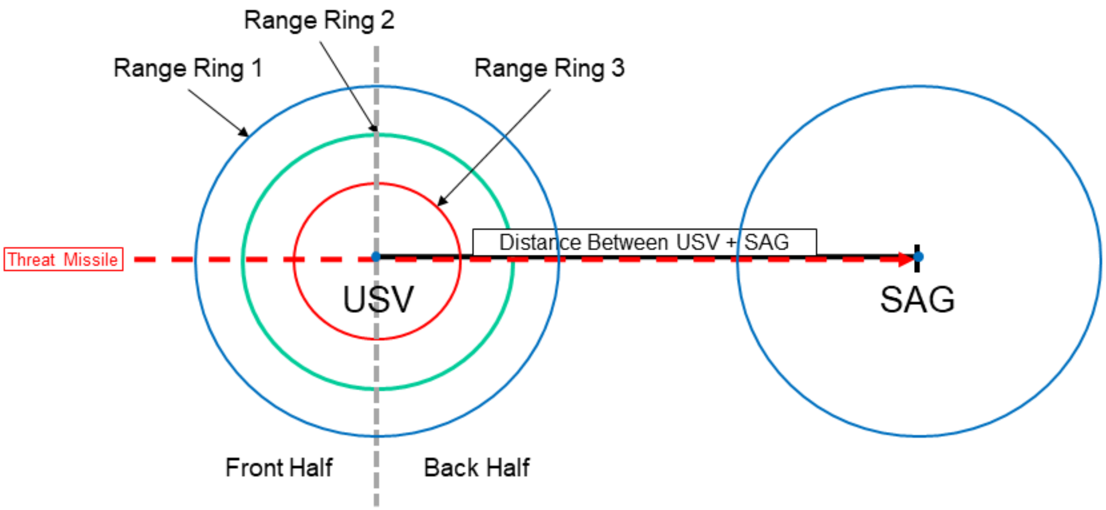


Figure 27. Scenarios 2 and 3—Based on OPSIT 1B

Figure 28 displays Scenario 4, which is based on OPSIT 1B with Range Ring 2 and Range Ring 3 removed. This scenario was used to evaluate USV threat response with only SAMs by removing the EW, soft-kill countermeasure, and CIWS response options.

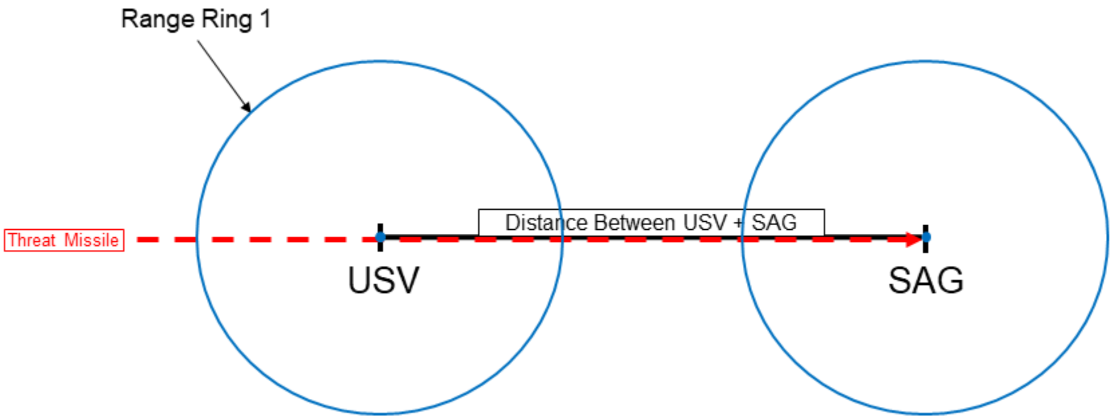


Figure 28. Scenario 4—Based on OPSIT 1B with Range Ring 1 Only

2. Kill Chain Model Inputs

The Markov kill chain model was developed using the following assumptions:

1. The USV is not targeted in the scenarios.

2. The USV is in a defensive mode only.
3. Each response subsystem onboard the USV is assigned to a range ring, with multiple systems able to be assigned to the same range ring.
4. The SAG and its units are counted as a single target.
5. Given the speeds of the missiles relative to the USV and SAG, the USV and SAG shall be considered stationary for the purposes of this model.
6. ASCMs are launched from sanctuary (maximum distance), so low and medium threats will be detected after they have reached cruise speed and altitude, while the high threat will be detected only after reaching its terminal speed and altitude.
7. SAM effectiveness is equivalent on both sides of the USV.
8. The USV and SAG are both in battle-ready state (equipment and systems onboard the USV and SAG are available, energized, and not malfunctioning, and system operators are awake and alert).

Using the state transition diagram, a state machine was developed in Microsoft Excel to analyze the scenarios. Probabilities were assigned to each transition between states based on previous research, unclassified data, and estimation. Table 2 uses the states and transitions identified in Figure 25 and shows the possible transitions from each state and the associated probabilities of transition. The far-left column displays the state that is being transitioned out of. The following columns on the same row show the possible states that can be transitioned to, and the probabilities for each transition are shown in bold font. This table was used to develop the probabilities for reaching the three final states.

For example, from the Search state, there is a 99% probability of transitioning to the Detect state and a 1% chance of transitioning to the final No Kill state (meaning the track was never gained and therefore could not be engaged). After transitioning to the Detect state, there is a 99% probability of transitioning to the Track state and a 1% of losing the target and therefore returning to the Search state. These transition probabilities continue until a final state is reached. All the states in Table 2 transition in this style with exception of State 8 Determine Response. To transition from this state, a determination is made as to which range ring response is appropriate based on how close the incoming ASCM threat is to the USV. In a given situation, the overall probability for reaching the final state is the product of the previously realized probabilities. The full state machine models for the scenarios can be viewed in Appendix B.

Table 2. Machine States and Transition Probabilities. Adapted from Smith (2010) and Giachetti (2015).

Current State	Transition Probabilities				Source
	Transition State 1	Transition State 2	Transition State 3	Transition State 4	
1. Search	2. Detect **0.99**	20. No Kill **0.01**	NA	NA	Smith (2010)
2. Detect	3. Track **0.99**	1. Search **0.01**	NA	NA	Smith (2010)
3. Track	4. Identify **1.00**	NA	NA	NA	Primarily used for state transition time
4. Identify	5. Track Shared **0.95**	1. Search- **0.05**	NA	NA	Giachetti (2015)
5. Track Shared	6. Networked TEWA **1.00**	NA	NA	NA	Primarily used for state transition time
6. Networked TEWA	8. Determine Response **1.00**	NA	NA	NA	Primarily used for state transition time
7. SAG Response	NA	NA	NA	NA	This state was not used during model execution

Current State	Transition Probabilities				Source
	Transition State 1	Transition State 2	Transition State 3	Transition State 4	
8. Determine Response	9. Respond RR1 OR 11. Respond RR2 OR 13. Respond RR3 OR 15. RR2 Backhalf OR 17. RR1 Backhalf **1.00**	NA	NA	NA	Assumption: based on current state time, the appropriate RR can be selected to engage at the ASCM's expected position
9. Respond RR1	10. Assess RR1 Engagement **1.00**	NA	NA	NA	Primarily used for state transition time
10. Assess RR1 Engagement	18. Hard Kill **0.82**	11. Respond RR2 **0.13**	1. Search **0.05**	NA	Giachetti (2015)
11. Respond RR2	12. Assess RR2 Engagement **1.00**	NA	NA	NA	Primarily used for state transition time
12. Assess RR2 Engagement	19. Soft Kill **0.20**	13. Respond RR3 **0.75**	1. Search **0.05**	NA	Smith (2010)
13. Respond RR3	14. Assess RR3 Engagement **1.00**	NA	NA	NA	Primarily used for state transition time

Current State	Transition Probabilities				Source
	Transition State 1	Transition State 2	Transition State 3	Transition State 4	
14. Assess RR3 Engagement	18. Hard Kill **0.70**	19. Soft Kill **0.10**	15. Respond RR2 Backhalf **0.15**	1. Search **0.05**	Smith (2010)
15. Respond RR2 Backhalf	16. Assess RR2 Backhalf Engagement **1.00**	NA	NA	NA	Primarily used for state transition time
16. Assess RR2 Backhalf Engagement	19. Soft Kill **0.20**	17. Respond RR1 Backhalf **0.75**	1. Search **0.05**	NA	Smith (2010)
17. Respond RR1 Backhalf	18. Hard Kill **0.82**	20. No Kill **0.18**	NA	NA	Giachetti (2015)
18. Hard Kill	NA	NA	NA	NA	Terminal state – no transition
19. Soft Kill	NA	NA	NA	NA	Terminal state – no transition
20. No Kill	NA	NA	NA	NA	Terminal state – no transition

Neither the amount of time spent in each state nor the corresponding distributions could be determined from supporting literature, so best estimates for the average state times were used in a normal distribution. The primary defined input was the mean time in each state, and it was desired to have the modeled time evenly distributed about the mean rather than using a skewed distribution. A standard deviation of 10% was used for all non-human dependent state times, and a standard deviation of 25% was used for states requiring operator interactions.

For instance, it is assumed it takes two seconds on average, with a standard deviation about that mean of 0.2 seconds, for the USV to detect an incoming ASCM threat because of the time for the software to establish enough consistent data on the threat to rule out clutter. The only state requiring operator interaction was state 6 "Networked TEWA," during which a SAG operator gives the USV authorization to employ threat responses. These state times and their associated standard deviations are displayed in Table 3. States 18, 19, and 20 are the possible end states for the state machine. These states represent the final battle damage assessment from the USV's perspective when the USV has either physically destroyed the ASCM (hard kill), managed to force the ASCM to miss its target (soft kill), or failed to defeat the ASCM resulting in it penetrating to the SAG self-defense area (no kill).

Table 3. Machine State Times and Standard Deviations

State	Mean Time in State (seconds)	Requires Operator Interaction?	Standard Deviation (seconds)
1. Search	1	No	0.1
2. Detect	2	No	0.2
3. Track	2	No	0.2
4. Identify	1	No	0.1
5. Track Shared	1	No	0.1
6. Networked TEWA	4	Yes	1.0
7. SAG Response	0	N/A	0.0
8. Determine Response	1	No	0.1
9. Respond RR 1	4	No	0.4
10. Assess RR 1 Engagement	1	No	0.1
11. Respond RR 2	5	No	0.5
12. Assess RR 2 Engagement	1	No	0.1
13. Respond RR 3	5	No	0.5
14. Assess RR 3 Engagement	1	No	0.1
15. Respond RR 2 Backhalf	5	No	0.5
16. Assess RR 2 Backhalf Engagement	1	No	0.1
17. Respond RR 1 Backhalf	8	No	0.8
18. Hard Kill	0	N/A	0.0
19. Soft Kill	0	N/A	0.0
20. No Kill	0	N/A	0.0

3. Kill Chain Model Execution

In the kill chain analysis, the metrics of interest are the amounts of hard kills, soft kills, and failed engagements (no kills) of the incoming ASCM. Using the state time distributions shown in Table 3, the model calculates the time it takes for each state transition to occur. This allows for an estimate of available engagement time for the range rings for the medium threat—the CSS-N-8—and the high threat—the SS-N-27. As shown in Table 1, the CSS-N-8 has the greatest cruise speed so it was used in the state machine for an ASCM moving at cruise speed. Similarly, the SS-N-27 was used in the state machine for an ASCM moving at terminal speed. In order to determine the state that is transitioned to, a random number is generated between zero and one.

This random number is used to determine the next state by comparing it against the cumulative probabilities of the possible transition states, derived from Table 2. If the random number is equal to or less than the probability for the first possible state transition, that transition is made. If it is greater, it is compared against the next possible transition, and so on, until a transition is determined.

As an example, once in state 10 "Assess RR1 Engagement," the possible transitions are to state 18 "Hard Kill," state 11 "Respond RR2," or state 1 "Search." The probabilities for these transitions are 0.82, 0.13, and 0.05, respectively. Therefore, if the random number generated is 0.82 or less, the transition to state 18 "Hard Kill" will occur, and the model will complete since that state is a final state. If, however, the random number generated is greater than 0.82, it will evaluate for the next possible transition—to state 11 "Respond RR2"—which would occur if the random number is greater than 0.82 but less than or equal to 0.95. Finally, if the random number is greater than 0.95, the transition to state 1 "Search" will occur.

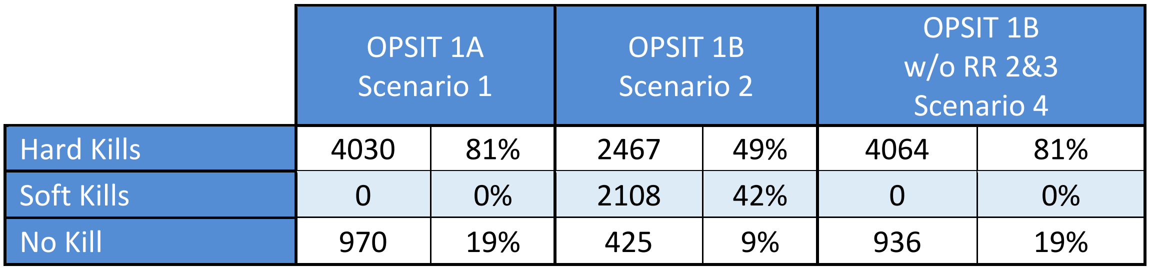
The model uses logic that determines the response the USV will be capable of making. This occurs during state 8 "Determine Response." Using ASCM time-based position versus the current cumulative state hold time, the USV is forced to transition to the appropriate range ring response. The potential for some state transitions are eliminated based on the total elapsed run time, precluding transitions to ineligible states. For example, if the current elapsed time is 9.5 seconds when the model reaches state 8, then the ASCM will be past the RR1 engagement zone, and state 8 will be forced to transition directly to state 11 "Respond RR2." Similarly, if a kill chain execution has been returned from the "Respond RR2" state to "Search," it is not then able to enter "Respond RR1" based on elapsed time, because the ASCM has already passed through the front half of Range Ring 1.

Using Real Options Valuation's statistical modeling and simulation tool Risk Simulator, a Monte Carlo simulation with 5000 trials for each scenario was executed for the Markov Kill Chain model. For these trials, the mean state times and their distributions serve as input assumptions and the final state of each run—hard kill, soft kill, or no kill—serves as the output forecast. This resulted in data being collected showing the number of runs that ended in each final state over 5000 runs for the medium threat ASCM traveling at cruise speed in OPSIT 1A (Scenario 1), the medium threat ASCM traveling at cruise speed in OPSIT 1B (Scenario 2), the high threat ASCM traveling at terminal speed in OPSIT 1B (Scenario 3), and the medium threat ASCM traveling at cruise speed in OPSIT 1B without Range Ring 2 and Range Ring 3 for engagement (Scenario 4).

4. Kill Chain Model Results and Analysis

Table 4 displays the results of Scenario 1, Scenario 2, and Scenario 4 in numerical and percentage values.

Table 4. Results of Markov Kill Chain Analysis Scenarios 1, 2, and 4 (5000 Runs)



	OPSIT 1A Scenario 1		OPSIT 1B Scenario 2		OPSIT 1B w/o RR 2&3 Scenario 4	
Hard Kills	4030	81%	2467	49%	4064	81%
Soft Kills	0	0%	2108	42%	0	0%
No Kill	970	19%	425	9%	936	19%

Figure 29 displays the total percentage of hard kills and soft kills for Scenario 1, which was OPSIT 1A with a medium threat at cruise speed, versus Scenario 2, which was OPSIT 1B with a medium threat at cruise speed. There are no soft kills in Scenario 1 because the ASCM does not pass through Range Ring 2 or Range Ring 3, so the USV is only able to engage with SAMs. In Scenario 2, when the USV is able to respond with soft-kill deception countermeasures and EA, roughly 10% more threats are defeated.

