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# THESIS

**UNDERSEA COMMUNICATIONS BETWEEN SUBMARINES AND UNMANNED UNDERSEA VEHICLES IN A COMMAND AND CONTROL DENIED ENVIRONMENT**

by

Forest B. Mclaughlin

March 2015

Thesis Advisor:          Thomas W. Lucas
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**13. ABSTRACT (maximum 200 words)**

Nuclear powered submarines are most vulnerable to detection and attack while at periscope depth. Submarines also have specific communication and time requirements they have to meet and the primary method of transmitting and receiving data is via satellite, which requires the submarine to be at periscope depth. This means that in a command and control denied environment (C2DE), a submarine may be incapable of receiving orders or transmitting required reports. In order to meet its communications requirements, the submarine has to navigate outside of the denied environment, conduct all necessary satellite communications, and proceed back to the C2DE zone.

Through great improvements in unmanned underwater vehicle (UUV) technology and the development of new line-of-sight rapid data transmission methods, submarines may be able to operate in C2DEs and conduct all necessary communications without ever going to periscope depth. This study analyzes different configurations for UUV and submarine interaction in a C2DE area using a series of models in the Map Aware Non- Uniform Automata (MANA) modeling environment. This analysis explores the value of several different UUV characteristics as well as undersea garage configurations in minimizing the time it takes for a submarine to conduct its communications, the latency of the data received, and the cost of construction for the system.

The system as modeled shows that the combination of the UUV and blue-green laser can provide the submarine with service times comparable to the time it takes for a submarine to reach periscope depth and expected data latency of less than an hour.

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# UNDERSEA COMMUNICATIONS BETWEEN SUBMARINES AND UNMANNED UNDERSEA VEHICLES IN A COMMAND AND CONTROL DENIED ENVIRONMENT

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Submitted in partial fulfillment of the
requirements for the degree of

**MASTER OF SCIENCE IN OPERATIONS RESEARCH**

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# ABSTRACT

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# THESIS DISCLAIMER

The reader is cautioned that the computer programs presented in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logical errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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# TABLE OF CONTENTS

# LIST OF FIGURES

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# LIST OF TABLES

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# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| ABD | Agent Based Distillation |
| ABMS | Agent Based Modeling System |
| ASW | Anti-Submarine Warfare |
| BMP | Bitmap |
| bps | Bits Per Second |
| CA | Cellular Automaton |
| C2DE | Command and Control Denied Environment |
| DARPA | Defense Advanced Research Projects Agency |
| DoD | Department of Defense |
| DOE | Design of Experiments |
| DPs | Design Points |
| GUI | Graphical User Interface |
| ISR | Intelligence, Surveillance, and Reconnaissance |
| LCS | Littoral Combat Ship |
| LCT | Laser Communication Terminal |
| LH | Latin Hypercube |
| LOS | Line-of-Sight |
| MANA | Map Aware Non-Uniform Automata |
| MANA-V | Map Aware Non-Uniform Automata-Vector |
| Mbps | Mega-bits Per Second |
| MOE | Measure of Effectiveness |
| MSE | Mean Square Error |
| NOLH | Nearly Orthogonal Latin Hypercube |
| NM | Nautical Mile |
| NPS | Naval Postgraduate School |
| OR | Operations Research |
| PD | Periscope Depth |
| PEO C4I | Program Executive Office Command, Control, Communications, Computers and Intelligence |
| SEED | Simulation Experiments and Effectiveness Design |

| | |
|---|---|
| STORM | Synthetic Theater Operations Research Model |
| UAV | Unmanned Aerial Vehicle |
| UUV | Unmanned Underwater Vehicle |

# EXECUTIVE SUMMARY

Naval nuclear submarines make their own water and air and can travel thousands of miles without ever coming to the surface. While at periscope depth (PD) and transitioning from deep water to PD the submarine is most vulnerable to detection or collision. The primary reason for routine trips to PD is to conduct communications operations. While operating in a command and control denied environment (C2DE), the only option for a submarine to conduct communications is to leave the area. This means critical on station time is wasted in transit into and out of the mission area.

The current method by which the submarine conducts these communications is via the Milstar satellite network. The Milstar satellite network data transfer rate is slow by today's standards, and communications are susceptible to disruption, spoofing, and interception. New line-of-sight (LOS) communication technologies, like the blue-green laser, are being developed to overcome the communications vulnerability. The laser works much in the same way as a fiber optic cable, with the medium for data transfer being the air instead of the cable. As long as there is a clear LOS between the transmitter and receiver, high data transfer rates are available. The technology also works under water, but the range of transmission is greatly diminished.

The Navy is investing heavily in the use of unmanned underwater vehicles (UUVs) to help in areas including mine warfare, oceanography, salvage, and rescue operations. This study explores expanding the role of the UUV to include underwater communications as part of an undersea constellation supporting various Navy missions. Used in conjunction with the blue-green laser, the UUV is be able to meet all of the submarine's communication needs without the submarine ever coming to PD. The laser-fitted UUVs relays information from anchored data nodes to a sensor in the submarine's sail. Figure 1 illustrates how this would work.
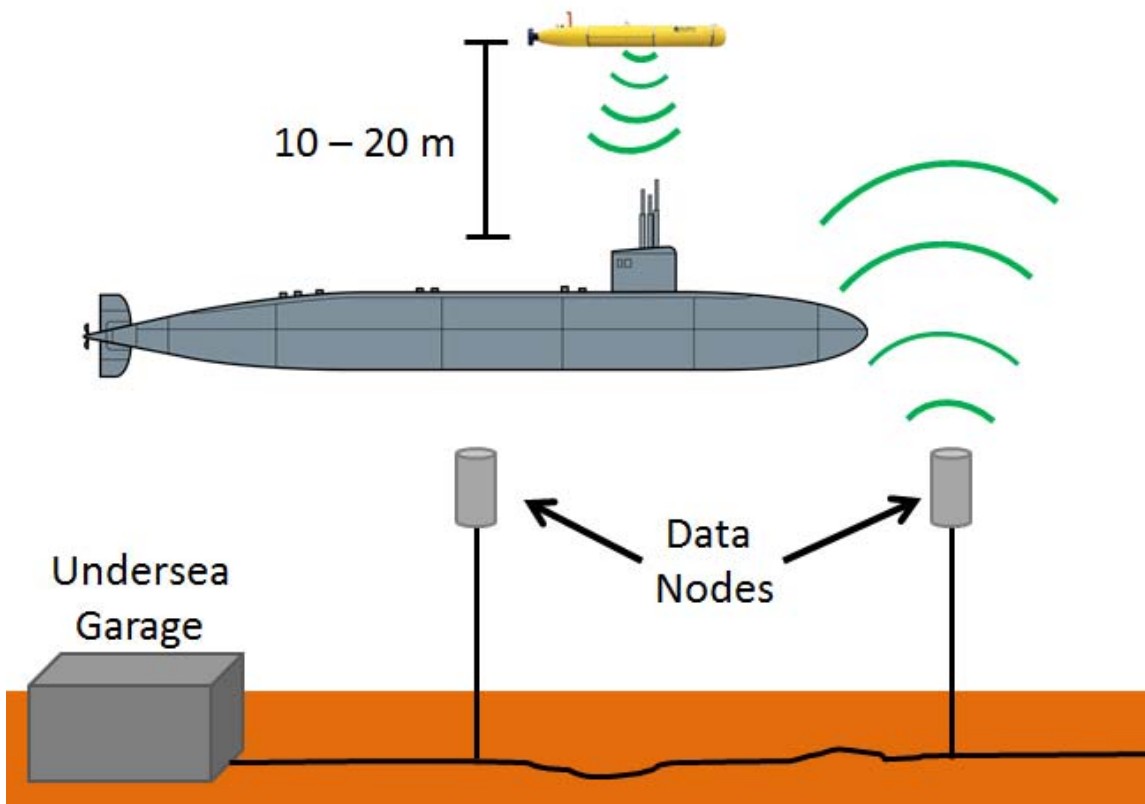
Figure 1. Interface between submarine, UUV, and data nodes.