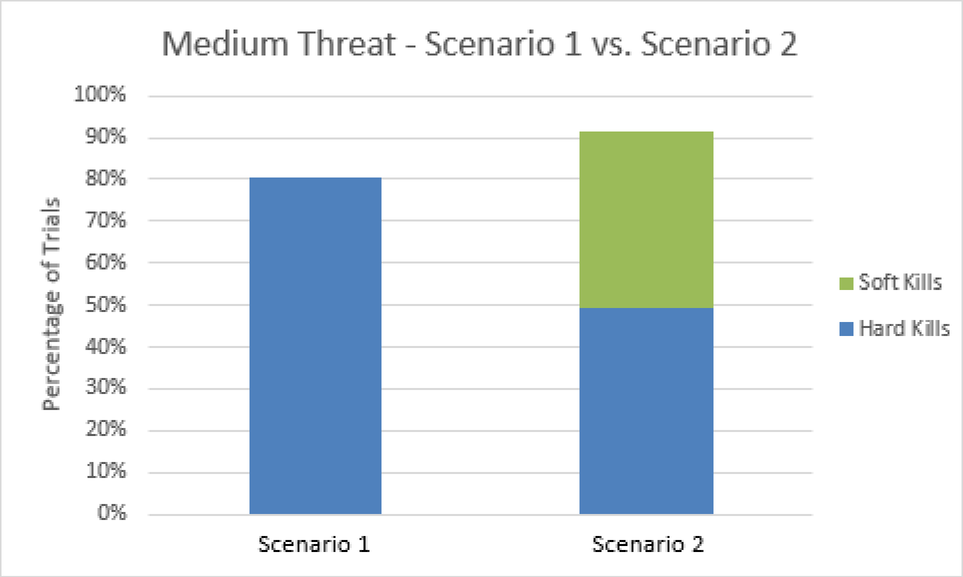


Figure 29. USV Percentage of Kills in Scenarios 1 and 2 (5000 Runs)

Figure 30 displays the percentage of hard kills and soft kills for Scenario 2, which was OPSIT 1B with a medium threat at cruise speed, versus Scenario 4, which was the same as Scenario 2 except with Range Ring 2 and Range Ring 3 removed. There are no soft kills in Scenario 4 because the USV does not respond with soft-kill deception countermeasures or EA. The USV is able to engage with SAMs on the front half and the back half in both of these scenarios. Again, the scenario where the USV employs both hard-kill and soft-kill methods proves more effective by approximately 10%.

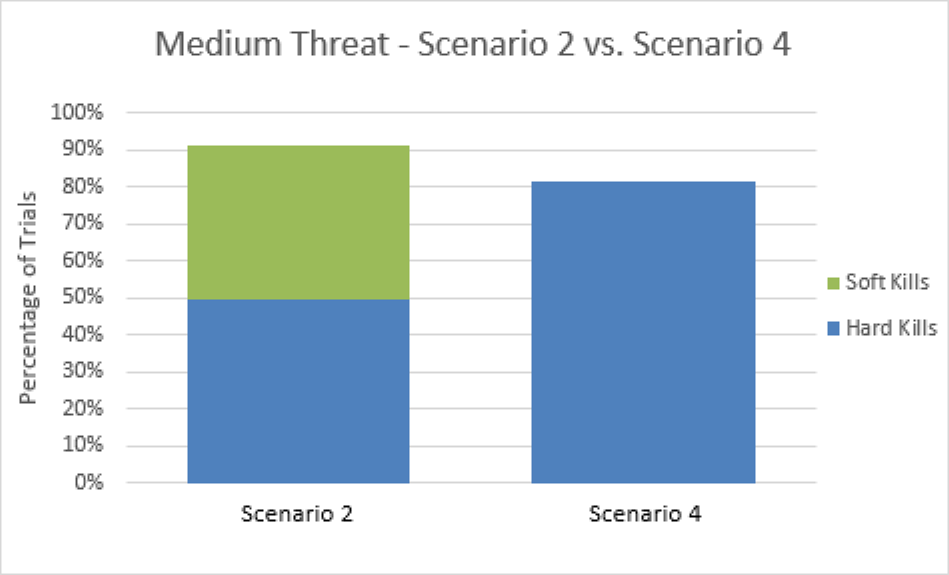


Figure 30. USV Percentage of Kills in Scenarios 2 and 4 (5000 Runs)

Scenario 3, the high threat at terminal speed, was also completed in the model. The results of this model indicated that at the time state 6 "Networked TEWA" was completed—representing when the SAG provided authorization to the USV to respond—the ASCM had already passed through all the range rings around the USV. The ASCM was therefore un-engageable by the USV, so no response options were employed. In terms of the metric of interest, there were 100% no kills (zero successful engagements).

In Scenario 1 and Scenario 4, the USV successfully engaged the threat 81% of the time, and in Scenario 2, the USV successfully engaged the threat 91% of the time. These kill chain analysis results therefore show the USV would provide the SAG with a defensive advantage against the medium threat ASCM.

B. USV CUEING TIME SERIES ANALYSIS

1. Time Series Analysis Description

Positioning the USV as a forward sensor platform is expected to offer the SAG additional time to react to inbound missile threats by having the USV serve as an early warning system. If the USV detects the missile, the SAG can be expected to receive alerts from the USV. This is especially useful since the proposed USV platform can provide target tracks to the SAG, enabling the SAG to fire beyond its organic detection distance, or radar horizon. For the purposes of this assessment, the rules of engagement are assumed to permit firing on over-the-horizon inbound missile threats.

Figure 31 presents the baseline case of a SAG against a missile threat without any USVs. Figure 32 displays OPSIT 2A, in which there is a SAG with a USV stationed off the threat axis such that it can only identify inbound threats tangential to its maximum detection range. This represents the minimal early warning benefit early detection scenario. Figure 33, on the other hand, represents the maximum benefit early detection scenario, where the USV is stationed on the threat axis with the inbound threat ASCM passing directly overhead the USV, as prescribed by OPSIT 2B.

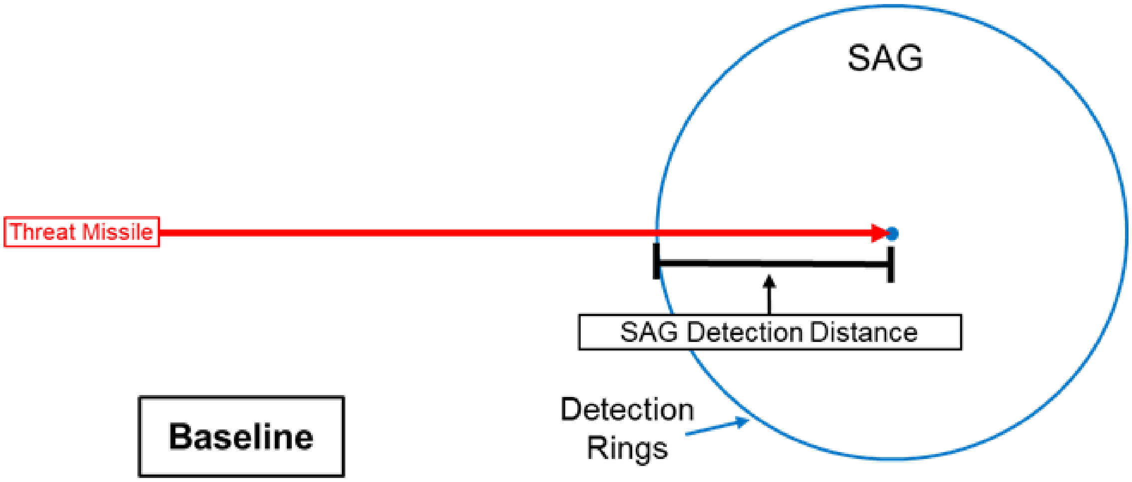


Figure 31. Topdown View of ASCM Threat against SAG—Baseline Case

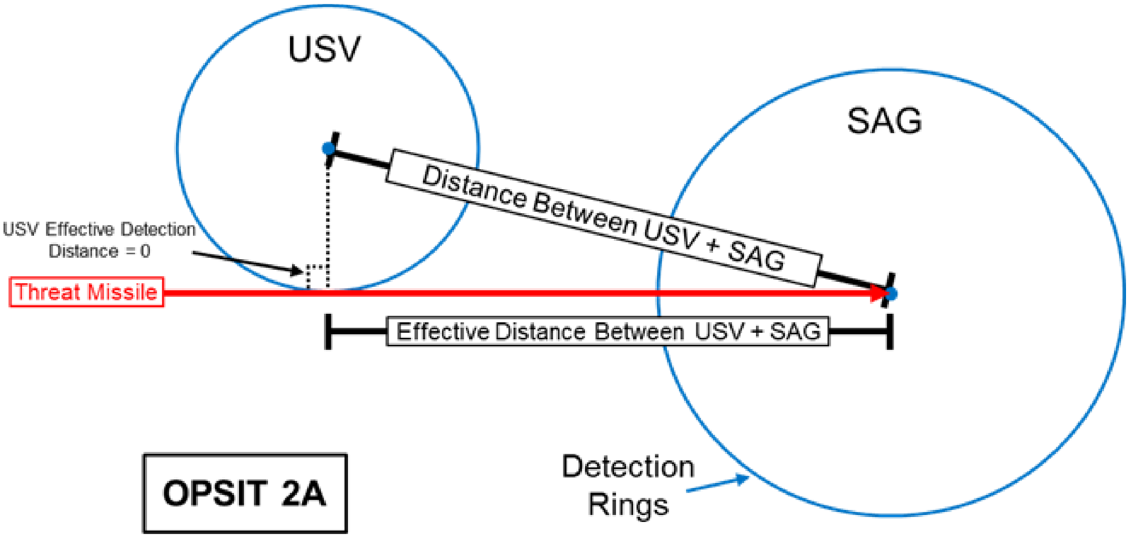


Figure 32. Topdown View of ASCM Threat against SAG—OPSIT 2A

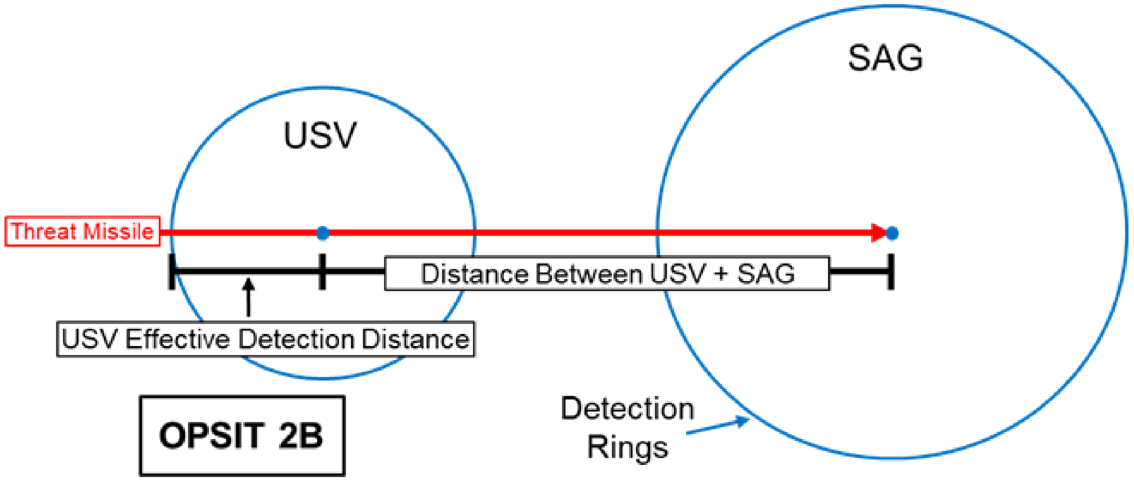


Figure 33. Topdown View of ASCM Threat against SAG—OPSIT 2B

In each of these situations, the SAG is modeled as a single point. The circles around the USV and the SAG represent the detection range rings for their onboard detection systems. In Figure 32 and Figure 33, the “Distance Between USV + SAG” is the straight-line distance measurement between the USV’s position and the SAG’s position. The

"Effective Distance Between USV + SAG" is the straight-line separation between the USV and the SAG along the threat axis. For OPSIT 2A, the threat axis is tangential to the USV's maximum detection range. Thus, the effective USV to SAG distance is one side of the triangle formed by the USV detection range and the distance between the USV and SAG. The effective distance between units is not displayed for OPSIT 2B because the USV is on the threat axis in that scenario, so the effective distance is therefore equal to the "Distance Between USV + SAG".

Similarly, the "USV Effective Detection Distance" is the separation between the USV and the point of ASCM detection by USV sensors measured along the threat axis. In OPSIT 2A, there is no separation along the threat axis between the USV position and the point of ASCM detection by its sensors, so the effective USV detection distance is equal to zero. In OPSIT 2B, the USV effective detection distance is afforded by the entirety of the radius of the USV detection range. This is the maximum early warning benefit scenario.

The effective early warning benefit depends on the detection made in the baseline case due to the SAG's organic sensors, the effective distance between the USV and the SAG, and the USV effective detection distance. Since the effective USV detection distance is reduced to zero in OPSIT 2A, the early warning benefit is attributed solely to the effective distance between the USV and SAG minus the detection made in the baseline case. For OPSIT 2B, the early warning benefit is attributed to removing the baseline case detection from the sum of the effective USV detection distance and the effective distance between the USV and SAG.

For each of the scenarios in this model, an assessment of the time from initial detection until the ASCM reaches the SAG was made for each of the three threat missiles. The times obtained from analyzing the USV scenarios were compared against the baseline case, and the resulting early detection times were then used to quantitatively assess whether this early detection afforded by screening USVs provided the SAG with extra counter-fire opportunities and was therefore tactically relevant.

2. Time Series Analysis Inputs

To begin the assessment, assumptions were made consistent with performance information for the threat missiles. Missile flight profile altitudes of 20 meters for cruise and five meters for terminal were based on data common to all three missiles (Jane's by IHS Markit 2018a, 2018c, 2018d, 2018e, 2018f, 2018h). Information about cruise to terminal transition standoff distances from their targets as well as information regarding presence of terminal pop-up maneuvers could not be identified in the unclassified research. The cruise to terminal mode transition standoff distance assumptions were therefore made based on educated guess, and threat ASCMs were treated as targets proceeding straight inbound at terminal altitude (five meters) and speed with no additional pop-up or zig-zag maneuvers. For each missile, the transition from cruise to terminal mode is treated as an instantaneous event.

The following list summarizes these assumptions:

1. Each missile operates in a sea-skimming mode following transition to cruise.
2. The cruise altitude of each sea-skimming missile is 20 meters (Jane's by IHS Markit 2018a, 2018c, 2018d, 2018e, 2018f, 2018h).
3. The terminal altitude of each sea-skimming missile is five meters (Jane's by IHS Markit 2018a, 2018c, 2018d, 2018e, 2018f, 2018h).
4. The low-missile threat, C-704, and the medium missile threat, CSS-N-8 Saccade, maintain their cruise speeds—Mach 0.875 and Mach 0.9, respectively (Jane's by IHS Markit 2018c, 2018d, 2018f, 2018h).
5. The high missile threat, SS-N-27 Sizzler, has a terminal supersonic speed of Mach 2.9 (Jane's by IHS Markit 2018a).
6. The low and medium threats have an assumed transition from cruise to terminal modes 10 nautical miles (18.52 kilometers) from their target.

7. The high missile threat has an assumed transition from cruise to terminal modes 20 nautical miles (37.04 kilometers) from its target.

Given the cruise and terminal altitudes of the threat missile sea-skimming profiles, the USV and SAG detection distances could be derived from Equation 1, the simplified radar horizon equation against a target at elevation in metric units. Utilizing the earlier assumption that the USV radar height is 12 meters and given the threat missile profile altitudes of 20 meters cruise altitude and five meters terminal altitude (Jane's by IHS Markit 2018a, 2018c, 2018d, 2018e, 2018f, 2018h), the resultant USV maximum detection range is 33 kilometers for missiles in cruise mode and 24 kilometers for missiles in terminal mode. Threat missile cruise and terminal profile altitudes were treated as constants in this analysis, and USV radar height will be further explored.

Assumptions were made about the probability of the SAG and USV detecting ASCMs at these maximum detection ranges based upon Smith's 2010 thesis "Using Kill-Chain Analysis to Develop Surface Ship CONOPs To Defend Against Anti-Ship Cruise Missiles." In his analysis, Smith evaluated characteristics of 19 missiles and determined the probability for the targeted ship to detect the ASCM was greater than 0.995 at the radar range horizon (2010). Further, 16 of his 19 missiles had at least a 0.999 probability of detection (Smith 2010). Based on these findings, this time series analysis model assumes a 100% probability of detection at the maximum detection distances for simplicity.