This configuration is modeled in agent based modeling software called Map Aware Non-uniform Automata (MANA). The scenarios consist of a submarine entering a network of UUVs and data nodes and determining how long it takes for the UUV to find and transfer data to the submarine, and the latency of the transferred data. Factors varied in the modeling include: the number and speed of the UUVs, the number of data nodes, the range at which the UUV and submarine detects each other, and how long the data transfer takes to complete. Thirty-six separate models are required to capture all of the discrete combinations of number of UUVs and data nodes, as well as the UUV's speed. The thirty-six models are combined with 17 combinations of five continuous variables using a Nearly Orthogonal Latin Hypercube (NOLH). Each of the 612 design points (DPs) was run 40 times to produce a data set consisting of 24,480 simulated submarine communication missions.

Descriptive statistics, stepwise linear regression, and partition trees are used to analyze the 24,480 submarine-UUV interactions. The most important factors for both the time the submarine waits to get contacted by the UUV and the age of the UUV data received are discovered, plus some additional insights. To summarize, this research concludes that:

- Agent-based models are a powerful tool for modeling a variety of scenarios in a relatively short time period.

- Data farming using NOLHs enables the efficient investigation of models that have multiple factors.

- UUVs equipped with the blue-green laser are a feasible option to replace or aid submarine periscope depth communications, as modeled.

- UUVs' internal navigation needs to be sufficient to pass within 500 meters of a data node to ensure that communication will take place.

- Ranges at which a UUV and a submarine detect one another are very important. Due to the disparity in detection ranges, once the submarine has detected the UUV, it should wait until it has closed distance to slow down and the UUV should speed up immediately to minimize the submarine wait time.

- Combination of four UUVs traveling at five knots and four data nodes resulted in a mean submarine wait time of about 54 minutes and a mean UUV data age of 38 minutes.

- Addition of one UUV to a system reduces the submarine wait time by 23 minutes, on average.

- Addition of one data node to a system reduces the UUV data age by 24 minutes, on average.

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# ACKNOWLEDGMENTS

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# I.    INTRODUCTION

## A.    BACKGROUND

Nuclear powered submarines make their own air and water and store months of food on board. They can stay submerged for days at a time and only have to come to periscope depth (PD) for communications and minor house-keeping items. Only when on the surface or at PD are submarines detectable visually or by radar. Submarines are completely reliant on satellites for communications and orders from their commanders ashore. A command and control denied environment (C2DE) is an area in which communications are jammed or degraded. There is no technology currently available that allows submarines to conduct communications in a C2DE. The only method currently available is for the submarine to navigate to unaffected waters, conduct all of its communications, and then to travel back to the C2DE. These actions waste valuable time and possibly compromise the submarine's mission. Figure 1 illustrates how visible a US Los Angeles Class submarine can be at PD.
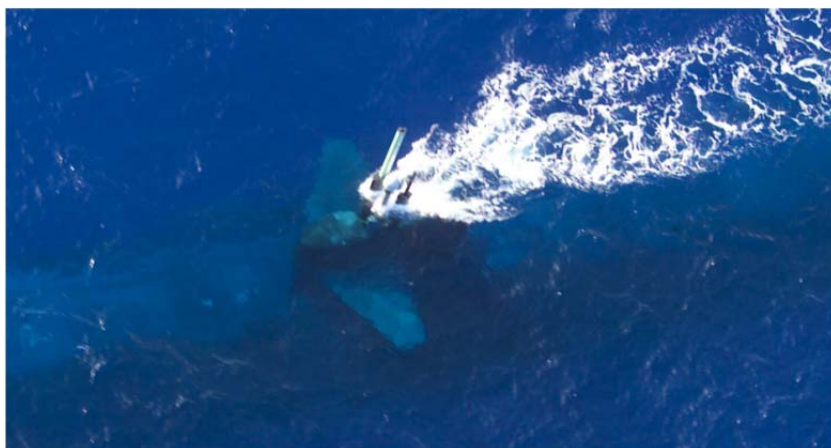


Figure 1.    U.S. submarine at periscope depth. Image from en.wikipedia.org/wiki/Los_Angeles-class_submarine.

### 1.    Current Submarine Communications

Today's nuclear submarines have very strict communications requirements. They receive regular broadcast updates, GPS fixes, and even daily news from periodic satellite

communications. The only secure method of issuing orders or making reports back to command and control centers on shore is via a satellite link.

The Navy's current communication workhorse is the Milstar satellite network. The system consists of five satellites, two Milstar I, and three Milstar II, which have peak data transfer rates of 2400 bits per second (bps) and 1.544 mega-bits per second (Mbps), respectively [1]. This low data rate means that the submarine has to maintain PD for long periods of time, thus exposing itself to unnecessary risk of detection or collision.

## 2. New Undersea Communication Technologies

Emerging technologies in the communications field will soon revolutionize communications between at sea vessels. Decreased reliance on satellite technology is the key to secure communications.

### a. *Blue-Green Laser*

The blue-green laser is an emerging technology first tested by the US Naval Research Lab in 2006 [2]. During the test, two aircraft carriers were fitted with next generation laser communication terminals (LCTs). The tests revealed a 99% reliable data stream at 90 Mbps at 10 km distance. According to AT&T, the current 4G LTE cellular network averages about 16.7 Mbps to your phone. This means that the laser communication via LOS is about five times faster than current cellular technology and up to sixty times faster than the currently used Milstar satellites. This excellent data rate and range only holds true above the surface of the ocean. Although a submarine could theoretically get updates at PD via line-of-sight (LOS) blue-green laser interface with a surface vessel or aircraft, ideally the submarine will not come up to PD at all.

The blue-green laser was later tested underwater in 2009 [2] and it was immediately apparent that the limited range of the data transfer, and the proximity between vessels it requires, will be a safety issue. Data transfer rates of between 7 and 10 Mbps with a 99.99% success rate were observed, but only in the 10 to 20 meter range. This initially appears to pose a difficult challenge, but with the application of an

underwater network of data transfer nodes and UUV carriers, short data transfer ranges may not be an insurmountable issue.