To implement the model, the following input variables were identified:

1. Blue Forces: Distance between USV and SAG
2. Blue Forces: USV Antenna Height
3. Blue Forces: SAG Antenna Height

The following inputs were also identified but set as constants in this analysis:

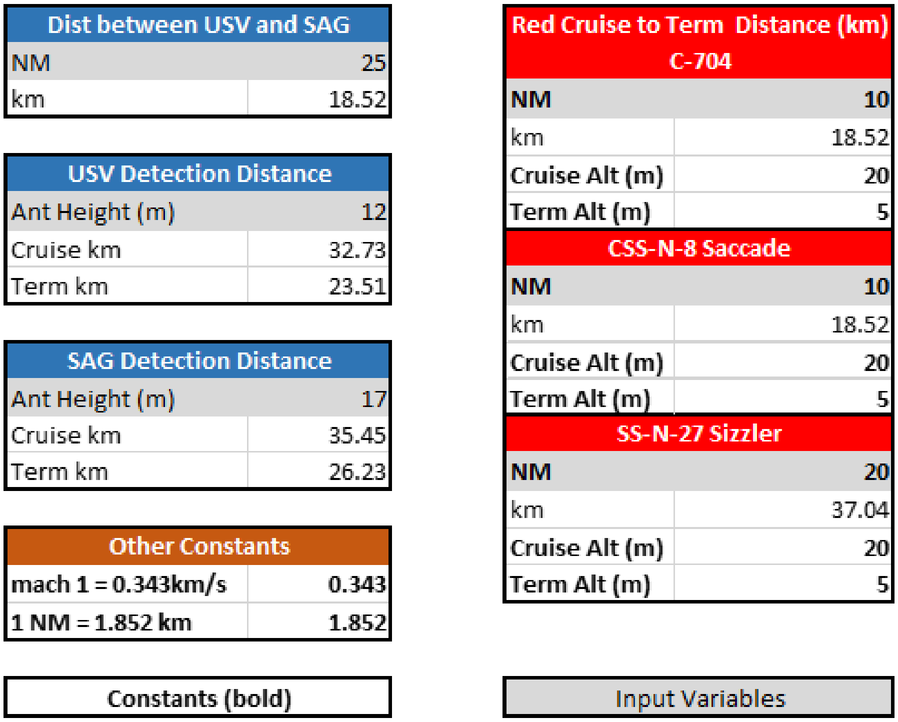
1. Red Forces: Low Missile Threat (C-704) Cruise to Terminal Distance from Target

2. Red Forces: Medium Missile Threat (YJ-83 or CSS-N-8) Cruise to Terminal Distance from Target

3. Red Forces: High Missile Threat (3M-54 or SS-N-27) Cruise to Terminal Distance from Target

The combination of known threat missile speeds, calculated blue force detection distances, and assumed USV to SAG standoff distances was determined to be sufficient to calculate assessed total detection time for OPSITs 2A, 2B, and the baseline case of the SAG without a USV screen. An example of inputs for this time-distance based model is presented in Table 5, where variable inputs are highlighted in gray, constants are typed in bold, and calculations based on the variable inputs and constants are shown normally, with no highlight or text effects. The missile cruise to terminal distance input variables were held constant throughout this analysis but could serve as independent variables in future analyses. All standoff distances are given in nautical miles (NM) and converted into kilometers (km) using the conversion constants.

Table 5. Example USV Cueing Time Series Analysis Model Inputs



Dist between USV and SAG	
NM	25
km	18.52

USV Detection Distance	
Ant Height (m)	12
Cruise km	32.73
Term km	23.51

SAG Detection Distance	
Ant Height (m)	17
Cruise km	35.45
Term km	26.23

Other Constants	
mach 1 = 0.343km/s	**0.343**
1 NM = 1.852 km	**1.852**

Red Cruise to Term Distance (km)	
C-704	
NM	**10**
km	18.52
Cruise Alt (m)	**20**
Term Alt (m)	**5**
CSS-N-8 Saccade	
NM	**10**
km	18.52
Cruise Alt (m)	**20**
Term Alt (m)	**5**
SS-N-27 Sizzler	
NM	**20**
km	37.04
Cruise Alt (m)	**20**
Term Alt (m)	**5**

Constants (bold)

Input Variables

3. Time Series Analysis Model Execution

In the evaluation of each scenario against all three missile threats, the metric of interest is total time-to-SAG. Time-to-SAG is a representation in seconds of the amount of missile flight time from the first detection by any system to the point where the missile reaches the logical center of the SAG, synonymous with a missile hit.

For the baseline SAG-only scenario, the time-to-SAG metric is calculated by assessing the missile speed against the SAG organic detection distance. For the OPSIT 2A off axis scenario, the total time-to-SAG is calculated by assessing the missile speed against the effective USV to SAG distance as in Figure 32. This scenario represents a detection scenario with the least amount of early warning benefit to the SAG. If the effective USV to SAG distance is less than the SAG organic detection distance, the latter is used to assess the time-to-SAG calculation because the early warning benefit will be zero seconds in that case. The USV detection range for OPSIT 2A scenarios will be based on threat missiles in cruise profiles.

The rationale for this is based on the geometries presented in Figure 34. Minimal early warning in OPSIT 2A requires that the USV detection occur at the tangent of its maximum detection range. If the missile is detected while in its cruise phase, the detection range is greater than the detection range associated with the terminal phase missile. If the distance between the USV and the SAG is held constant, this scenario results in a counterintuitive result that the effective distance between the USV and SAG is greater when the detection ring is smaller and the missile is in its terminal phase. As the desired result is to determine the minimal early warning time, the effective distance between the USV and SAG in this evaluation will be based on cruise phase derived detection rings and the resulting smaller effective distances.

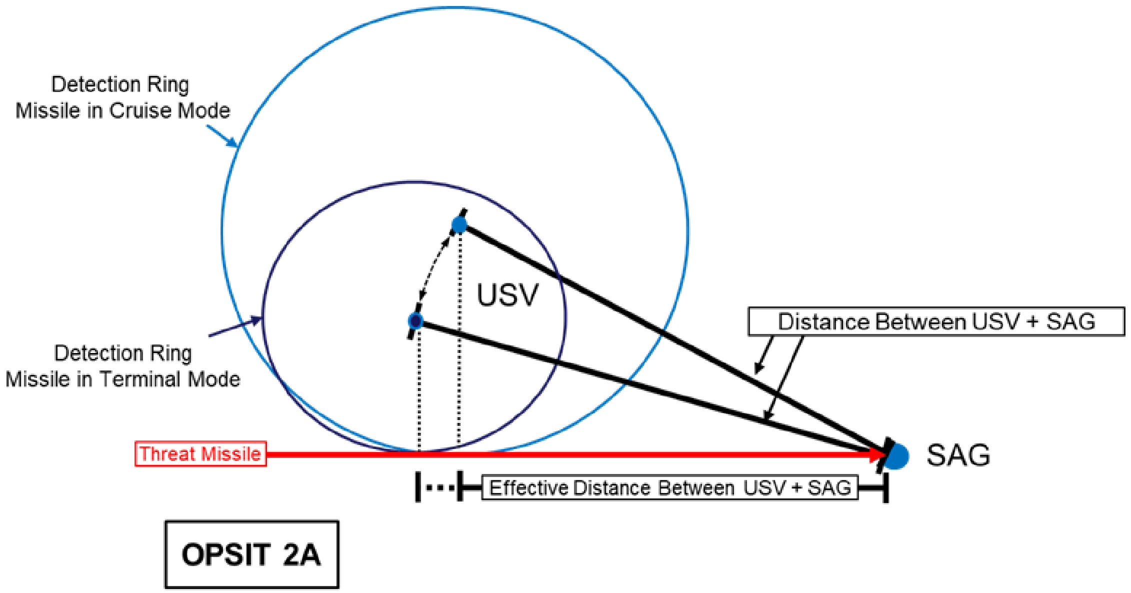


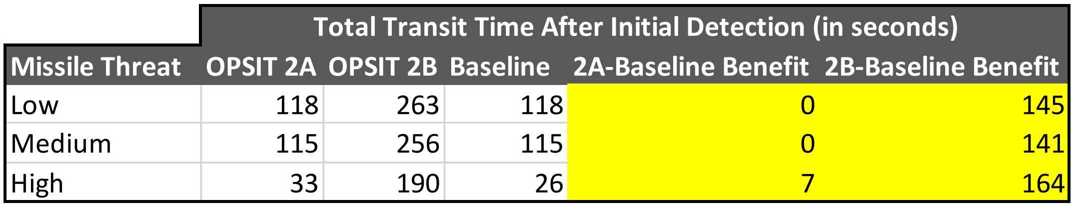
Figure 34. Topdown View of ASCM USV Detection Ranges in OPSIT 2A

For the OPSIT 2B on-axis scenario, the missile speed is assessed against the USV detection distance and the USV to SAG distance as in Figure 33. If the total effective USV early detection distance falls inside the SAG organic detection distance, the latter is used to assess the time-to-SAG calculation. This would represent a situation with no early warning benefit.

For each of the three scenarios, the threat missile transition from cruise to terminal mode is accounted for in terms of USV and SAG detection ranges as missile altitude changes. In the case of a terminal boost, such as the high threat SS-N-27 Sizzler, the model treats the transition from a lower cruise speed to the higher terminal speed as an instantaneous event, though in reality there is a lag.

The model results for the set of inputs given in Table 5 are presented in Table 6. These results reflect the time, rounded to the nearest second, between the first detection by any ship and the time the missile will hit the SAG. Results are displayed for OPSITs 2A, 2B, and the baseline case against the three threat missiles. The yellow highlighted 2A-Baseline Benefit and 2B-Baseline Benefit columns present the differences between the OPSITs and the baseline, which serve as the early warning detection benefit afforded by the USV in either OPSIT. The early warning detection benefit is a combination of the effective USV detection range and the effective USV distance from the SAG minus the SAG detection range. For example, in the case of the low threat missile for inputs specified in Table 5, OPSIT 2B presents 263 seconds of total detection time. Removing the 118 seconds of organic SAG detection time shows that the USV offers a net 145 seconds of early warning detection time benefit against the low threat missile in OPSIT 2B.

Table 6. Early Detection Benefit Outputs for Inputs from Table 5



	Total Transit Time After Initial Detection (in seconds)				
Missile Threat	OPSIT 2A	OPSIT 2B	Baseline	2A-Baseline Benefit	2B-Baseline Benefit
Low	118	263	118	0	145
Medium	115	256	115	0	141
High	33	190	26	7	164

4. Time Series Analysis Results

The USV-SAG distance and USV antenna height inputs were separately varied to explore the relationship between those inputs and the early warning benefit. As the USV-SAG distance was varied in the model, the USV antenna height was kept constant at 12 meters. This value was selected by taking two thirds of the given SAG antenna height of 17 meters. As USV antenna height was varied, the USV-SAG distance was kept constant at 25 nautical miles, which was selected to place the USV just over five nautical miles outside the SAG detection distance for missiles in their cruise phase.

The relationship of these input variables against the metric of interest—early warning detection time—is illustrated in Figure 35 and Figure 36. Each chart shows clear delineations in OPSIT results for the given relationship, with OPSIT 2B providing a distinct advantage in early warning detection time.

Figure 35 shows the early warning detection time compared to the USV-SAG distance has immediate benefit in OPSIT 2B and benefit in OPSIT 2A starting at a 25 NM distance between the USV and SAG. This inflection point is a result of the USV detection distance surpassing that of the organic SAG detection range.

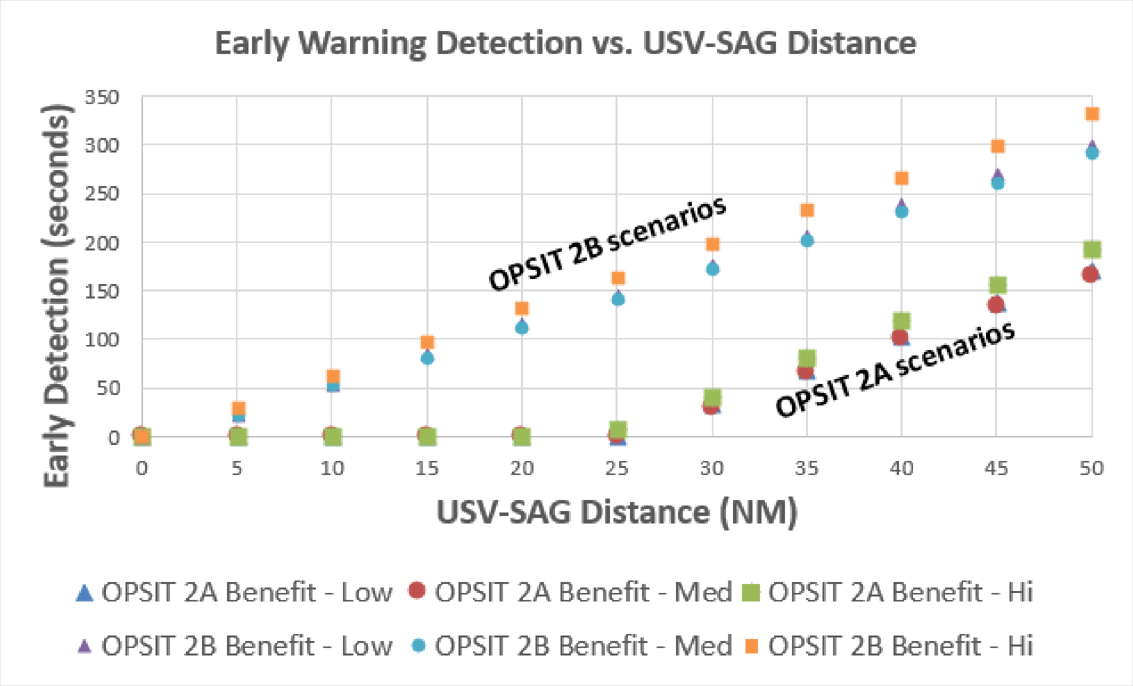


Figure 35. Early Warning Detection versus USV-SAG Distance

Figure 36 displays the early warning detection time compared to the USV antenna height. The USV antenna height has a direct effect on the USV detection distance. For the missiles against the OPSIT 2B scenarios, as the antenna height and detection distance increase, so does the early warning detection time as one might expect. Counterintuitively, as the antenna height and detection distance increase, the OPSIT 2A scenarios display a decline in USV early warning detection distance. This is a result of the geometries described in Figure 34. The OPSIT 2A scenario is the minimal early warning benefit with detection occurring just as the missile passes tangentially to the maximum USV detection range. In order to maintain this with the USV-SAG distance held constant, the effective distance between the USV and the SAG decreases as the USV antenna height and detection distance increase, resulting in lower early detection times.

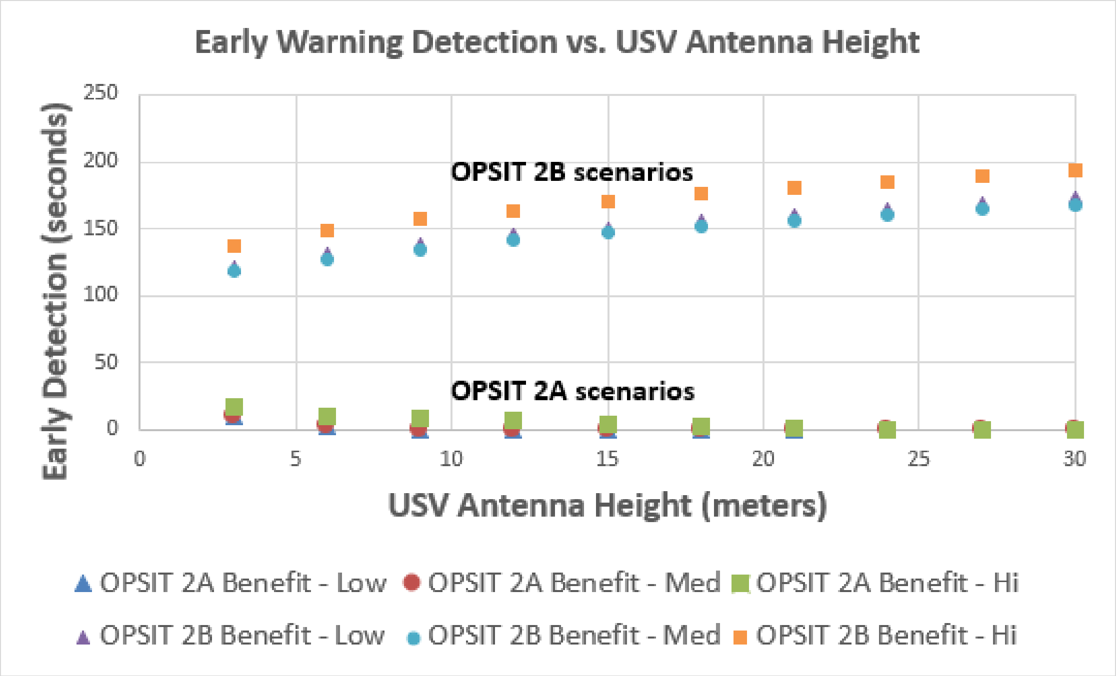


Figure 36. Early Warning Detection versus USV Antenna Height

From the analysis described, it can be concluded that a forward-positioned USV can provide the SAG an increased reaction time to respond to the missiles. To better quantify the above findings and determine if this increased reaction time is tactically relevant to the SAG, Smith's (2010) methodology was again leveraged.

In his work, Smith describes 19 different missiles of varying capabilities and their assessed effectiveness against a notional surface ship equipped with long-range and short-range SAMs and a CIWS (Smith 2010). Of particular interest to this study is Smith's timeline analysis of counter-fire shot opportunities from the ship against the threat missiles in his "Table 4. Line diagram range results" (Smith 2010, 28). An adapted version of this table is presented in Table 7. In this table, columns R1 through R8 represent counter-fire opportunities from a SAM launching unit. The data inside column R1 represents the intercept range in kilometers for the first SAM launched against the threat missile. R2 is the intercept range for the second, and so on. Some shot opportunities, however, will not be viable due to the threat missile being beyond the radar horizon range. These are shaded in gray. For example, against the CSS-N-8 Saccade, the platform has seven columns populated with data (R1–R7) but can only realize three counter-fire opportunities since R1–R4 are beyond the radar horizon and shaded gray.