### b. *Undersea Constellation*

The Undersea Constellation [3] is a proposed system that will integrate secure communications between the space, air, surface, and underwater domains. The program is currently being spearheaded by the Navy Program Executive Office Command, Control, Communications, Computers and Intelligence (PEO C4I). Although the concept focuses on various aspects of communication, this study focuses specifically on the interface that takes place undersea.

### 3. Current and Future UUV Employment

The Navy hopes to increase the scope of UUV employment in the near future. The Littoral Combat Ship (LCS) will soon use UUVs almost exclusively for mine-clearing operations [4] and further applications are currently being explored. This study models UUVs as data conveyers with the following as alternatives along with their supporting systems.

### a. *Bluefin-21*

The Bluefin-21 is a UUV currently manufactured by Bluefin Robotics [5]. The Bluefin-21 is currently employed by the US Navy and was recently used in the 2014 search for missing Malaysian flight 370 [6]. This UUV can endure up to 25 hours at three knots with a standard payload and can reach depths of almost 15,000 feet. Bluefin-21 is shown in Figure 2.

Figure 2.     Bluefin 21 UUV. Image from bluefinrobotics.com.

### b.     *Knifefish*

The Knifefish is a specialized version of the Bluefin 21 UUV developed specifically for anti-mine operations onboard the US Navy's LCS [7]. It will begin sea trials in 2015 and is scheduled to be employed by the Navy in 2017. Although it has a reduced endurance of 16 hours compared to the Bluefin-21, it has a higher top speed and increased modularity and payload. An illustration of the Knifefish is shown in Figure 3.
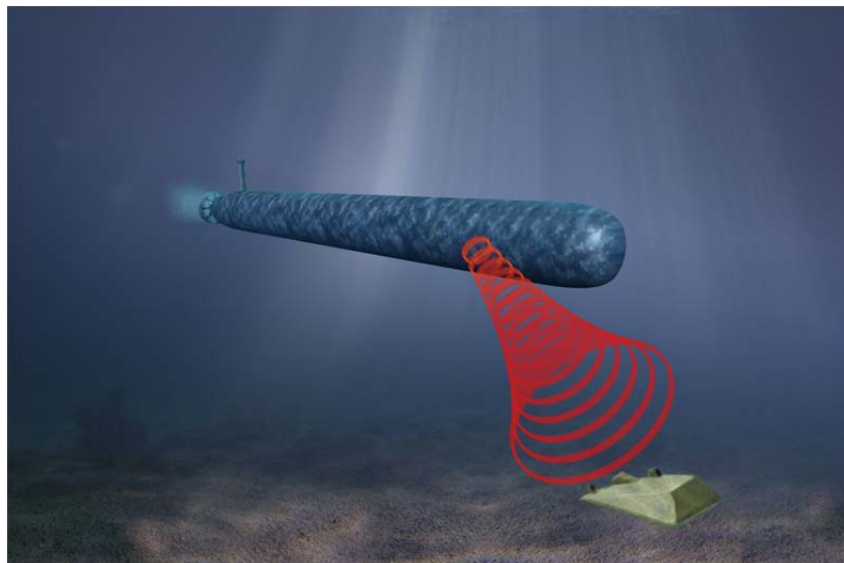


Figure 3.     Knifefish UUV. Image from gd-ais.com/Capabilities/Mission-
Integration-Systems/Submarine-Systems.

### c. Undersea Garage

The undersea garage is a proposed future technology currently being tested by the Naval Postgraduate School's (NPS's) robotics department in Monterey Bay, California. The basic principle is that a UUV can dock and recharge itself with an underwater terminal without regular trips to the surface.

A similar system, known as Hydra, is currently being developed by the Defense Advanced Research Projects Agency (DARPA) [8]. Hydra aims to develop an independent underwater distributed network that provides an interface and recharge station for UUVs and a modular payload system. Figure 4 shows an abstraction of the proposed system.
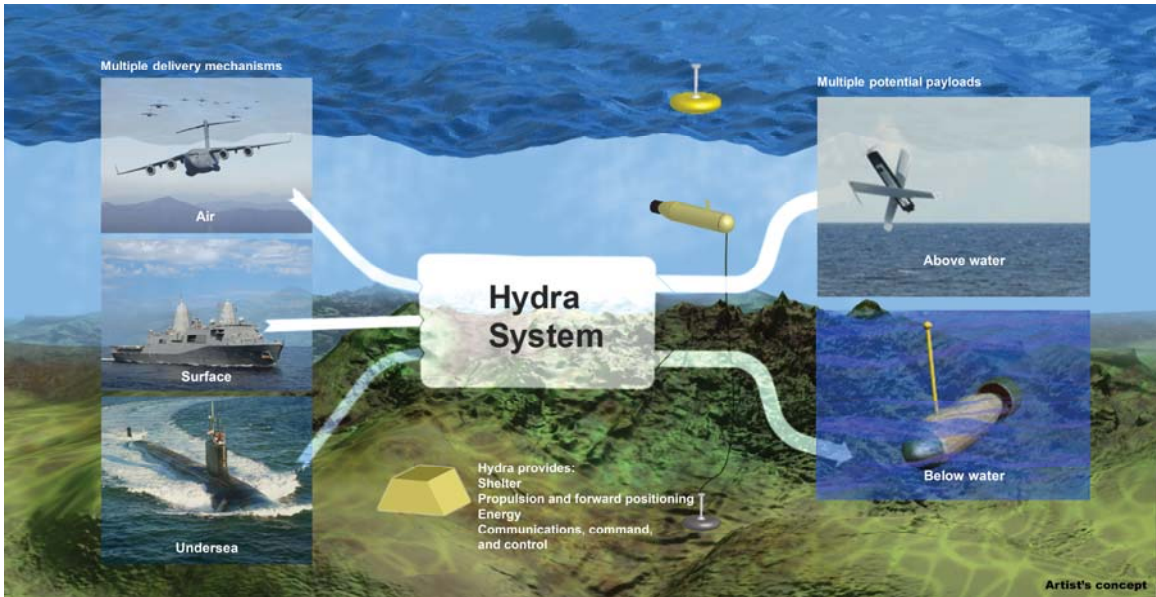


Figure 4.    Proposed DARPA Hydra system, from [8].

### 4.    Combining Technologies

Through the use of the different technologies mentioned above, there may be a solution to the problem of submarines needing to come to PD to exchange information. By using a series of patrolling UUVs receiving regular data updates via the blue-green laser, we hope to relay information to submerged submarines independent of surface

conditions. This means a submarine can operate continuously in a C2DE and still receive orders from its command and the periodic updates it requires.

## B.    RESEARCH QUESTIONS

This research is guided by the following questions:

1. Used in conjunction with the undersea garage, are UUVs a viable option for conducting communications between submarines and their command and control structure?

2. What number of UUVs and what performance characteristics are necessary to ensure communication requirements are met?

3. How many UUVs and data nodes are necessary to ensure that the submarine is not receiving information that is more than two hours old?

## C.    SCOPE OF THESIS

UUVs are currently being employed world-wide for a variety of tasks and their applications are continuously growing. In addition to replacing the US Navy's marine mammal program for counter-mine operations, the new Navy UUV Master Plan envisions using UUVs for Intelligence, Surveillance and Reconnaissance (ISR), anti-submarine warfare (ASW), inspection and identification, oceanography, payload delivery, and navigation [4].

The specific UUV technology application this study focuses on is the potential direct communication between UUVs and submerged submarines in a C2DE. The modeled UUVs will patrol a linear area recharging at the completion of each patrol at an undersea garage. The garage will receive continuous updates from a sensor placed outside of the C2DE, but tethered to the garage. The garage will update the UUVs while they recharge and relay its continuous data feed to data links spaced along the patrol route of the UUVs. The UUVs will then download updates while passing by the data links to refresh their current information. When a submarine comes in contact with one of these UUVs, it will slow down and allow the UUV to approach. The submarine will then receive the UUVs broadcast via LOS blue-green laser transmission from above. Figure 5

provides a schematic picture on how the UUV-undersea garage-data node interface would work.
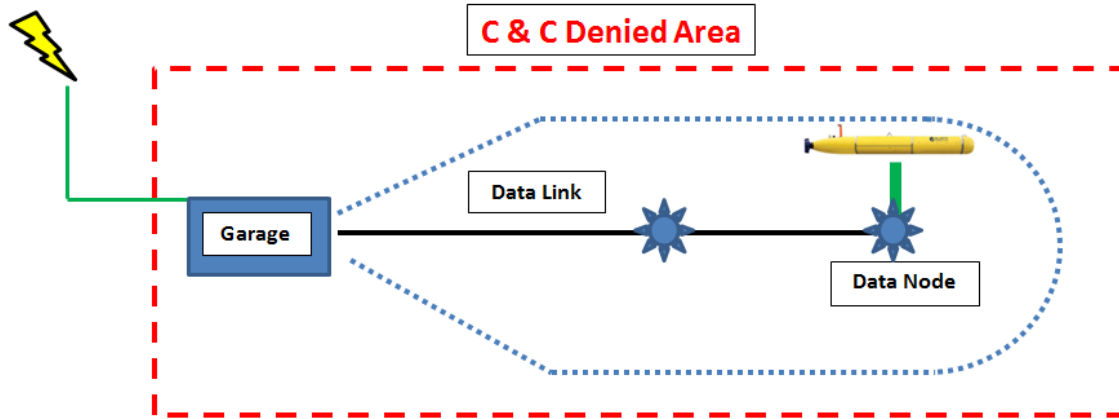


Figure 5.    UUV patrol route explained

## D.    LITERATURE REVIEW

A literature review on underwater communications as well as applications of UUV and unmanned aerial vehicle (UAV) technologies revealed multiple systems engineering and operations analysis theses on these topics. The theses focusing on underwater communications primarily dealt with acoustic based sensors, and the UUV based theses were systems engineering architecture designs with little simulation or data analysis. The theses exploring UAV technology however, often used Map Aware Non-uniform Automata software (MANA) and included in depth analysis of the simulation results. The application of MANA used to model UAVs is an excellent analog to how it can be used to model the undersea environment.

In both the theses of Kriewaldt (2006) and Hendrickson (2013), undersea communications between submarines and distributed acoustic networks is investigated [9], [10]. Both studies address the limitations of range, bandwidth, and security, but seem to define these parameters differently. The range of the acoustic network analyzed is superior to that of the blue-green laser (3-5 km). The laser however is inherently more secure, due to its proximity during transmission, and has a bandwidth over 100 times

larger than the acoustic transmitter. Although the acoustic network is defined as secure, simply being able to locate the sensors acoustically means they are susceptible to attack.

While deciding on a UUV platform to use in the MANA model, the theses of French (2010) and Vandenberg (2010) were instrumental in evaluating necessary platform characteristics [11], [12]. It was their work and the Navy's UUV Master Plan [8] that drove the decision to use the Bluefin-21 as the platform on which to base the model. Further research and personal correspondence [13] with Bluefin Robotics, revealed that the Knifefish UUV would be implemented on board the LCS by 2017. This, combined with the promise of increased modularity, made the Knifefish the candidate to model.

Although there were no theses dealing directly with the use of MANA or similar modeling software to look at UUVs, there were many that modeled UAVs. The thesis of Hakola (2004), deals specifically with modeling convoy security with UAV supplementation [14]. The search for UAV related modeling work lead to this study, but it was the implementation of random interdiction that drew attention. Although this study uses an older version of MANA, the methodology is applicable to modeling UUVs.

The thesis most applicable to this study is the research of Ozcan (2013). This thesis presents a study of using UAVs to provide border security between Iraq and Turkey [15]. At a glance it is difficult to see how this work is applicable to the undersea domain. The UAVs in the model patrol a border in a specific pattern looking for terrorists crossing using optical (LOS) sensors. This is a close analog for UUVs traveling in a similar set pattern attempting to detect incoming submarines. By removing the factors of altitude and differing terrain and by changing the overall scale of the problem to something more applicable to the undersea domain, a parallel can be drawn. Additionally, the data analysis method in Ozcan's thesis is similar to methods used later in this thesis.

# II.    MANA

This chapter describes the concept of agent-based modeling and the specific application of the Map Aware Non Uniform Automata (MANA) software used for simulation of the scenarios.

## A.    AGENT-BASED MODELING

Agent-based modeling and simulation (ABMS) is a newer type of simulation that has evolved immensely in the last 20 years. It is widely used to simulate complex systems where a large number of autonomous entities (agents) interact stochastically with themselves, each other, and the environment [16], [17]. ABMS is especially useful in detecting emerging behaviors. By giving each agent (or group of agents) a set of rules (or behaviors) by which to make decisions instead of a script, the agents' environment and interactions with each other are allowed to evolve overall system behaviors.

## B.    WHY MANA

MANA is a specific type of ABMS often referred to as an agent-based distillation (ABD) [18]. Distillation type models are somewhat simplified versions of the more complex programs designed to simulate combat, such as the Synthetic Theater Operations Rehearsal Model (STORM) [19]. The ABD's purpose is to extract overall behaviors without the time and effort required to program all of the details of the larger model. Think days and weeks for an ABD versus months and years for a more complex model like STORM. MANA can be used to quickly create a bottom-up abstraction of a specific scenario that will capture pertinent data without any non-essential detail. The MANA terms of use screen list the developers and New Zealand Army and Defense force as a user and is shown in Figure 6.

Figure 6.    MANA terms of use screen.

MANA falls into a subset of ABMS known as Cellular Automaton (CA) models. CA models evolved to model complicated physics and biology. The advantage again being that they can model very specific small parts with known behaviors and an overall behavior that might be unexpected emerges. The MANA model attempts to create a complex adaptive system for some real-world factors of combat such as: [18]

- Change of plans due to the evolving battle,

- The influence of situational awareness when deciding on an action,

- The importance of sensors and how to use them to best advantage.

Although MANA is primarily designed to model ground combat, it is well suited for the undersea domain. A wide variety of sensors exist in MANA that can be used to model real-world equipment. For example, radar might be modeled as an over the horizon sensor that will not immediately result in a classification, and visual detection as a LOS sensor resulting in immediate classification. The variety and specificity of the

different sensors allow quick modeling of very complex real world systems. The undersea domain is easily modeled because essentially there is no terrain in open water. Elevation can be used to simulate depth and the battlefield is completely scalable to the large distances typically seen when dealing with naval combat.