Table 7. Ship Counter-fire Shot Opportunities against ASCMs by Range (km). Adapted from Smith (2010).

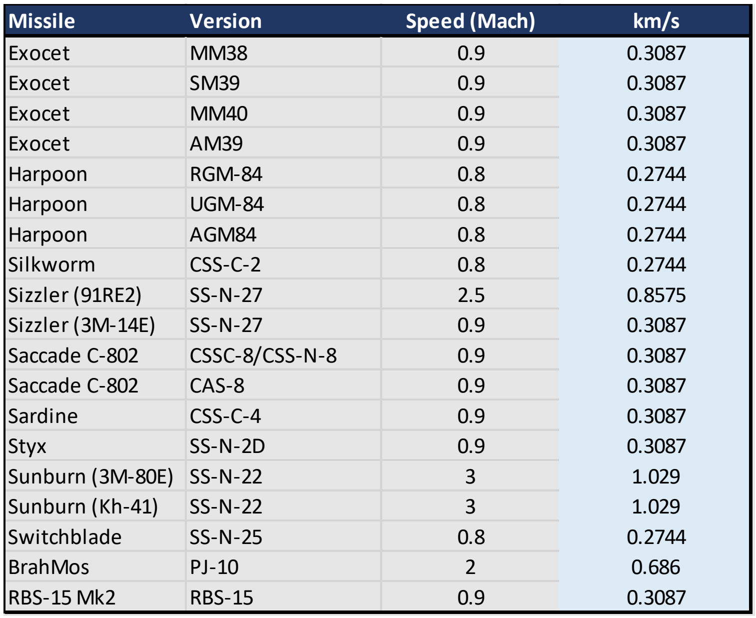
Shots by Range (km)					Radar Horizon				
Missile	**Version**	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**
Exocet	MM38	32	23	16	9	5			
Exocet	SM39	42	38	19	12	8			
Exocet	MM40	56	40	30	20	14	8		
Exocet	AM39	56	40	30	20	14	8		
Harpoon	RGM-84	103	78	55	39	25	18	9	
Harpoon	UGM-84	103	78	55	39	25	18	9	
Harpoon	AGM84	140	99	74	55	40	28	10	
Silkworm	CSS-C-2	74	55	41	31	22	14	9	4
Sizzler (91RE2)	SS-N-27	22	7						
Sizzler (3M-14E)	SS-N-27	122	80	65	42	26	19	8	
Saccade C-802	CSSC-8/CSS-N-8	84	55	40	30	20	12	9	
Saccade C-802	CAS-8	97	72	54	38	29	20	14	8
Sardine	CSS-C-4	33	23	15	9	4			
Styx	SS-N-2D	73	54	39	28	19	11	7	
Sunburn (3M-80E)	SS-N-22	55	23	7					
Sunburn (Kh-41)	SS-N-22	51	20	6					
Switchblade	SS-N-25	98	80	55	40	30	20	11	7
BrahMos	PJ-10	160	75	48	23				
RBS-15 Mk2	RBS-15	153	116	82	64	45	36	24	16

To make these assessments, Smith considered missile factors such as speed, radar cross section and the resultant detectability, and cruise altitude. Smith also included the SS-N-27 Sizzler missile in his study. From the matching row, it is shown that Smith assessed seven shot opportunities against it at the ranges in kilometers specified in columns R1 through R7. Only three shot opportunities are assessed to be within the radar horizon meaning that the missile is detectable and can be counter-fired upon. In the case of a lower capability missile like the SS-N-22 Sunburn (Kh-41), only three total shot opportunities are assessed with two being within the radar horizon.

Using Smith's framework, the early warning detection times afforded by the USV can be introduced and ship or SAG counter-fire impacts can be assessed. Providing the ship or SAG additional early warning detection will effectively push back the radar horizon allowing for more counter-fire opportunities. This will correspond to the gray shaded area in Table 7 moving to the left (un-shading a previously shaded cell), denoting more shot opportunities available to the SAG compared to a no-USV scenario. An increased number of shot opportunities will thus reveal the utility of the USV-SAG cueing in a quantifiable manner.

To assess these shot opportunities against the early warning detection timelines afforded by the USV, the range-based shot opportunities must be translated into time-based shot opportunities. Using Smith's missile speeds in his "Table 24. RCS and probability of detection computations for several ASCMs at 167 km and at their radar horizon," the speed of each missile is calculated in kilometers per second as presented in Table 8 and applied to Table 7 to produce the time-based shot opportunities chart presented in Table 9 (Smith 2010, 55). Table 9 therefore depicts the number of shot opportunities in columns R1–R8 with the time-to-SAG entered in each cell where there is a shot opportunity, provided detection occurs. Cells shaded in gray again represent when the missile is beyond the radar horizon, and therefore not detected, so the shot opportunity is lost.

Table 8. Smith's Missile Speeds Calculated in Kilometers per Second. Adapted from Smith (2010).



Missile	Version	Speed (Mach)	km/s
Exocet	MM38	0.9	0.3087
Exocet	SM39	0.9	0.3087
Exocet	MM40	0.9	0.3087
Exocet	AM39	0.9	0.3087
Harpoon	RGM-84	0.8	0.2744
Harpoon	UGM-84	0.8	0.2744
Harpoon	AGM84	0.8	0.2744
Silkworm	CSS-C-2	0.8	0.2744
Sizzler (91RE2)	SS-N-27	2.5	0.8575
Sizzler (3M-14E)	SS-N-27	0.9	0.3087
Saccade C-802	CSSC-8/CSS-N-8	0.9	0.3087
Saccade C-802	CAS-8	0.9	0.3087
Sardine	CSS-C-4	0.9	0.3087
Styx	SS-N-2D	0.9	0.3087
Sunburn (3M-80E)	SS-N-22	3	1.029
Sunburn (Kh-41)	SS-N-22	3	1.029
Switchblade	SS-N-25	0.8	0.2744
BrahMos	PJ-10	2	0.686
RBS-15 Mk2	RBS-15	0.9	0.3087

Table 9. Ship Counter-fire Shot Opportunities against ASCMs by Time (Seconds). Adapted from Smith (2010).

Shots by Time (s)					Radar Horizon				
Missile	**Version**	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**
Exocet	MM38	104	75	52	29	16			
Exocet	SM39	136	123	62	39	26			
Exocet	MM40	181	130	97	65	45	26		
Exocet	AM39	181	130	97	65	45	26		
Harpoon	RGM-84	375	284	200	142	91	66	33	
Harpoon	UGM-84	375	284	200	142	91	66	33	
Harpoon	AGM84	510	361	270	200	146	102	36	
Silkworm	CSS-C-2	270	200	149	113	80	51	33	15
Sizzler (91RE2)	SS-N-27	26	8						
Sizzler (3M-14E)	SS-N-27	395	259	211	136	84	62	26	
Saccade C-802	CSSC-8/CSS-N-8	272	178	130	97	65	39	29	
Saccade C-802	CAS-8	314	233	175	123	94	65	45	26
Sardine	CSS-C-4	107	75	49	29	13			
Styx	SS-N-2D	236	175	126	91	62	36	23	
Sunburn (3M-80E)	SS-N-22	53	22	7					
Sunburn (Kh-41)	SS-N-22	50	19	6					
Switchblade	SS-N-25	357	292	200	146	109	73	40	26
BrahMos	PJ-10	233	109	70	34				
RBS-15 Mk2	RBS-15	496	376	266	207	146	117	78	52

Gray Denotes Missed Opportunies due to Missile Being Beyond Radar Horizon

From these time-based shot opportunities, the impacts of early warning afforded by the USV can be assessed. The three threat missiles in this study were characterized as low, medium, and high threat missiles based on their relative capabilities with focus on speed and range. The 19 missiles in Smith's study can be similarly binned based their performance characteristics for range, speed, and detectability. For each missile in Smith's study, the metric of interest was compared against the population, and three equal sized bins were created covering the span of the worst to best performing characteristics. For each metric, missiles who met the top performing bin criteria were awarded one point, the middle third were awarded two points, and the bottom third were awarded three points. As such, low points indicate a higher threat missile. Metric scores by missile were tallied for a total missile score range from 4–9, resulting in missiles being assessed as a high threat with a score of 4–5, a medium threat with a score of 6–7, and low threat with a final score of 8–9. Smith's original 19 missiles assessed against low, medium, and high threat bins are presented in Table 10.

Table 10. Low, Medium, and High Threat Binning Applied to Missiles from Smith's Analysis

Smith Thesis Missile Chart		Low is Good				
Missile	**Version**	**Range Bin**	**Radar Horizon Bin**	**Speed Bin**	**Score**	**Assessed Threat**
Exocet	MM38	3	1	3	7	Medium
Exocet	MM40	3	1	3	7	Medium
Exocet	SM39	3	1	3	7	Medium
Exocet	AM39	3	1	3	7	Medium
Harpoon	RGM-84	2	1	3	6	Medium
Harpoon	UGM-84	2	1	3	6	Medium
Harpoon	AGM84	1	1	3	5	High
Silkworm	CSS-C-2	3	3	3	9	Low
Sizzler	(91RE2) SS-N-27	3	1	1	5	High
Sizzler	(3M-14E) SS-N-27	1	1	3	5	High
C-802 [Ship]	C-802	3	1	3	7	Medium
C-802 [Air]	C-802(CAS-8)	3	1	3	7	Medium
Sardine	CSS-C-4	3	2	3	8	Low
Styx	SS-N-2	3	2	3	8	Low
Sunburn (3M-80E) [A]	SS-N-22	3	2	1	6	Medium
Sunburn (Kh-41) [A,D]	SS-N-22	3	1	1	5	High
Switchblade	SS-N-25	3	1	3	7	Medium
BrahMos	PJ-10	1	1	2	4	High
RBS-15	RBS-15	2	1	3	6	Medium

With the Smith missiles assessed in terms of low, medium, and high threats, the USV cueing early warning detection times calculated in the OPSIT 2A and OPSIT 2B models could be incorporated into the baseline time-based counter-fire shot opportunities chart from Table 9, using the following input parameters:

1. Distance Between USV and SAG: 25 NM
2. USV Antenna Height: 12 meters
3. SAG Antenna Height: 17 meters

The counter-fire opportunities were thus updated to include USV cueing and reassessed. The results for OPSIT 2A are shown in Table 11, and those for OPSIT 2B are in Table 12. The early warning detection time benefits, in seconds, is displayed for each missile in the far-right column in these tables. Note there are no additional counter-fire shot opportunities against any missile in OPSIT 2A, as shown by comparing Tables 9 and 11, but there are several additional shot opportunities in OPSIT 2B as presented by comparing

Tables 9 and 12. This is most easily observed by the reduced number of gray shaded boxes indicating that fewer shot opportunities are beyond the radar horizon, and additional counter-fire opportunities are therefore available.

Table 11. Ship Counter-fire Shot Opportunities by Time against ASCMs with OPSIT 2A Benefits Considered (USV-SAG Distance = 25 NM)

OPSIT 2A (all value are in seconds)											
Missile	**Version**	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**From Missile Info Tab**	**2A Benefit (s)**
Exocet	MM38	104	75	52	29	16				Medium	0
Exocet	SM39	136	123	62	39	26				Medium	0
Exocet	MM40	181	130	97	65	45	26			Medium	0
Exocet	AM39	181	130	97	65	45	26			Medium	0
Harpoon	RGM-84	375	284	200	142	91	66	33		Medium	0
Harpoon	UGM-84	375	284	200	142	91	66	33		Medium	0
Harpoon	AGM84	510	361	270	200	146	102	36		High	7
Silkworm	CSS-C-2	270	200	149	113	80	51	33	15	Low	0
Sizzler (91RE2)	SS-N-27	26	8							High	7
Sizzler (3M-14E)	SS-N-27	395	259	211	136	84	62	26		High	7
Saccade C-802	CSSC-8/CSS-N-8	272	178	130	97	65	39	29		Medium	0
Saccade C-802	CAS-8	314	233	175	123	94	65	45	26	Medium	0
Sardine	CSS-C-4	107	75	49	29	13				Low	0
Styx	SS-N-2D	236	175	126	91	62	36	23		Low	0
Sunburn (3M-80E)	SS-N-22	53	22	7						Medium	0
Sunburn (Kh-41)	SS-N-22	50	19	6						High	7
Switchblade	SS-N-25	357	292	200	146	109	73	40	26	Medium	0
BrahMos	PJ-10	233	109	70	34					High	7
RBS-15 Mk2	RBS-15	496	376	266	207	146	117	78	52	Medium	0

Gray Denotes Missed Opportunies due to Missile Being Beyond Radar Horizon

Table 12. Ship Counter-fire Shot Opportunities by Time against ASCMs with OPSIT 2B Benefits Considered (USV-SAG Distance = 25 NM)

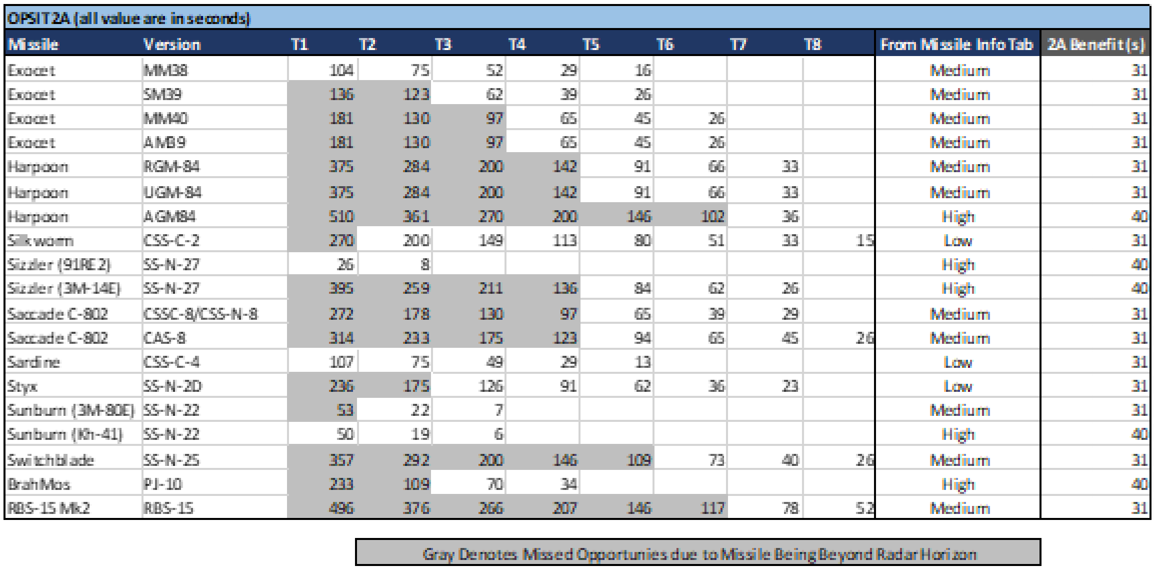
OPSIT 2B (all value are in seconds)											
Missile	**Version**	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**From Missile Info Tab**	**2B Benefit (s)**
Exocet	MM38	104	75	52	29	16				Medium	141
Exocet	SM39	136	123	62	39	26				Medium	141
Exocet	MM40	181	130	97	65	45	26			Medium	141
Exocet	AM39	181	130	97	65	45	26			Medium	141
Harpoon	RGM-84	375	284	200	142	91	66	33		Medium	141
Harpoon	UGM-84	375	284	200	142	91	66	33		Medium	141
Harpoon	AGM84	510	361	270	200	146	102	36		High	164
Silkworm	CSS-C-2	270	200	149	113	80	51	33	15	Low	145
Sizzler (91RE2)	SS-N-27	26	8							High	164
Sizzler (3M-14E)	SS-N-27	395	259	211	136	84	62	26		High	164
Saccade C-802	CSSC-8/CSS-N-8	272	178	130	97	65	39	29		Medium	141
Saccade C-802	CAS-8	314	233	175	123	94	65	45	26	Medium	141
Sardine	CSS-C-4	107	75	49	29	13				Low	145
Styx	SS-N-2D	236	175	126	91	62	36	23		Low	145
Sunburn (3M-80E)	SS-N-22	53	22	7						Medium	141
Sunburn (Kh-41)	SS-N-22	50	19	6						High	164
Switchblade	SS-N-25	357	292	200	146	109	73	40	26	Medium	141
BrahMos	PJ-10	233	109	70	34					High	164
RBS-15 Mk2	RBS-15	496	376	266	207	146	117	78	52	Medium	141

Gray Denotes Missed Opportunies due to Missile Being Beyond Radar Horizon

For example, the baseline case in Table 9 shows two viable counter-fire opportunities against an inbound RGM-84 Harpoon in columns T6 and T7, at 66 and 33 seconds, respectively, prior to the missile impacting the ship. The RGM-84 is assessed to be a medium threat per Table 10, and at a USV-SAG spacing of 25 NM in OPSIT 2B, it presents 141 seconds of early warning benefit per Table 12. This table also shows five viable shot opportunities against the RGM-84 in columns T3–T7, at 200, 142, 91, 66, and 33 seconds, which is a benefit of three additional shot opportunities compared to the baseline in Table 9. These times corresponding with each shot opportunity are the same in Table 9, but the engagements at 200, 142, and 91 seconds are outside the radar horizon in that scenario, and therefore not viable opportunities.