Another advantage of MANA is in its ease of use. Learning to use the software is part of the Naval Postgraduate School Operations Analysis curriculum, and the software provides a Graphical User Interface (GUI) for ease of inputting parameters. Indeed, MANA has been used by over 50 thesis students at NPS [20]. Through the use of several different tabs in the main GUI , data entered in MANA is then converted to Extensible Markup Language (XML) for computation. One of the tabs of the MANA GUI, used to modify some of the agents' physical properties, is shown in Figure 7.
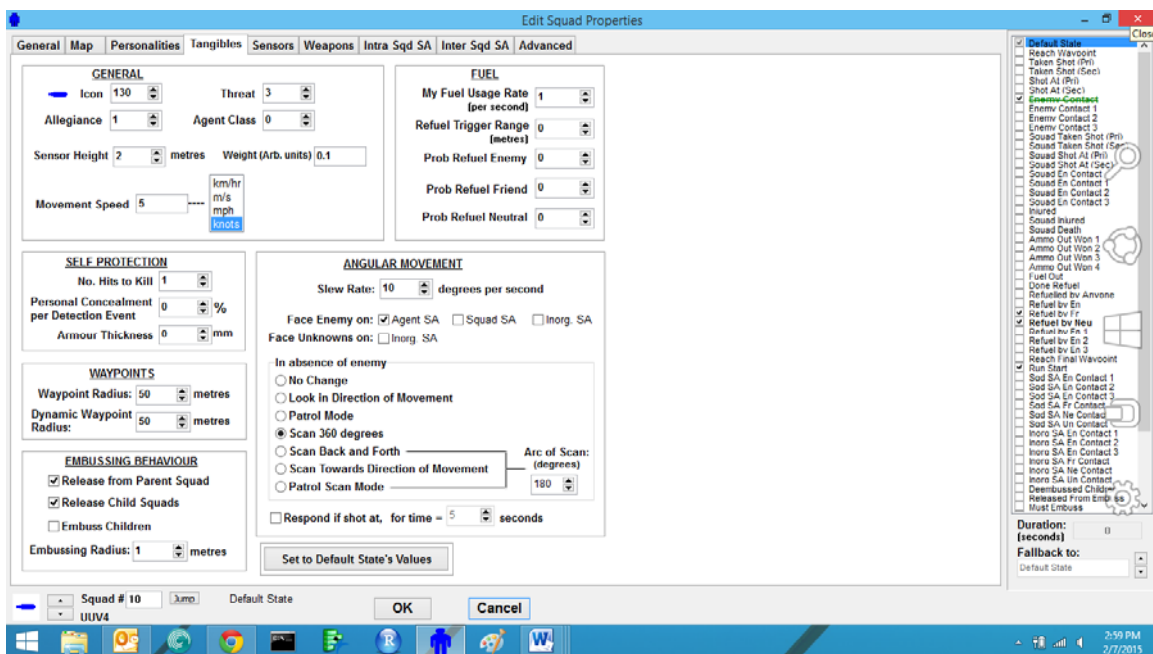


Figure 7.    MANA graphical user interface.

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# III.    SCENARIO AND MODEL DEVELOPMENT

This chapter discusses how the undersea environment is modeled using the Map Aware Non-uniform Automata (MANA) software, the specific performance characteristics of all of the agents modeled, and the variety of scenarios in which they are tested.

## A.    SIMULATING THE UNDERSEA ENVIRONMENT

### 1.    Battlefield

The battlefield in MANA is a bounded area in which the agents operate. There is a separate local map area, which must be smaller than or equal to the whole battlefield that defines the area visible in the main MANA display window. At the time of creating a new MANA model, the size of the battlefield in X and Y coordinates, the units of distance, and the size of the time step that will be used throughout the scenario modeled is defined. Figure 8 shows the battlefield settings GUI.
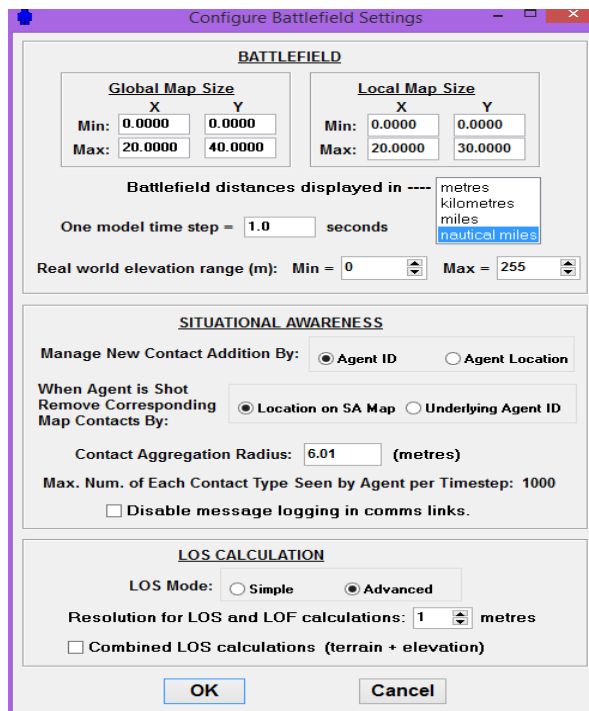


Figure 8.    Configure battlefield settings GUI.

All scenarios investigated in this study use a 20 by 40 nautical mile (NM) battlefield and a one second time step. The one second time step is selected to allow easy conversion of fuel usage and firing rates into units of time. The blue-green laser is modeled as a weapon employed by the UUV. Modeling the laser as a weapon allows the range and rate of fire, which represents the data transfer rate, to be used as variables in the model. The use of these factors to model time is discussed in detail later. In all scenarios, the UUVs travel a continuous path from the undersea garage to a waypoint 20 NM away. Data nodes are evenly spaced between the undersea garage and the waypoint. Figure 9 illustrates the layout of the battlefield for the simplest scenario, which consists of two UUVs (one is charging in the garage) and one data node.
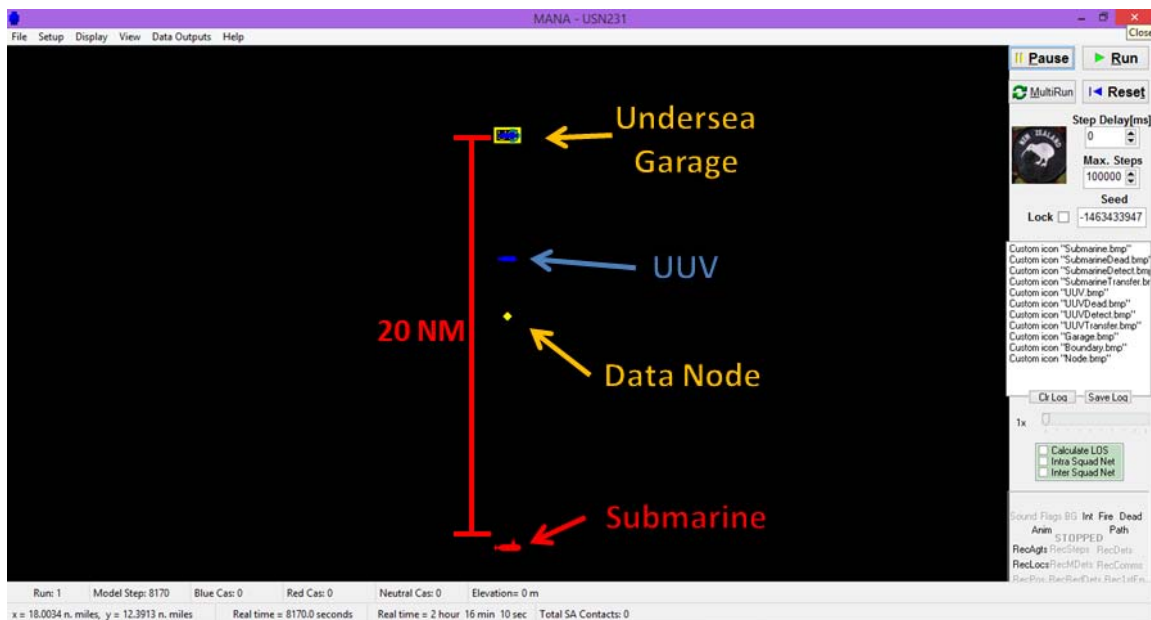