Modifying only the USV-SAG spacing input from 25 NM to 30 NM, clear improvement in the number of shot opportunities was discovered in both OPSITs 2A and 2B. These results are shown in Table 13 and Table 14, respectively.

Table 13. Ship Counter-fire Shot Opportunities by Time against ASCMs with OPSIT 2A Benefits Considered (USV-SAG Distance = 30 NM)

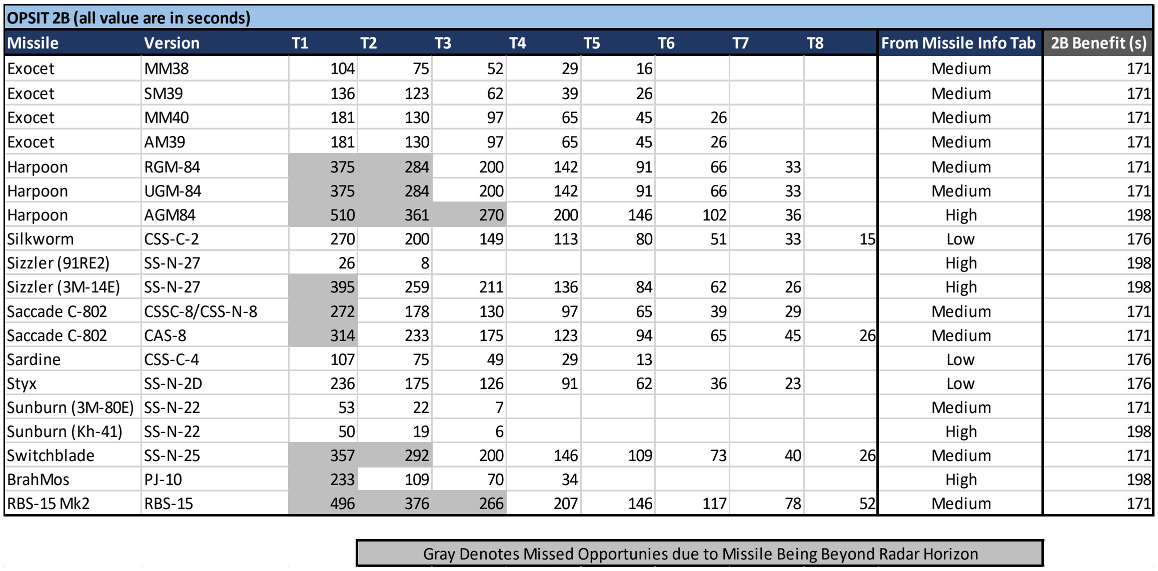


OPSIT 2A (all value are in seconds)

Missile	Version	T1	T2	T3	T4	T5	T6	T7	T8	From Missile Info Tab	2A Benefit (s)
Exocet	MM38	104	75	52	29	16				Medium	31
Exocet	SM39	136	123	62	39	26				Medium	31
Exocet	MM40	181	130	97	65	45	26			Medium	31
Exocet	AM39	181	130	97	65	45	26			Medium	31
Harpoon	RGM-84	375	284	200	142	91	66	33		Medium	31
Harpoon	UGM-84	375	284	200	142	91	66	33		Medium	31
Harpoon	AGM84	510	361	270	200	146	102	36		High	40
Silkworm	CSS-C-2	270	200	149	113	80	51	33	15	Low	31
Sizzler (91RE2)	SS-N-27	26	8							High	40
Sizzler (3M-14E)	SS-N-27	395	259	211	136	84	62	26		High	40
Saccade C-802	CSSC-8/CSS-N-8	272	178	130	97	65	39	29		Medium	31
Saccade C-802	CAS-8	314	233	175	123	94	65	45	26	Medium	31
Sardine	CSS-C-4	107	75	49	29	13				Low	31
Styx	SS-N-2D	236	175	126	91	62	36	23		Low	31
Sunburn (3M-80E)	SS-N-22	53	22	7						Medium	31
Sunburn (Kh-41)	SS-N-22	50	19	6						High	40
Switchblade	SS-N-25	357	292	200	146	109	73	40	26	Medium	31
BrahMos	PJ-10	233	109	70	34					High	40
RBS-15 Mk2	RBS-15	496	376	266	207	146	117	78	52	Medium	31

Gray Denotes Missed Opportunies due to Missile Being Beyond Radar Horizon

Table 14. Ship Counter-fire Shot Opportunities by Time against ASCMs with OPSIT 2B Benefits Considered (USV-SAG Distance = 30 NM)



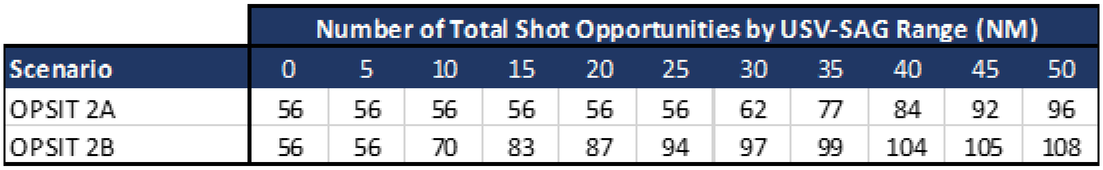
OPSIT 2B (all value are in seconds)

Missile	Version	T1	T2	T3	T4	T5	T6	T7	T8	From Missile Info Tab	2B Benefit (s)
Exocet	MM38	104	75	52	29	16				Medium	171
Exocet	SM39	136	123	62	39	26				Medium	171
Exocet	MM40	181	130	97	65	45	26			Medium	171
Exocet	AM39	181	130	97	65	45	26			Medium	171
Harpoon	RGM-84	375	284	200	142	91	66	33		Medium	171
Harpoon	UGM-84	375	284	200	142	91	66	33		Medium	171
Harpoon	AGM84	510	361	270	200	146	102	36		High	198
Silkworm	CSS-C-2	270	200	149	113	80	51	33	15	Low	176
Sizzler (91RE2)	SS-N-27	26	8							High	198
Sizzler (3M-14E)	SS-N-27	395	259	211	136	84	62	26		High	198
Saccade C-802	CSSC-8/CSS-N-8	272	178	130	97	65	39	29		Medium	171
Saccade C-802	CAS-8	314	233	175	123	94	65	45	26	Medium	171
Sardine	CSS-C-4	107	75	49	29	13				Low	176
Styx	SS-N-2D	236	175	126	91	62	36	23		Low	176
Sunburn (3M-80E)	SS-N-22	53	22	7						Medium	171
Sunburn (Kh-41)	SS-N-22	50	19	6						High	198
Switchblade	SS-N-25	357	292	200	146	109	73	40	26	Medium	171
BrahMos	PJ-10	233	109	70	34					High	198
RBS-15 Mk2	RBS-15	496	376	266	207	146	117	78	52	Medium	171

Gray Denotes Missed Opportunies due to Missile Being Beyond Radar Horizon

In Table 15, the number of total shot opportunities is displayed for each OPSIT against USV-SAG ranges, assessed every five NM from 0–50 NM. This total is the aggregate of all viable shot opportunities for Smith’s 19 missiles and is determined by the count of all shot opportunities inside the radar horizon at each USV-SAG spacing interval. Note, the minimum number of total counter-fire opportunities as assessed by Smith and displayed in Table 7 is 56, and the maximum possible counter-fire opportunities is 113 if all shots displayed in Table 7 were within the radar horizon.

Table 15. Total Counter-fire Shot Opportunities Assessed against USV-SAG Range

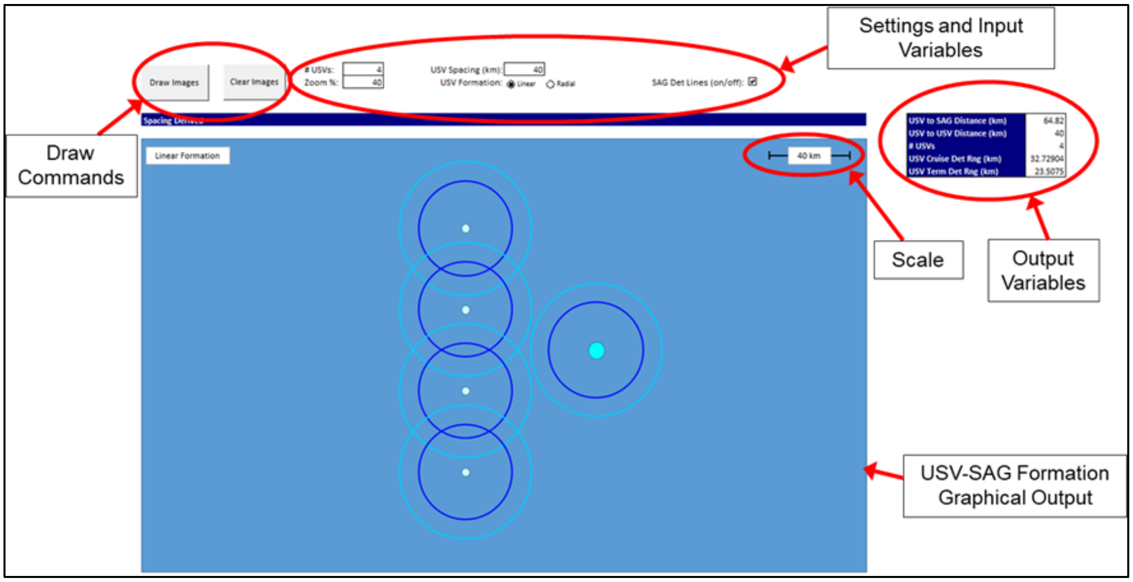


	Number of Total Shot Opportunities by USV-SAG Range (NM)										
Scenario	0	5	10	15	20	25	30	35	40	45	50
OPSIT 2A	56	56	56	56	56	56	62	77	84	92	96
OPSIT 2B	56	56	70	83	87	94	97	99	104	105	108

The above analysis quantifiably determines that the use of a USV as an ASCM screen for SAG defense is viable and tactically useful. The assessed time benefit can be directly translated to additional counter-fire opportunities for the SAG to engage the threat missiles.

C. EVALUATION OF USV GEOMETRIES

To evaluate prospective USV formations with respect to the SAG, the evaluation tool presented in Figure 37 was built to graphically depict potential formations. This tool was developed in Microsoft Excel using Visual Basic for Applications. The SAG is represented by the larger solid circle, and the USVs are depicted by the smaller solid circles. In the screenshot from Figure 37, the USVs are depicted in a vertical line to the left of the HVU. Each unit has two concentric circles enveloping them, representing detection ranges against ASCMs. The inner circle represents detection range when the missile is in its terminal phase, and the outer circle represents detection range when the missile is in cruise range. The ranges differ because of the different missile altitudes in each phase of flight, commensurate with Equation 1.



USVs: 4
Zoom %: 40
USV Spacing (km): 40
USV Formation: ● Linear ○ Radial
SAG Det Lines (on/off): ☑

USV to SAG Distance (km)	64.82
USV to USV Distance (km)	40
# USVs	4
USV Cruise Det Rng (km)	32.72904
USV Term Det Rng (km)	23.5075

Figure 37. Screenshot of USV Formation Evaluation Tool

The purpose of this tool is to graphically display the USV-SAG formation including corresponding detection range rings for the single SAG and a user-defined number of USVs. The tool was built upon the increased SAG reaction time due to USV cueing model and leverages the same USV and SAG input parameters contained in that model. Specifically, it makes use of the inputs for USV-SAG spacing, and USV and SAG antenna heights to generate the detection range rings and display USV and SAG positions. In addition, this tool allows for user specification of USV-USV spacing as part of the "Settings and Input Variables" callout in Figure 37. Explicit inputs to this tool include:

1. Number of USVs: one to any number (no maximum)
2. Zoom Percentage: Scales the graphical output display accordingly
3. USV Spacing (km): Inter-USV spacing
4. USV Formation (linear or radial)
5. SAG Detection Lines (on or off)

Additional inputs to this tool that leverage the USV cueing model include:

6. USV antenna height (m)

7. SAG antenna height (m)

8. USV-SAG distance (NM)

9. Threat missile cruise phase altitude (m)

10. Threat missile terminal phase altitude (m)

As before, detection range rings for the USV and SAG pertain to their radar range equation derived detection distances against missiles in cruise flight profile at 20 meters altitude and missiles in a terminal flight profile at five meters altitude. These detection ranges are presented in Table 16.

Table 16. Baseline Parameters for USV Formation Evaluation Tool

	NM	km
USV to SAG Distance	25.0	46.3
USV Cruise Detection Range	17.7	32.7
USV Terminal Detection Range	12.7	23.5
SAG Cruise Detection Range	19.1	35.4
SAG Terminal Detection Range	14.2	26.2

Two types of USV formations were considered. The first was a linear formation where the USVs form a straight screen, and the second was a radial formation where the USVs are arranged in a circle around the SAG. In the linear formation, the USV to SAG distance is applicable to the closest USV, the line forms perpendicular to that closest USV-SAG axis. In the event of an even number of USVs, the USV to SAG distance applies to the closest two USVs and the line forms perpendicular to the axis formed from the SAG to the midpoint between the two closest USVs. In the radial formation, the USV to SAG distance is the same for each USV, and each USV maintains a consistent distance with each neighboring USV. Examples of each formation are presented in Figure 38.

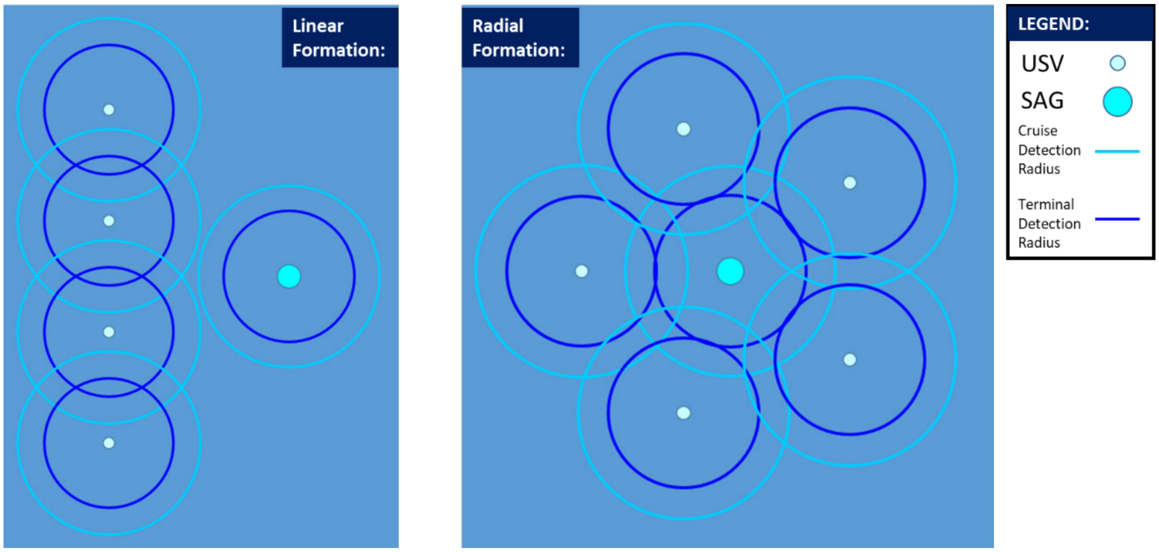
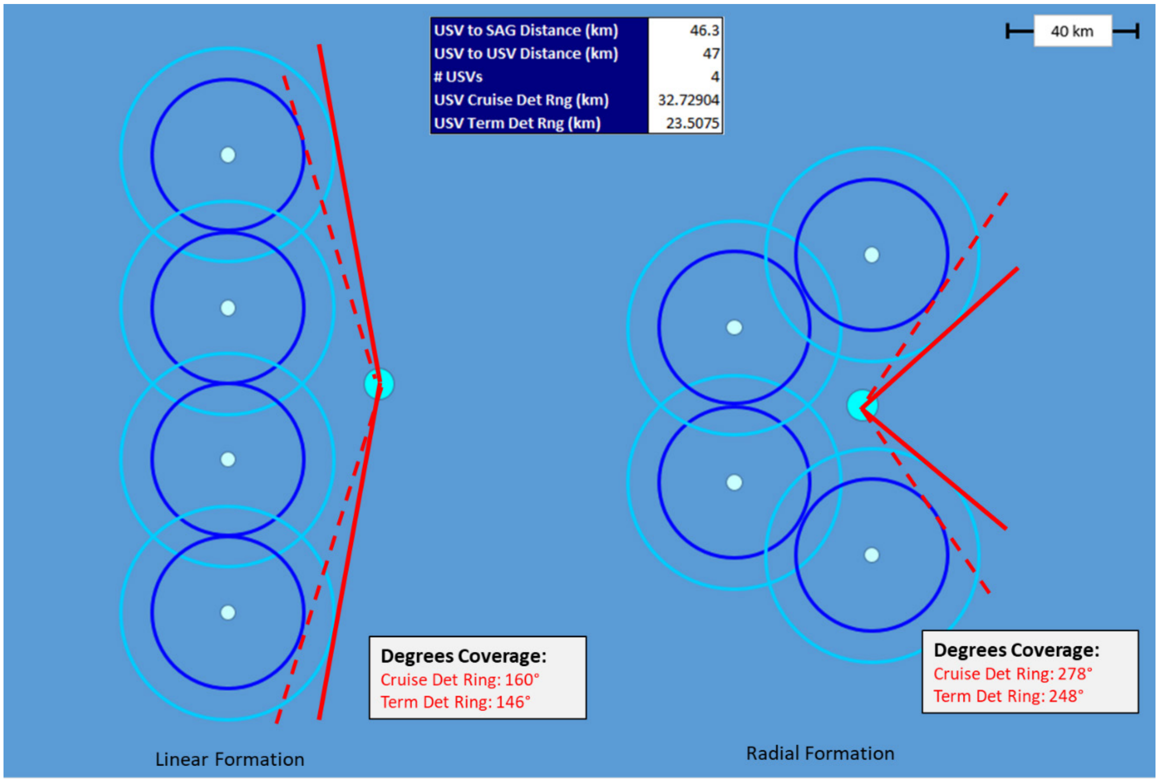