Figure 9.     Battlefield layout.

The simplest way to model open ocean in MANA is simply an area without any terrain. MANA has the capability to model many types of terrain through the use of terrain and elevation maps, and a unit's movement speed and concealment can be affected by the type of terrain they are crossing. None of these features are used in the creation of these scenarios simulating the undersea domain.

14

### 2. Physical Interactions Between Agents

UUVs and submarines detect each other through the use of passive sonar. This sensor is modeled in MANA as simple visual recognition, and both the submarines and UUVs detection ranges were varied for this study. Upon the submarine detecting the UUV, it slows from 10 knots to 5 knots to allow the UUV to approach. Once the UUV detects the submarine, it speeds up to 5 knots and follows the sub as close as possible. In MANA this appears as though the two are trying to occupy the same space, but in reality the UUV will be above the submarine transferring its data to a sensor in the submarine's sail. Data nodes are set to float at a specific depth, and the submarine will occupy the space above the nodes and below the UUVs. This configuration is shown in Figure 10.
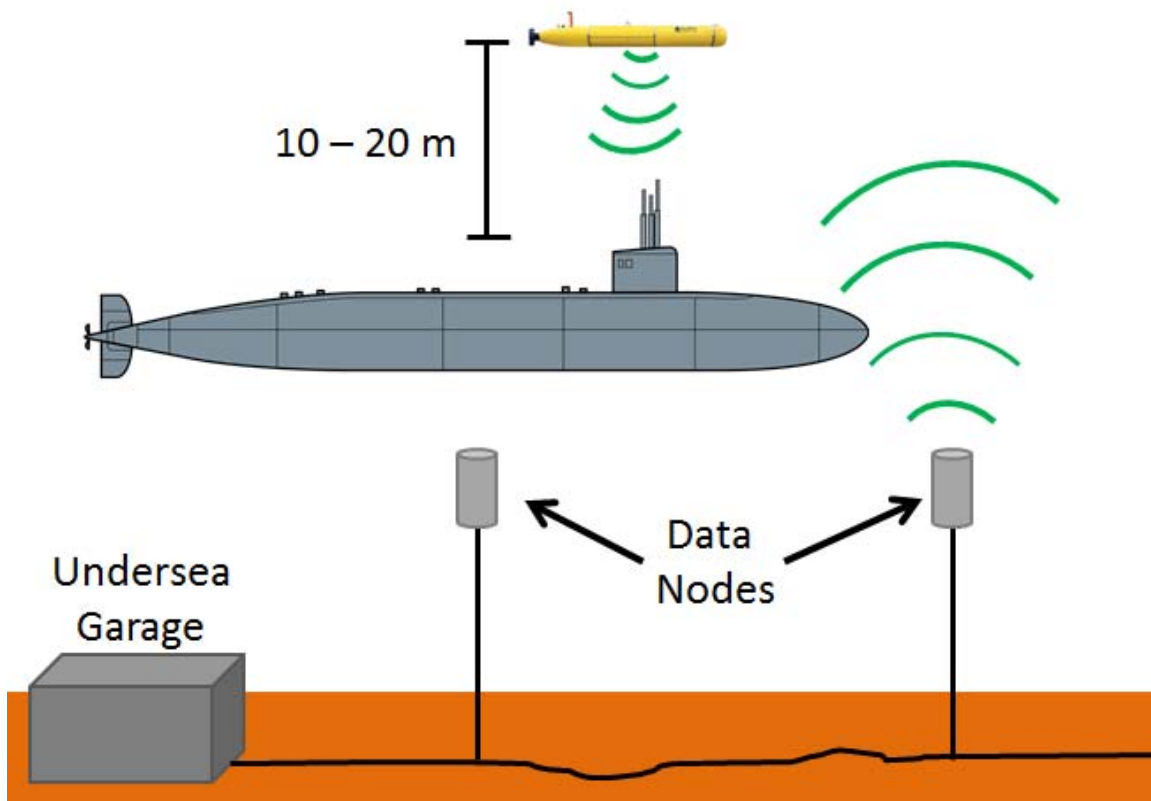


Figure 10.    Depth separation of UUV, submarine, and data nodes In this figure, data nodes pass information to a UUV, which in turn passes to a sensor on the submarine's sail area.

The configuration in Figure 10 was selected primarily because it is costly and difficult to add new penetrations to the hull of a submarine, especially on the bottom. New sensors are much more easily integrated, and are easier to maintain, in the submarine's sail.

## B.    SCENARIOS

A separate model is required for each combination of the number of UUVs, UUV speed, and the number of data nodes. Each scenario uses either two, three, or four UUVs moving at a speed of three, four, or five knots. The number of data nodes modeled are one, two, three, or four. In order to capture all possible combinations 3 x 3 x 4 = 36 separate models are required. Each model uses a naming convention of USN###, with each # corresponding to a value for its associated variable. The U of USN is the number of UUVs in the scenario, the S is the patrol speed of those UUVs, and the N is the number of data nodes. For example, USN234 consists of two UUVs moving at three knots over four data nodes. A complete list of the scenarios is provided in Table 1.