Figure 38. Example Linear and Radial Formations

For the purposes of this study, the metric of interest is degrees of coverage. Degrees of coverage are derived from the lines of sight from the SAG drawn to the tangent of USV detection rings and were measured using computer tools. They are a product of the USV-SAG distance, the USV-USV distance, the USV formation type, and USV detection ring radii. A formation presenting degrees of coverage over 360 is possible and denotes overlap in USV detection rings.

Linear and radial formations using default input parameters were first assessed for one through six USVs using a spacing of 47 kilometers to eliminate gaps between the detection ring radii against a terminal missile. With these parameters, six USVs provide over 360 degrees of coverage in a radial formation. An example of linear and radial formations for four USVs is presented in Figure 39, in which an angled solid line shows the degrees of coverage against an ASCM in cruise phase, and an angled dashed line shows the degrees of coverage against an ASCM in its terminal phase. A summary table of degrees of coverage for one through six USVs is presented in Table 17.



USV to SAG Distance (km)	46.3
USV to USV Distance (km)	47
# USVs	4
USV Cruise Det Rng (km)	32.72904
USV Term Det Rng (km)	23.5075

Figure 39. Examples of Degrees of Coverage

Table 17. Degrees of Coverage and Total USV-SAG Distance per Number of USVs

	Degrees of Coverage				Total Distance (km)	
	Linear Formation		Radial Formation		Linear Formation	Radial Formation
Number USVs	Lin Cruise Det °	Lin Term Det °	Rad Cruise Det °	Rad Term Det °	Linear Distance	Radial Distance
1	91°	62°	91°	62°	47.5	46.3
2	133°	118°	155°	124°	105.2	92.6
3	150°	134°	214°	186°	180.8	138.9
4	160°	140°	278°	248°	274.9	185.2
5	163°	152°	338°	308°	390.6	231.5
6	166°	161°	402°	372°	528.319	277.8

The linear degrees of coverage reach diminishing returns before the 175 degree mark. This aligns to the natural upper bound of 180 degrees, assuming an unlimited number of USVs. In contrast, 360 degree coverage and beyond (denoting coverage overlaps) can be obtained by a radial formation. If degrees of coverage are the only metric of concern, a radial formation is clearly the superior option.

Figure 40 shows the evaluation of these same formations of one through six USVs for total distance between the USV and SAG. The benefit of a linear formation is made clear in terms of total USV-SAG distance. The USV-SAG distance has direct influence on the overall early warning time. USVs at the periphery of the linear formation provide additional early warning time over those in a radial formation located closer to the SAG.

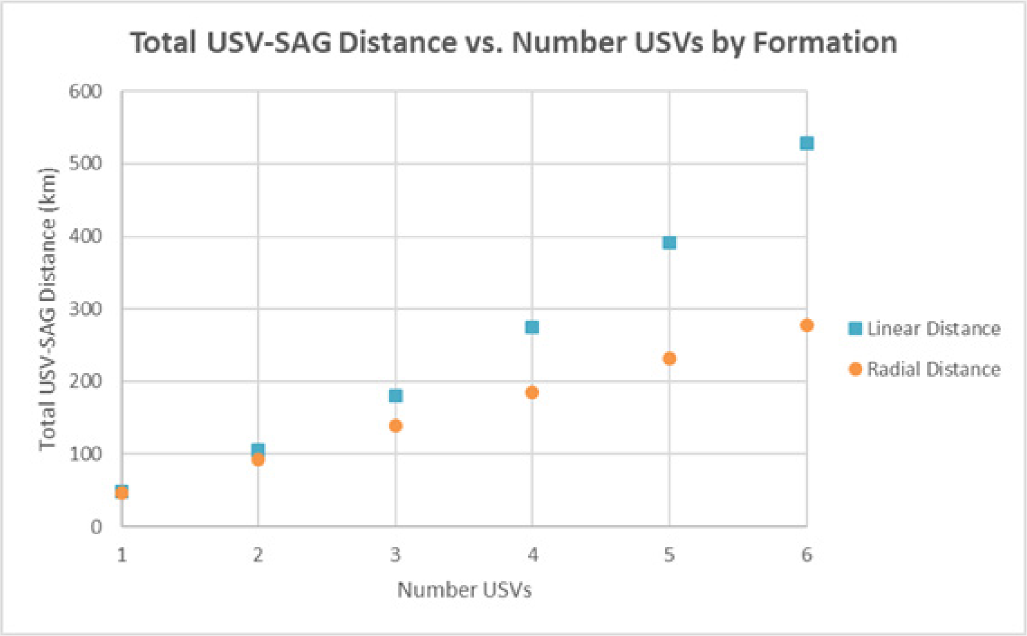


Figure 40. Total USV-SAG Distance versus Number of USVs by Formation for Baseline Parameters

The above relationships represent only two of many combinations of factors that an operational commander determining SAG formations must consider. In many cases, the number of USVs provided to the SAG may be non-negotiable. In the case where two or three are provided, given the degrees of coverage and total USV-SAG distance considerations, it would likely be more favorable to employ the USVs radially to increase degrees of coverage at marginal early detection costs. Given the ability to employ six USVs, the decision changes as the tradeoffs are more meaningful.

Additional factors to consider again include the spacing of the USVs to the SAG and the spacing between the USVs. The above examples assumed an effective zero gap between the USV detection radii against threat missiles in terminal flight profiles. Increasing the USV spacing could increase the overall cruise flight profile detection rings without increasing the number of USVs involved but at increased risk to terminal phase threat missiles sneaking through the screen in gapped detection zones. Follow on studies could further explore the tradeoffs of USV to SAG spacing, USV spacing, and alternative formations.

THIS PAGE INTENTIONALLY LEFT BLANK

VII. CONCLUSIONS

This study attempted to determine whether using medium-sized USVs in support of a SAG will positively impact the SAG's survivability against ASCM attacks. First, the systems engineering process was followed to develop a notional medium-sized USV. High level needs and functional requirements were determined, and component subsystems were then selected. Following development of the USV, two operational situations where the SAG was targeted by enemy ASCMs were investigated: a situation where the USV responded to the threat and a situation where the USV did not directly respond but provided early warning and threat cueing to the SAG.

Both situations were analyzed to determine if the USV mitigated the probability of an ASCM hitting the SAG. The first situation was meant to examine this mitigation by way of the USV defeating the threats before they reached the SAG. The second situation examined the mitigation by way of the USV offering the SAG additional reaction time and counter-fire opportunities to organically respond to the ASCM. Analysis of both situations revealed there is clear tactical utility in using USVs to defend SAGs against ASCMs. Finally, the utility of different formations between USVs and the SAG was also explored.

A. SYSTEM ENGINEERING ANALYSIS SUMMARY

Operational requirements were derived by developing a DRM to illustrate a projected operational environment for the USV. It was determined that to mitigate the probability of an ASCM hit on the SAG, the USV needs to either defeat the threat or increase the SAG's available reaction time by providing threat cueing. From these high-level operational requirements, the need for two categories of USV subsystems was identified. First, detection subsystems, which were an air search radar and an ES system, would find and track any incoming ASCM. Second, response subsystems in the form of soft-kill deception countermeasures, SAMs, CIWS, and EA were needed to defeat the detected ASCM. Specific subsystem functional requirements were derived and formed the basis for selection of currently available COTS and GOTS systems. The process identified that multiple potential system selection outcomes are possible and chose the best systems to meet the operational needs and remain within SWaP constraints imposed by the maximum size of a medium USV.

B. SUBSYSTEM SELECTION

To provide the functionality required, research was conducted to determine what capabilities are available currently or in the near-term that could be integrated onto a medium-sized USV. Additional functional requirements were derived for the USV based on the chosen subsystems, including communications, electrical power, cooling, hydraulics, positioning, navigation, and timing services.

The specific detection and response subsystems selected were:

1. Air search radar – Enterprise Air Search Radar Variant 2
2. Electronic support system – Surface Electronic Warfare Improvement Program Block 3
3. Soft-kill deception countermeasures – Centurion countermeasure launcher
4. Surface-to-air missile system – Evolved Sea Sparrow Missile Block 2 and Mk 29 Guided Missile Launching System
5. Close-in weapons system – Phalanx
6. Radio frequency jamming (electronic attack) – Surface Electronic Warfare Improvement Program Block 3

These subsystems were chosen because of their small footprint yet high level of capability. Because the USVs are significantly smaller than a typical warship, the subsystems must optimize the space available. It was also determined that communications requirements could be met with current communication capabilities.

From analysis of physical attributes for each selected subsystem, the overall SWaP requirements were developed. These requirements were assessed against the notional medium-sized USV host platform characteristics including length, width, and displacement. This assessment concluded that the overall subsystem requirements do not exceed the medium-sized USV host platform limits and that medium-sized USVs can be equipped with the combination of prescribed detection and response subsystems.

C. MODELING AND ANALYSIS FINDINGS

1. Markov Kill Chain Model

Using a Markov kill chain, the first model presents the use of a single USV as a line of defense for the SAG. The USV utilizes SAMs, soft-kill deception countermeasures, EA, and CIWS to respond to incoming ASCM threats. The model uses a state transition diagram that is developed into a state machine. The state machine uses the time in each state and the probability of transitioning between states to determine the time until and probabilities for reaching one of the three final states: hard kill, soft kill, or no kill. Risk Simulator was used to run 5000 trials in each scenario.

This model ran four different scenarios using a combination of OPSITs 1A and 1B and the medium and high threats. Scenario 2—based on OPSIT 1B with all USV response options available to use against the medium threat—proved to be the most effective in eliminating incoming threats. Scenarios 1 and 4, however, with the USV in OPSIT 1A and in OPSIT 1B employing only SAMs, respectively, both still proved to be highly effective with over 81% success rate at defeating ASCMs.

In Scenario 3, the model shows that the USV is not provided authorization from the SAG in sufficient time and is therefore unable to engage the high threat at terminal speed. By the time the SAG issues a direction to the USV, the incoming ASCM will already have passed through the USV's range rings. A good candidate for further study would be to determine if there is any difference when taking the man out of the loop in this scenario.

In Scenario 4, the USV responds to OPSIT 1B with the use of Range Ring 1 only. When comparing the results for OPSIT 1B for use of all three range rings and the use of only one range ring, it is evident that soft-kill deception countermeasures, EW, and CIWS increase USV effectiveness in engaging incoming ASCM threats.

While limitations of this model include that it does not take into consideration the limited number of SAMs available for utilization or the SAG's ability to also engage the incoming threats, the results show that the USV as a weapon platform can greatly reduce the incoming ASCM threats, providing a defensive advantage for the SAG.

2. Time Series Analysis

The utility of the USV as an early warning cueing sensor for SAG counter-fire was demonstrated using a time-distance analysis model created in Excel. Assessments for each threat missile were conducted, and the relationships of USV and SAG detection rings as a function of radar antenna height and USV-SAG spacing were explored. The early detection times for high, medium, and low threat missiles were then translated into SAG counter-fire shot opportunities to quantitatively demonstrate the potential early warning benefit. The results of this analysis show that USVs providing early warning cueing of incoming threats has clear benefit in the SAG's ability to engage incoming threat missiles.

In the assessment of the USV as an early warning cueing sensor, additional takeaways were realized. As antenna height on the USV increases, the detection radius of the USV also grows corresponding in increased early warning detection time. As such, the radar should be positioned as high as feasible within the limits of ship design. The more significant means of increasing the early warning detection time is to position the USV further from the SAG. Increasing the spacing between the USV and the SAG does present a tradeoff in the effective coverage arc, explored in the final assessment.

3. USV Formation Analysis

Tradeoffs in effective arc coverage were examined in the analysis of USV formations around the SAG using a graphical tool developed in Excel using Visual Basic for Applications. The tool accounted for relative USV-SAG spacing, detection rings for threat missiles derived from USV and SAG antenna heights, and inter-USV spacing. The metrics of interest include degrees of coverage in terms of the USV detection screen, and total linear distance between the USVs and SAG. The total linear distance corresponds to early warning time for SAG counter-fire. Two generic formations were evaluated, a linear screen where USVs formed a line perpendicular to a given threat access and a radial formation with even spacing around the SAG.

The analysis showed that as the number of USVs increased, the radial formation provided the best degrees of coverage. The linear formation, however, presented an advantage in the total linear distance and corresponding early warning detection times. In any case, an increase in USV-SAG spacing will result in increased early warning detection times but can result in reduced degrees of coverage. USV-USV spacing impacts are situational, but for both linear and radial formations, an increase in this spacing will generally also produce radar coverage gaps. Tradeoffs in these measures of interest will have to be considered when deciding on the USV formation with respect to the SAG.

D. AREAS FOR FUTURE STUDY

Two broad categories were identified for further research into USV applications to defend SAGs against ASCMs. The first was additional research needed to complete the total USV system design, and the second was expanded research into realistic scenarios for USV operational employment.

1. Future Study Areas in USV Design

This study considers capabilities that exist in the present, leaving future technology analysis for another study. It is however assumed that the fielding of technological advancements in the maritime environment will progress such that the findings herein will still be valid should the Navy implement a USV defensive line in the coming years.

Another area for continued research is the selection of specific subsystems necessary to support the detection and response subsystems, such as communications, electrical power, cooling, hydraulics, positioning, navigation, and timing services. In the conduct of this study, it was assumed these necessary services would be provided. To ensure a complete system design, a detailed investigation into these support subsystems must therefore be conducted, including a selection of specific components and identification of total support requirements for each subsystem.

As a part of vessel design, development of the interior and exterior component layout of the USV will then be necessary. This includes designing the USV with weight balance in mind. Trade-offs in vessel stability and placement of identified subsystems to optimize tactical performance and minimize blockage zones must be considered. A future research project could be to perform a stability study to determine the righting moments and roll angles of various configurations.

A further area that will require additional research is systems integration onboard the USV. Since all detection, response, and support subsystems interact with the ICS, integrating all these systems with the ICS is paramount. Effective tactical performance demands these interactions occur seamlessly. While there are currently combat systems that integrate each of the subsystems recommended by this study, no ICS has been designed to integrate with all of them together and operate on an unmanned vessel of this size. Similarly, as the functional requirements show, each subsystem also depends on others to varying degrees. Further efforts are needed to study the integration of all interfacing systems.

Adversaries may also be able to pinpoint and exploit weaknesses in an unmanned systems' command and control system, giving the adversaries the ability to misdirect the USV and cause defensive gaps for friendly units. Cybersecurity for all USV systems is a critical design area for further research.

2. Future Study Areas in USV Operational Employment

Large numbers of USVs could be used to create an expansive common tactical picture covering thousands of square miles. While some studies have considered the problem of the robustness of smaller networks, a very large network compounding said problem would be a good candidate for future study.

It is also likely the USV will be deployed to regions where adversaries can contest the electromagnetic environment. As this study found, the benefits of this vessel are not fully realized unless it is networked into the common tactical picture collectively produced by friendly forces in the area. Anti-jamming capabilities should be explored to ensure the USV can participate in the tactical picture network.

Another important method of adapting to the expected contested electromagnetic environment are emissions control procedures. By securing equipment operating on certain portions of the electromagnetic spectrum, military units can avoid being identified as a U.S. or friendly military unit or even avoid being passively detected altogether. With respect to the USV, further studies should be conducted to develop emissions control procedures such that its systems can quickly be de-energized (and re-energized) by remote command.

This study examined three particular threats with a wide variation in range, speed, and explosive yield between them. Of course, there are many types of ASCMs employed around the world, with still more in development. Further examination of these threats is necessary to thoroughly assess the utility of medium-sized USVs as an ASCM defense option.

Future explorations for modeling could include situations where the USV fires multiple SAMs, either at a single threat based on doctrine or based on necessity when there are multiple incoming ASCMs. This research would determine at what point the USV will become ineffective as a defensive measure against a raid of ASCM threats due to depletion of missile inventory or oversaturation of threats. Additionally, it would be worthwhile for a study to investigate the effects of multiple USVs engaging incoming threats. This would further explore the benefits of having different geometries with various numbers of USVs in the path of the incoming ASCMs.

Finally, as USVs prove to be tactically beneficial, our adversaries will notice and respond accordingly. As the USVs will likely be targeted directly by the threat missiles, future studies will need to be conducted to explore USV self-defense capabilities.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX A: DETAILED SYSTEM REQUIREMENTS

Air Search Radar

- The radar system shall fit within the footprint of the medium-sized USV.
- The radar system shall be capable of disregarding returns not meeting COI classification.
- The radar system shall be capable of remote configuration updates such as COI parameters, threat profiles, cued search areas, no transmission areas, power levels, and the like.
- The radar system shall be capable of large-scale search functionality and high-resolution tracking. This may be accomplished by one or multiple air search radars.
- The radar system shall automatically designate track COIs meeting pre-assigned parameters.
- The radar system shall fix the location of COIs.
- The radar system shall track the movement and path of COIs.
- The radar system shall not interfere with other radars, including USV navigation radars or response subsystem radars.
- The radar system shall provide target track data to the ICS for further transmission to the SAG.

Electronic Support

- The electronic support system shall fit within the footprint of the medium-sized USV.
- The electronic support system shall be capable of detecting threat missiles in their expected emitter operating frequency bands.
- The electronic support system shall process detection data onboard the USV, to include the threat emitter, line of bearing information, and signal strength.
- The electronic support system shall automatically designate COIs meeting pre-assigned parameters.
- The electronic support system shall provide all detection data for COIs to the ICS for further transmission to the SAG.
- The electronic support system shall provide high elevation angle coverage.
- The electronic support system shall isolate own ship emitters.
- The electronic support system shall be capable of remote configuration including threat profiles and cued search bearings or areas.

Soft-Kill Deception Countermeasures

- The soft-kill deception countermeasure system shall fit within the footprint of the medium-sized USV.

- The soft-kill deception countermeasure system shall be capable of launching either chaff or flare countermeasure payloads.
- The soft-kill deception countermeasure system shall be capable of launching countermeasure rounds in use by the USN or Allied forces.
- The soft-kill deception countermeasure system shall be capable of providing health and status messages to the ICS, including round inventory information.
- The soft-kill deception countermeasure system shall be capable of providing launch event status messages indicating status of countermeasure launches.
- The soft-kill deception countermeasure system shall be capable of receiving launch commands, ASCM track and ES signature data from the ICS.
- The soft-kill deception countermeasure system shall be capable of receiving automatic launch parameter updates from the SAG via the ICS.

Surface-to-Air Missiles

- The surface-to-air missile system shall fit within the footprint of the medium-sized USV.
- The surface-to-air missile system shall be capable of launch from a launcher employed on the USV.
- The surface-to-air missile system shall be capable of receiving guidance information from the USV and the SAG.
- The surface-to-air missile system shall be capable of in-flight maneuvering and speed required to address threat ASCM targets.
- The surface-to-air missile system shall be capable of receiving in-flight target updates.
- The surface-to-air missile system shall be equipped with an infrared seeker at a minimum to enable target engagement.
- The surface-to-air missile system shall be capable of receiving launch orders from the ICS.
- The surface-to-air missile system shall integrate with the ICS to be capable of receiving weapons posture and engagement configuration updates from the SAG.
- The surface-to-air missile system shall use a single variant of SAM.
- The surface-to-air missile system shall enable the USV to auto-fire SAMs on incoming ASCM threats.
- The surface-to-air missile system shall generate and provide the ICS and SAG general health and status messages and launch event reports.

Close-in Weapons System

- The close-in weapons system shall fit within the footprint of the medium-sized USV.
- The close-in weapons system shall have a detection and engagement range of at least 3.7 kilometers (2 nautical miles).

- The close-in weapons system shall be capable of receiving track hand-off from the ICS.
- The close-in weapons system shall be capable of automatically detecting ASCMs.
- The close-in weapons system shall automatically fire when a threat is detected, is in range, and meets the engagement criteria.
- The close-in weapons system shall automatically cease firing when it no longer detects the threat, has detected the elimination of the threat, detects the threat is outbound or outside engagement range, or to prevent accidental engagement of blue forces.
- The close-in weapons system shall be capable of firing rounds in use by the USN or Allied forces.
- The close-in weapons system shall be compatible with a centralized cooling system to cool system electronics.
- The close-in weapons system shall generate and provide the ICS health and status messages and firing event status messages indicating engagement events.
- The close-in weapons system shall be capable of remote configuration including engagement settings and threat profiles.

Electronic Attack

- The electronic attack system shall fit within the footprint of the medium-sized USV.
- The electronic attack system shall be capable of receiving engagement cueing from the ICS.
- The electronic attack system shall automatically begin emitting when a threat is detected, is in range, and meets engagement criteria.
- The electronic attack system shall automatically cease emitting when it no longer detects the threat, has detected the elimination of the threat, detects the threat is outside engagement parameters, or to prevent mutual interference with other blue forces.
- The electronic attack system shall be compatible with a centralized cooling system to cool system electronics.
- The electronic attack system shall be able to provide health and status messages and firing event status messages indicating engagement events.
- The electronic attack system shall be capable of remote configuration including engagement settings and threat profiles.

Integrated Combat System

- The integrated combat system shall be capable of passing ASCM track and ES signature data to the deception countermeasure, SAM, CIWS, and EA systems.
- The integrated combat system shall be capable of commanding deception countermeasure launches and SAM launches and specifying payload type to

launch for either subsystem, to include commanding other USV subsystems to provide information or services as required.

- The integrated combat system shall be capable of commanding EA subsystem engagement against an ASCM target, to include commanding other USV subsystems to provide information or services as required.
- The integrated combat system shall be capable of receiving and disseminating (to the SAG) health and status reports from the air search radar, ES, deception countermeasure, SAM, CIWS, and EA subsystems, or any other subsystem integrated with the ICS.
- The integrated combat system shall be capable of receiving and disseminating (to the SAG) launch or emit reports from the deception countermeasure, SAM, CIWS, and EA subsystems.
- The integrated combat system shall be capable of receiving remote configuration updates from the SAG and applying them to applicable subsystems. These include rules of engagement settings and threat profiles for all USV subsystems.
- The integrated combat system shall merge contact data from the air search radar and ES systems.
- The integrated combat system shall interface with the off-hull communications subsystems.
- The integrated combat system shall leverage a common architecture like the Common Object Request Broker Architecture or similar.
- The integrated combat system shall be capable of directing the positioning, navigation, and timing system to ignore COLREGs, UNCLOS, or other international agreements as necessary and proceed as tactically directed when the operational situation warrants.

Electrical Power System

- The electrical power system shall provide enough power to support all onboard systems.
- The electrical power system shall generate and distribute power at 450 volts alternating current at 60 hertz in 3-phase and in single-phase for use by requisite 440 volt rated systems and for transformation down to 120 volts.
- The electrical power system shall use transformers to generate and distribute power at 120 volts alternating current at 60 hertz in 3-phase and in single-phase for use by requisite 115 volt rated systems.
- The electrical power system shall use frequency converters to generate power at 115 volts alternating current at 400 hertz and in 3-phase and shall distribute that power as necessary.
- The electrical power system shall comply with safety design requirements set forth in Naval Ship's Technical Manual Chapter 300.
- The electrical power system shall be capable of self-monitoring for potential and confirmed system faults.

- The electrical power system shall send periodic system health and status messages to the ICS for further transmission to the SAG.
- The electrical power system shall be capable of autonomously initiating procedures to maintain USV equipment in the event of electrical problems, such as isolation, generator shutdown, and load-shed procedures.

Cooling System

- The cooling system shall have separate chill water and seawater cooling capabilities.
- The cooling system shall use seawater to cool systems able to withstand high amounts of heat.
- The cooling system shall use chill water to cool systems sensitive to changes in heat.

Hydraulics System

- The hydraulics system shall use an automated control system.
- The hydraulics system shall move hydraulic oil to open or close hydraulic operated valves and move machinery parts as necessary.
- The hydraulics system shall be capable of receiving and responding to direction from the ICS to open or close valves or move machinery in order to properly employ combat systems.
- The hydraulics system shall generate and provide the ICS and SAG general health and status messages, to include hydraulic oil tank levels and reports on any detected hydraulic oil leaks.

Positioning, Navigation, and Timing System

- The positioning, navigation, and timing system shall comply with Chairman, Joint Chiefs of Staff Instruction 6130.01, the Department of Defense Master Positioning, Navigation, and Timing Plan.
- The positioning, navigation, and timing system shall operate with Department of Defense approved positioning, navigation, and timing equipment.
- The positioning, navigation, and timing system shall accurately and precisely determine USV location three-dimensionally, referenced to World Geodetic System 1984.
- The positioning, navigation, and timing system shall use an inertial navigation system capable of determining position absent GPS input in case of GPS denial.
- The positioning, navigation, and timing system shall provide for effective and safe navigation in accordance with COLREGs and other international agreements, such as UNCLOS, unless overridden by the ICS due to tactical considerations.
- The positioning, navigation, and timing system shall apply course and speed corrections to attain position and maintain station as directed by the SAG via the ICS.

- The positioning, navigation, and timing system shall determine and maintain Coordinated Universal Time and be capable of converting the time to any time zone specified by SAG operators via the ICS.
- The positioning, navigation, and timing system shall be resistant to jamming.
- The positioning, navigation, and timing system shall interact with the ICS to pass positioning, navigation, and timing data to all combat systems and to receive maneuvering directions and override orders to ignore COLREGs or UNCLOS if needed.

General Subsystem Requirements

Environmental

- The system shall be rugged in accordance with MIL-STD-810G for shock, vibration, and saltwater environments.
- The system shall be capable of operating in air temperatures from 0–50 degrees Celsius.
- The system shall be capable of operating in water temperatures from 2–35 degrees Celsius.

APPENDIX B: MARKOV KILL CHAIN STATE MACHINES

Tables 18 through 20 show the state machines used in the Markov kill chain analysis. Table 18 shows the state machine for Scenario 1, corresponding to OPSIT 1A. Table 19 shows the state machine for Scenario 2 and Scenario 3, corresponding to OPSIT 1B. Finally, Table 20 shows the state machine for Scenario 4, corresponding to OPSIT 1B without Range Ring 2 and Range Ring 3. The current state is represented by each row, and the state names are shown in the column on the far left. The states to be transitioned to are represented by the following columns and are named across the top of the tables. The values inside each cell are the probabilities for transitioning from the state identified by the cell's particular row to the state identified by the cell's particular column. Therefore, when viewing the tables, the value in the cell where the current state under investigation and the desired transition state intersect denotes the probability for that transition to occur. For example, based on the value at the intersection of the Identify row and the Track Shared column, Table 18 shows that the probability for transitioning from Identify to Track Shared is 0.95. To further aid in understanding, it is recommended to view these tables with Figure 25, the state transition diagram.

Table 18. State Machine for Scenario 1—Based on OPSIT 1A

		Search	Detect	Track	Identify	Track Shared	Networked TEWA	SAG Response	Determine Response	Respond RR1	Assess RR1 Engagement	Respond RR2	Assess RR2 Engagement	Respond RR3	Assess RR3 Engagement	Respond RR2 BH	Assess RR2 BH Engagement	Respond RR1 BH	Hard Kill	Soft Kill	No Kill
	P	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20
Search	S1	0	0.99	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.01
Detect	S2	0.01	0	0.99	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Track	S3	0.01	0	0	0.99	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Identify	S4	0.05	0	0	0	0.95	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Track Shared	S5	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Networked TEWA	S6	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
SAG Response	S7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.6	0.25	0.15
Determine Response	S8	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Respond RR1	S9	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Assess RR1 Engagement	S10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.82	0	0.18
Respond RR2	S11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Assess RR2 Engagement	S12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Respond RR3	S13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Assess RR3 Engagement	S14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Respond RR2 Backhalf	S15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Assess RR2 Backhalf Engagement	S16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Respond RR1 Backhalf	S17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hard Kill	S18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Soft Kill	S19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
No Kill	S20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Table 19. State Machine for Scenarios 2 and 3—Based on OPSIT 1B

		Search	Detect	Track	Identify	Track Shared	Networked TEWA	SAG Response	Determine Response	Respond RR1	Assess RR1 Engagement	Respond RR2	Assess RR2 Engagement	Respond RR3	Assess RR3 Engagement	Respond RR2 BH	Assess RR2 BH Engagement	Respond RR1 BH	Hard Kill	Soft Kill	No Kill
	P	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20
Search	S1	0	0.99	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.01
Detect	S2	0.01	0	0.99	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Track	S3	0.01	0	0	0.99	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Identify	S4	0.05	0	0	0	0.95	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Track Shared	S5	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Networked TEWA	S6	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
SAG Response	S7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.6	0.25	0.15
Determine Response	S8	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Respond RR1	S9	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Assess RR1 Engagement	S10	0.05	0	0	0	0	0	0	0	0	0	0.13	0	0	0	0	0	0	0.82	0	0
Respond RR2	S11	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Assess RR2 Engagement	S12	0.05	0	0	0	0	0	0	0	0	0	0	0	0.75	0	0	0	0	0	0.2	0
Respond RR3	S13	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Assess RR3 Engagement	S14	0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0.65	0	0	0.2	0.1	0
Respond RR2 Backhalf	S15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Assess RR2 Backhalf Engagement	S16	0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.75	0	0.2	0
Respond RR1 Backhalf	S17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.82	0	0.18
Hard Kill	S18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Soft Kill	S19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
No Kill	S20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Table 20. State Machine for Scenario 4—Based on OPSIT 1B with Range Ring 1 Engagements Only

		Search	Detect	Track	Identify	Track Shared	Networked TEWA	SAG Response	Determine Response	Respond RR1	Assess RR1 Engagement	Respond RR2	Assess RR2 Engagement	Respond RR3	Assess RR3 Engagement	Respond RR2 BH	Assess RR2 BH Engagement	Respond RR1 BH	Hard Kill	Soft Kill	No Kill
	P	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20
Search	S1	0	0.99	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.01
Detect	S2	0.01	0	0.99	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Track	S3	0.01	0	0	0.99	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Identify	S4	0.05	0	0	0	0.95	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Track Shared	S5	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Networked TEWA	S6	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
SAG Response	S7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.6	0.25	0.15
Determine Response	S8	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Respond RR1	S9	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Assess RR1 Engagement	S10	0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.13	0.82	0	0
Respond RR2	S11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Assess RR2 Engagement	S12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Respond RR3	S13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Assess RR3 Engagement	S14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Respond RR2 Backhalf	S15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Assess RR2 Backhalf Engagement	S16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Respond RR1 Backhalf	S17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.82	0	0.18
Hard Kill	S18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Soft Kill	S19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
No Kill	S20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

LIST OF REFERENCES

BAE Systems. 2019. “Mk 36 Super Rapid Bloom Offboard Countermeasures (SRBOC) Chaff and Decoy Launching System.” Accessed April 1, 2019. https://www.baesystems.com/en/product/mk-36-super-rapid-bloom-offboard-countermeasures-srboc-chaff-and-decoy-launching-system.

Berkoff, Howard. 2018. “Expanding the Navy’s Unmanned Systems Portfolio, An Update.” *Defense Systems Informational Analysis Center Journal* 5, no. 1 (Winter): 33–38. https://www.dsiac.org/sites/default/files/journals/survice_dsiac_winterjournal_singlepgs_dr8_031918.pdf.

Blanchard, Benjamin S. and Wolter J. Fabrycky. 2011. *Systems Engineering and Analysis*. 5th ed. Upper Saddle River, NJ: Prentice Hall.