Table 1.　　Scenarios modeled.

| Model | UUVs | UUV Speed | Nodes | Model | UUVs | UUV Speed | Nodes |
|-------|------|-----------|-------|-------|------|-----------|-------|
| USN231 | 2 | 3 | 1 | USN343 | 3 | 4 | 3 |
| USN232 | 2 | 3 | 2 | USN344 | 3 | 4 | 4 |
| USN233 | 2 | 3 | 3 | USN351 | 3 | 5 | 1 |
| USN234 | 2 | 3 | 4 | USN352 | 3 | 5 | 2 |
| USN241 | 2 | 4 | 1 | USN353 | 3 | 5 | 3 |
| USN242 | 2 | 4 | 2 | USN354 | 3 | 5 | 4 |
| USN243 | 2 | 4 | 3 | USN431 | 4 | 3 | 1 |
| USN244 | 2 | 4 | 4 | USN432 | 4 | 3 | 2 |
| USN251 | 2 | 5 | 1 | USN433 | 4 | 3 | 3 |
| USN252 | 2 | 5 | 2 | USN434 | 4 | 3 | 4 |
| USN253 | 2 | 5 | 3 | USN441 | 4 | 4 | 1 |
| USN254 | 2 | 5 | 4 | USN442 | 4 | 4 | 2 |
| USN331 | 3 | 3 | 1 | USN443 | 4 | 4 | 3 |
| USN332 | 3 | 3 | 2 | USN444 | 4 | 4 | 4 |
| USN333 | 3 | 3 | 3 | USN451 | 4 | 5 | 1 |
| USN332 | 3 | 3 | 4 | USN452 | 4 | 5 | 2 |
| USN341 | 3 | 4 | 1 | USN453 | 4 | 5 | 3 |
| USN342 | 3 | 4 | 2 | USN454 | 4 | 5 | 4 |

## C.　　AGENTS

Since MANA was originally and primarily designed to model ground combat, no bitmap designs exist to represent submarines or UUVs on MANA's screen. Custom bitmaps were developed for this research for each agent modeled. Additional bitmaps were developed for the Enemy Contact state in which the UUV and submarine have detected each other and for when actual data transfer is taking place. This allows for the user to see when these events occur. The custom bitmaps are shown in Figure 11. These new have been made available for future MANA modelers.
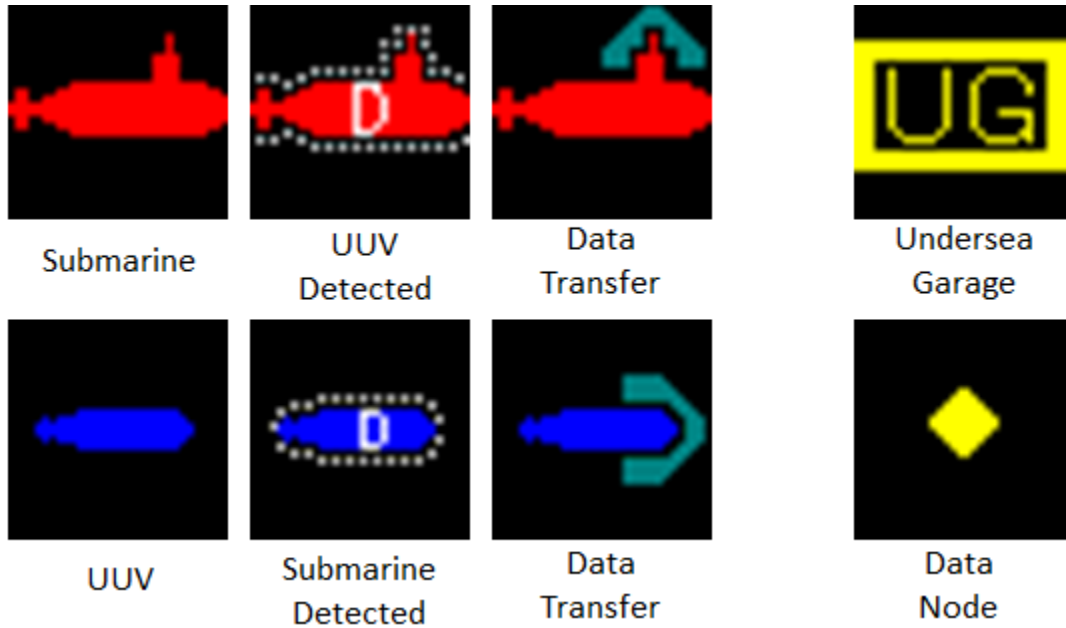
Figure 11.    Custom MANA bitmaps designed for this research.

MANA uses an allegiance system to determine interactions between agents. Agents of the same allegiance are treated as friends, opposite allegiance as enemies. There is also a neutral allegiance to simulate an agent that can interact with either red or blue allegiance or only with other neutral agents. UUVs and data nodes are allegiance 1, the submarine is allegiance 2, and the undersea garage is allegiance 0 (neutral). The opposite allegiance of UUVs and submarines allows the UUVs to "shoot" data at the submarine as a representation of data transfer.

### 1.    Submarine

The submarine begins each scenario past the 20 NM UUV waypoint at the maximum range of the UUV sensor. It is cloaked (undetectable by the UUV) until all UUVs have reached their proper place in the model. Proper place is defined as the UUVs having traveled from the garage until they are equally spaced, preserving correct fuel levels—which will be used in later analysis. The submarine enters the scenario at a randomized time from 0 to the cycle length for that scenario. Cycle length is defined as the time it takes for the last UUV leaving the garage to complete its 40 NM round trip.

The goal of this is to simulate the UUVs and undersea garage system operating in steady state. By randomizing the entry time of the submarine, we can simulate a boat using the system in any condition.

### 2. Undersea Garage

The undersea garage is a neutral agent that is only used to recharge UUVs and a source for data update to the UUVs. All UUVs start in the garage at the beginning of the scenario and leave sequentially until all but one has left. The final UUV leaves when the first one that departed returns. This sets up the steady state cycle.

### 3. Data Nodes

The data nodes are stationary and equally spaced over the 20 NM track, depending on how many are included in the scenario. They are the same allegiance as the UUVs and are used solely to "refuel" UUVs. This "refueling" has nothing to do with recharging the UUV, but rather represents an update to the data packet the UUV left the garage with. By examining the remaining fuel level in the UUV that links up with the submarine, we can determine the latency of that data. A minimum "refuel" range of 500 meters was necessary to avoid frequent cases in which the UUV will pass a data node without "refueling". Essentially we use fuel usage as a clock for data latency.

### 4. UUVs

The UUVs in the scenarios are used to transfer data from the Undersea Garage to the submarine. They leave the garage at the appropriate time and the fuel used while traveling represents the age of the information on board. Every time a UUV passes a Data Node, it is "refueled". This simulates an update to the data package and resets the fuel level to the maximum level.

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# IV. DESIGN OF EXPERIMENTS AND MODEL RUNS

Design of experiment (DOE) techniques allow for estimating the effects of input variables on outputs and the testing of interactions between many factors that would otherwise be computationally prohibitive [21]. Through careful design of the input variables and application of a Nearly Orthogonal Latin Hypercube (NOLH) design, data is efficiently sampled and representative of a far larger data set. Factors can be classified as either controllable or uncontrollable. Controllable factors can be controlled or set by the system operator or have their values set by design or environmental limitation. Most physical parameters of a piece of equipment such as speed, sensor range, weapon parameters, etc., are therefore considered controllable factors. Uncontrollable factors are variables over which the system operator cannot reasonably exercise control. Examples include enemy characteristics and response, weather, and other environmental impacts.

## A. FACTORS

A wide range of factors may be varied in the design to examine their effects on selected measures of effectiveness (MOEs). Specific controllable factors are selected that are representative of existing UUV and submarine technology as well as future approximations of that technology.