Blattenberger, Kirt. 1996. “Electronic Warfare and Radar Systems Handbook: Radar Horizon / Line of Sight.” Accessed March 01, 2019. http://www.rfcafe.com/references/electrical/ew-radar-handbook/radar-horizon-line-of-sight.htm.

Blidberg, Richard. 2001. “The Development of Autonomous Underwater Vehicles (AUV); A Brief Summary.” Paper presented at the 2001 International Conference on Robotics and Automation, Seoul, Korea. http://ausi.org/publications/ICRA_01paper.pdf.

Carlson, Christopher. 2013. “China’s Eagle Strike-Eight Anti-ship Cruise Missiles: the YJ-83, C803, and the Family Tree Part 3.” Defense Media Network. February 8, 2013. https://www.defensemedianetwork.com/stories/chinas-eagle-strike-eight-anti-ship-cruise-missiles-the-yj-83-c803-and-the-family-tree/.

Chemring Countermeasures. 2013a. “Cart CM Chaff 130mm Mk36 Type 1.” http://www.chemringcm.com/~/media/Files/C/Chemring-CounterMeasures-V2/documents/mk36-type1.pdf.

———. 2013b. “Naval Platform Protection System Centurion.” http://www.chemringcm.com/~/media/Files/C/Chemring-CounterMeasures-V2/documents/centurion.pdf.

———. 2014. “Expendable Countermeasures for Sea and Air Systems.” Accessed April 1, 2019. https://www.chemring.co.uk/~/media/Files/C/Chemring-V2/PDFs/Chemring-Countermeasures.pdf.

Cole, Sally. 2015. “U.S. Navy’s Electronic Warfare Modernization Effort Centers on COTS.” *Military Embedded Systems*. Volume 11, No. 6, September 2015. http://pdf.cloud.opensystemsmedia.com/emag/MES_2015_SeptRG.pdf.

Defense Advanced Research Projects Agency. 2018. “ACTUV “Sea Hunter” Prototype Transitions to Office of Naval Research for Further Development.” January 30, 2018. https://www.darpa.mil/news-events/2018-01-30a.

Department of Defense. 2018. *Fiscal Year (FY) 2019 President’s Budget—Operation and Maintenance, Defense-Wide*. Washington, DC: Office of the Secretary of Defense. https://comptroller.defense.gov/Portals/45/Documents/defbudget/fy2019/budget_justification/pdfs/01_Operation_and_Maintenance/O_M_VOL_1_PART_1/OSD_OP-5.pdf.

Department of the Navy. 2007. *The Navy Unmanned Surface Vehicle (USV) Master Plan*. Washington, DC: Department of the Navy. https://www.navy.mil/navydata/technology/usvmppr.pdf.

———. 2017. “United States Navy Fact File: CEC – Cooperative Engagement Capability.” January 25, 2017. https://www.navy.mil/navydata/fact_display.asp?cid=2100&tid=325&ct=2.

———. 2019. “United States Navy Fact File: MK 15 – Phalanx Close-In Weapon System (CIWS).” January 15, 2019. https://www.navy.mil/navydata/fact_display.asp?cid=2100&tid=487&ct=2.

Eckstein, Megan. 2018. “Navy’s Next Large Surface Combatant Will Draw From DDG-51, DDG-1000 — But Don’t Call it a Destroyer Yet.” *U.S. Naval Institute News*, January 27, 2019. https://news.usni.org/2018/08/28/navys-next-large-surface-combatant-will-draw-ddg-51-ddg-1000-dont-call-destroyer.

Eurosam. 2019a. “Aster Hit-to-Kill Missile Interceptors.” Accessed February 19, 2019. https://www.eurosam.com/products/eurosams-building-block/aster/.

———. 2019b. “SYLVER Naval Vertical Launch System.” Accessed February 19, 2019. https://www.eurosam.com/products/eurosams-building-block/sylver/.

Forecast International. 1999. *Electronic Warfare Forecast Report: SLQ-32(V)*. Newtown, CT: Forecast International. https://www.forecastinternational.com/archive/disp_old_pdf.cfm?ARC_ID=733.

General Dynamics Ordnance and Tactical Systems. 2003a. “Goalkeeper 30mm Close-In Ship Defense System.” July, 2003. https://www.gd-ots.com/wp-content/uploads/2017/11/Goalkeeper.pdf.

———. 2003b. “PHALANX Close-In Weapon System (CIWS).” July, 2003. https://www.gd-ots.com/wp-content/uploads/2017/11/Phalanx.pdf.

Giachetti Ronald. 2015. “System of Systems Capability Needs Analysis via a Stochastic Network Model.” *Naval Engineers Journal* 127, no. 4 (Winter): 67–79. https://calhoun.nps.edu/bitstream/handle/10945/49635/Giachetti_System_of_Systems_Capability_Needs.pdf?sequence=1&isAllowed=y.

Giammarco, Kristin, Spencer Hunt and Clifford Whitcomb. 2015. *An Instructional Design Reference Mission for Search and Rescue Operations*. Report No. NPS-SE-15-002. https://calhoun.nps.edu/bitstream/handle/10945/46782/NPS-SE-15-002.pdf.

Hewson, Robert. 2010. “China Aerospace Science and Industry Corporation’s Radar-Guided C-704R Missile.” Jane’s by IHS Markit. Accessed March 1, 2019. https://janes-ihs-com.libproxy.nps.edu/ExternalItems/Janes/images/binder/jalw/jalw66/data/images/1296597.jpg.

Hpeterswald. 2013. “HMS Daring SAMPSON is a Multi-Function AESA Radar.” Wikimedia Commons. October 7, 2013. https://commons.wikimedia.org/wiki/File:HMS_Daring_SAMPSON_is_a_multi-function_AESA_radar.jpg.

Jane’s by IHS Markit. 2013. “[ARCHIVED] RIM-66/-67/-156 Standard SM-1/-2, RIM-161 Standard SM-3, and RIM-174 Standard SM-6.” July 30, 2013. https://janes-ihs-com.libproxy.nps.edu/Janes/DisplayFile/JSWS0208.

———. 2018a. “3M-54 (SS-N-27A ‘Sizzler’).” March 12, 2018. https://janes.ihs.com.libproxy.nps.edu/Janes/DisplayFile/JNWSA015.

———. 2018b. “AN/SPY-1.” September 26, 2018. https://janes-ihs-com.libproxy.nps.edu/Janes/Display/jc4im0028-jc4im.

———. 2018c. “C-704 (Nasr-1/Nasir).” April 18, 2018. https://janes.ihs.com.libproxy.nps.edu/Janes/Display/jnwsa036-jnw_.

———. 2018d. “C-704KD (Nasr).” October 3, 2018. https://janes.ihs.com.libproxy.nps.edu/Janes/DisplayFile/JALWA021.

———. 2018e. “The Club Family; Club-K/Club-M/Club-N/Club-S/Club-U; 3M-14E Series (SS-N-30B)/3M-54E Series (SS-N-27B)/91RE1 and 91RTE2.” March 5, 2018. https://janes.ihs.com.libproxy.nps.edu/Janes/DisplayFile/JNWSA030.

———. 2018f. “CSS-N-4 ‘Sardine’ (YJ-8/YJ-8A/C-801); CSS-N-8 ‘Saccade’ (YJ-82/YJ-83/C-802/C-802A/Noor/Ghader).” May 3, 2018. https://janes.ihs.com.libproxy.nps.edu/Janes/Display/jnws0132-jnw_.

———. 2018g. “GMVLS Mk 41/Mk 57.” April 18, 2018. https://janes-ihs-com.libproxy.nps.edu/Janes/Display/jnws0225-jnw_.

———. 2018h. “YJ-8K (C-801K), YJ-82K (C-802K), YJ-83K (C-802AK), YJ-83KH (CM-802AKG).” October 10, 2018. https://janes.ihs.com.libproxy.nps.edu/Janes/DisplayFile/JALW2892.

———. 2019a. “RIM-7 SeaSparrow and RIM-162 Evolved SeaSparrow Missile (ESSM).” March 26, 2019. https://janes-ihs-com.libproxy.nps.edu/Janes/DisplayFile/JNWS0168.

———. 2019b. “SAMPSON Multifunction Radar (MFR).” January 16, 2019. https://janes-ihs-com.libproxy.nps.edu/Janes/Display/jrew0365-jc4im.

Keane, John F., and Stephen S. Carr. 2013. “A Brief History of Early Unmanned Aircraft.” *Johns Hopkins APL Technical Digest* 32 (3): 558–571. https://www.jhuapl.edu/techdigest/TD/td3203/32_03-Keane.pdf.

Kelley, Stephen H. 2002. “Small Ships and Future Missions” *Proceedings* 128, no. 9 (September): 42–44. https://www.usni.org/magazines/proceedings/2002/september/small-ships-and-future-missions.

Kelly, Steve. n.d. “Vertical Launch System (VLS) – Mk 41 Strike-Length Module.” United Defense Armament Systems Division. Accessed March 10, 2019. https://fas.org/man/dod-101/sys/ship/weaps/mk41-strike.pdf.

Kopp, Carlo. 2012. *Soviet/Russian Cruise Missiles*. Report No. APA-TR-2009-0805 http://www.ausairpower.net/APA-Rus-Cruise-Missiles.html#mozTocId95513.

LaGrone, Sam. 2019. “Navy to Contract New Class of Unmanned Surface Vehicle by Year’s End.” *U.S. Naval Institute News*, March 6, 2019. https://news.usni.org/2019/03/06/navy-contract-new-class-unmanned-surface-vehicle-years-end.

Lockheed Martin. 2009. “SPY-1 Family of Radars.” https://web.archive.org/web/20110915180551/http://www.lockheedmartin.com/data/assets/ms2/pdf/SPY-1_Family_brochure_6-pager.pdf.

———. 2013. “MK 41 Vertical Launching System.” https://www.lockheedmartin.com/content/dam/lockheed-martin/rms/documents/naval-launchers-and-munitions/MK41_VLS_factsheet.pdf.

———. 2016. “Surface Electronic Warfare Improvement Program (SEWIP): Protecting the Fleet.” https://lockheedmartin.com/content/dam/lockheed-martin/rms/documents/electronic-warfare/SEWIP-brochure.pdf.

MBDA Missile Systems. 2016a. “Aster Anti-Air Missile.” January, 2016. https://www.mbda-systems.com/?action=force-download-attachment&attachment_id=13346.

———. 2016b. “Italian Navy First Launch Aster 30 Missile Nave Bergamini.” November 24, 2016. https://www.mbda-systems.com/2016/11/24/italian-navy-first-launch-aster-30-missile-nave-bergamini/.

Missile Defense Advocacy Alliance. 2018. “SAMPSON Radar.” June 1, 2018. http://missiledefenseadvocacy.org/air-defense/air-defense-of-u-s-partners/allied-air-defense-sensor-systems/sampson-radar/.

Missile Threat. 2018. “Evolved Seasparrow Missile (ESSM).” Center for Strategic and International Studies Missile Defense Project. July 12, 2018. https://missilethreat.csis.org/defsys/evolved-seasparrow-missile-essm/.

Northrop Grumman. 2014. *Understanding Voice and Data Link Networking: Northrop Grumman’s Guide to Secure Tactical Data Links, First Revision*. Document No 135–02-005. https://www.northropgrumman.com/Capabilities/DataLinkProcessingAndManagement/Documents/Understanding_Voice+Data_Link_Networking.pdf.

———. 2019. “Production to Begin on Game-Changing Electronic Warfare Capability for U.S. Navy Fleet.” *Northrop Grumman Newsroom*, January 24, 2019. https://news.northropgrumman.com/news/releases/northrop-grumman-authorized-to-build-sewip-block-3-low-rate-initial-production-systems-following-successful-milestone-c-decision.

Ostheim, Jakob. n.d. “Mk-41 VLS (8 Cells) Aboard a Royal Norwegian Navy Fridtjof Nansen Class Frigate.” Seaforces Naval Information. Accessed April 07, 2019. http://www.seaforces.org/wpnsys/SURFACE/Mk-41-missile-launcher.htm.

Pike, John. 1999. “AN/SPS-49 Very Long-Range Air Surveillance Radar.” Federation of American Scientists Military Analysis Network. June 30, 1999. https://fas.org/man/dod-101/sys/ship/weaps/an-sps-49.htm.

———. 2011a. “AN/SPG-62 Fire Control Radar.” Global Security Military Guide. July 7, 2011. https://www.globalsecurity.org/military/systems/ship/systems/an-spg-62.htm.

———. 2011b. “PC-1 Cyclone Class Patrol Coastal Boats.” Global Security Military Guide. July 7, 2011. https://www.globalsecurity.org/military/systems/ship/pc-1-specs.htm.

Program Executive Officer, Littoral & Mine Warfare. 2011. “Unmanned Maritime Systems Program Office Fact Sheet.” http://auvac.org/uploads/publication_pdf/Pms406_PROGRAM.pdf.

Raytheon Company. 2007. “MK 29 SEASPARROW Guided Missile Launching System with ESSM Upgrade.” January 25, 2007. http://www.alternatewars.com/BBOW/Weapons/Mk29_GMLS.pdf.

———. 2018. “Phalanx Close-In Weapon System.” Accessed December 13, 2018. https://www.raytheon.com/capabilities/products/phalanx.

———. 2019. “Enterprise Air Surveillance Radar.” Accessed March 4, 2019. https://www.raytheon.com/capabilities/products/easr.

Richards, Ron. n.d. “The AN/SPS-49(V)5 Antenna Aboard South Korea’s Chungmugong Yi Sun-sin (KDX-2)-Class Destroyer ROKS Gang Gam Chan.” Jane’s by IHS Markit. Accessed March 8, 2019. https://janes-ihs-com.libproxy.nps.edu/ExternalItems/Janes/images/yb/jc4im/jc4im2019/data/images/1574126.jpg.

Robertson, Sue. 2019. *Practical ESM Analysis*. Norwood, MA: Artech House.

Rogoway, Tyler. 2017. “Watch the Navy Fire Its New Evolved Sea Sparrow Block II Missile for the First Time.” *The Warzone Newsletter*, November 2, 2017. https://www.thedrive.com/the-war-zone/15718/watch-the-navy-fire-its-new-evolved-sea-sparrow-block-ii-missile-for-the-first-time.

Royal Australian Navy. 2011. “A Standard Missile (SM 2) is Fired from the Royal Australian Navy Guided-Missile Frigate HMAS Sydney During a Live-Fire Exercise.” June 18, 2011. https://www.flickr.com/photos/usnavy/5963900217/in/photostream/.

Rucker, Jon. 2018. “Status of Unmanned Systems: Executing!” PMS 406 January 2018 Status Brief. https://www.navsea.navy.mil/Portals/103/Documents/Exhibits/SNA2018/UnmannedSystems-Rucker.pdf?ver=2018-01-11-145102-270.

Seaforces Naval Information. n.d. “DCNS Sylver A-43 VLS (2 x 8 cells) for Aster 15 SAM aboard ITS Cavour (C 550).” Accessed April 07, 2019. http://www.seaforces.org/wpnsys/SURFACE/DCNS-Sylver-vertical-launching-system.htm.

Skolnick, Fred and Phillip Wilkins. 2000. “Laying the Foundation for Successful Systems Engineering.” *Johns Hopkins APL Technical Digest* 21 (2): 208–216. https://pdfs.semanticscholar.org/61d9/50c78437225bb6f18c280b2bd4c5d4741b8a.pdf.

Smith, Roy M. 2010. “Using Kill-Chain Analysis to Develop Surface Ship CONOPS to Defend Against Anti-Ship Cruise Missiles.” Master’s Thesis, Naval Postgraduate School, Monterey, CA. https://calhoun.nps.edu/bitstream/handle/10945/5345/10Jun_Smith_Roy.pdf.

Thales 7 Seas. n.d. "UAT." Accessed February 1, 2019. http://www.thales7seas.com/html_2014/product380.html.

Thales Group. n.d. "Goalkeeper – Close-In Weapon System." Accessed January 27, 2019. https://www.thalesgroup.com/en/goalkeeper-close-weapon-system.

Think Defence. 2013. "The Chemring Centurion." April 3, 2013. https://www.thinkdefence.co.uk/2013/04/the-chemring-centurion/.

Ward, Larry. n.d. "Mk 36 SRBOC Chaff and Decoy Launching System." United Defense Armament Systems Division. Accessed January 30, 2019. https://www.globalsecurity.org/military/systems/ship/systems/mk36-srboc.pdf.

Williams, John. 2016. "U.S. Navy Photo." Department of the Navy. April 07, 2016. https://www.navy.mil/view_image.asp?id=214556.

Wow Media Limited. 2013. "Chemring Centurion." YouTube video, 3:20. June 14, 2013. https://www.youtube.com/watch?v=jtTXYUaxQao.

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California