### 1. Discrete Controllable Factors

The discrete factors included in this study are the number of unmanned underwater vehicles (UUVs) continuously operating, the number of data nodes available, and the speed at which the UUVs travel. The number of data nodes and UUVs obviously has to be a discrete value, but the UUV speed was implemented as a discrete value only to facilitate model set-up in the Map Aware Non-uniform Automata (MANA) software. This decision is detailed in Section III.B of this study. A list of the discrete controllable factors is shown in Table 2.

Table 2.    Discrete factors varied in experimental design and their ranges.

| Factor Name | Low Level | High Level | Units | Variable Type |
|---|---|---|---|---|
| Number of UUVs | 2 | 4 | N/A | Discrete |
| Default UUV Speed | 3 | 5 | kts | Discrete |
| Number of Data Nodes | 1 | 4 | N/A | Discrete |

### 2.    Continuous Controllable Factors

The continuous factors selected for varying in the experimental design are select sensor and communication design characteristics of the UUV, blue-green laser, and submarine. The low level of each factor is either an approximation of currently existing technology, or a minimum value necessary for the model to work properly—as discovered while building the models.

The UUV side-scanning sonar's minimum detection range is selected based on the currently employed Edgetech 2200-S [22]. The maximum UUV sensor range is an arbitrary ten times the minimum range, and is selected to explore the factor space. Submarine sensor ranges represent approximations of the actual detection range that is highly dependent on, for example, the UUV's signal strength, and the skill of the sonar operators. UUV weapon range is used to model the blue-green laser. The blue-green laser's current unclassified range is about 20 meters [2], but a minimum value of 100 meters was used in the model. This minimum value was necessary to curb the large number of model runs which resulted in no transfer of data occurring. This 100 meter value is attributed to relative motion between the UUV and submarine in MANA that would not occur in real life. The maximum range of 2000 meters is again an arbitrarily large value set to explore possible gains made with increased range. Both the UUV hit rate and submarine hit to kill factors are approximations for how long the data transfer between the UUV and submarine will take. The UUV hit rate approximates the quality of the signal, while the submarine hits-to-kill is an approximate time frame of two to five minutes. The combination of the two factors approximates a minimum data transfer time of two minutes and a maximum of about 25 minutes. The continuous factors modeled and their ranges are exhibited in Table 3.

Table 3.    Continuous factors varied in experimental design and their ranges.

| Factor Name | Low Level | High Level | Units | Variable Type |
|---|---|---|---|---|
| UUV Sensor Range | 500 | 5000 | m | Continuous |
| Submarine Sensor Range | 1000 | 10000 | m | Continuous |
| UUV Weapon Range | 100 | 2000 | m | Continuous |
| UUV Hit Rate (Weapon Accuracy) | 0.4 | 1 | N/A | Continuous |
| Submarine Hits to Kill | 120 | 600 | N/A | Continuous |

### 3.    Robust Design

Robust design refers to an engineering productivity methodology developed by Dr. Genichi Taguchi [23], [24]. It has been widely used to increase engineering system productivity by evaluating criteria other than the system's mean performance. For example, alternatives are scored based on both mean performance and variability. Robust design seeks to manage uncontrollable sources of variation within the system and understand their impact on the controllable factors [25]. The controllable factors can then be optimized to work well in the presence of the noise factors by including approximations of the uncontrollable factors in the experimental design.

### 4.    Uncontrollable Factors

The uncontrollable, or "noise" factors included in the study are navigational uncertainty and the start time of the submarine. MANA can introduce uncertainty in an agent's navigational path through use of the Random Patrol feature. By adding a small amount or randomness to the UUV and submarines route, we can approximate real world navigational inconsistencies caused by ocean currents and inertial navigation errors. By varying the time the submarine enters the scenario, the real world application of a submarine navigating to the area for service is simulated. The system needs to function continuously to replace or supplement the submarine's ability to go to periscope depth (PD) at any time.

## B.    NEARLY ORTHOGONAL LATIN HYPERCUBE DESIGNS

The Nearly Orthogonal Latin Hypercube (NOLH) is an adapted form of Latin Hypercube (LH) design developed by Cioppa (2002) [26]. The NOLH design allows for

the exploration of a factor space that would be impossible for even the fastest computers of today to analyze without a sophisticated design of experiments. The Roadrunner supercomputer unveiled in 2008 can perform a thousand trillion operations every second. It would still take this computer 40 million years to conduct an experiment that explored every possible combination of just one hundred factors, each with only two levels. And that's if the simulation only took a nanosecond to run. And, that is with only two levels per factor. To model a continuous factor (much more than two levels), the computation time increases exponentially. NOLH designs allow a regular computer to analyze a representative sample of the factor space that approximates the entire space. For a broader set of NOLH designs, see [27].

## 1.     SEED Center Spreadsheets

The Naval Postgraduate School's SEED Center for Data Farming provides Excel spreadsheets that are used to efficiently generate a sampling of the factor space [28]. The spreadsheets were developed by Professor Susan Sanchez for applications of up to 29 factors. The spreadsheet uses high and low levels for each factor as inputs and outputs an evenly spaced permutation of values in between defined levels for each factor. The seven factor spreadsheet used in this study is shown in Figure 12.

| low level | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
|---|---|---|---|---|---|---|---|
| high level | 17 | 17 | 17 | 17 | 17 | 17 | 17 |
| decimals | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| factor name | | | | | | | |
| | 6 | 17 | 14 | 7 | 5 | 16 | 10 |
| | 2 | 5 | 15 | 10 | 1 | 6 | 11 |
| | 3 | 8 | 2 | 5 | 11 | 14 | 17 |
| | 4 | 11 | 6 | 17 | 10 | 3 | 13 |
| | 13 | 16 | 8 | 3 | 6 | 1 | 14 |
| | 17 | 6 | 7 | 14 | 2 | 13 | 15 |
| | 11 | 4 | 17 | 6 | 15 | 8 | 16 |
| | 10 | 15 | 13 | 16 | 14 | 11 | 12 |
| | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| | 12 | 1 | 4 | 11 | 13 | 2 | 8 |
| | 16 | 13 | 3 | 8 | 17 | 12 | 7 |
| | 15 | 10 | 16 | 13 | 7 | 4 | 1 |
| | 14 | 7 | 12 | 1 | 8 | 15 | 5 |
| | 5 | 2 | 10 | 15 | 12 | 17 | 4 |
| | 1 | 12 | 11 | 4 | 16 | 5 | 3 |
| | 7 | 14 | 1 | 12 | 3 | 10 | 2 |
| | 8 | 3 | 5 | 2 | 4 | 7 | 6 |

Figure 12.    NOLH for up to 7 factors, from [28].

## 2.    NOLH Space-Filling Property

One of NOLH design's primary advantages is its good space-filling property [29]. Space-filling refers to the approximately uniform distribution of design points (DPs) across the entire possible input range. Figure 13 is a scatterplot showing the pairwise plots of the five continuous factors. Notice that the points are scattered throughout the region with minimal white space (i.e., regions where no samples are taken).
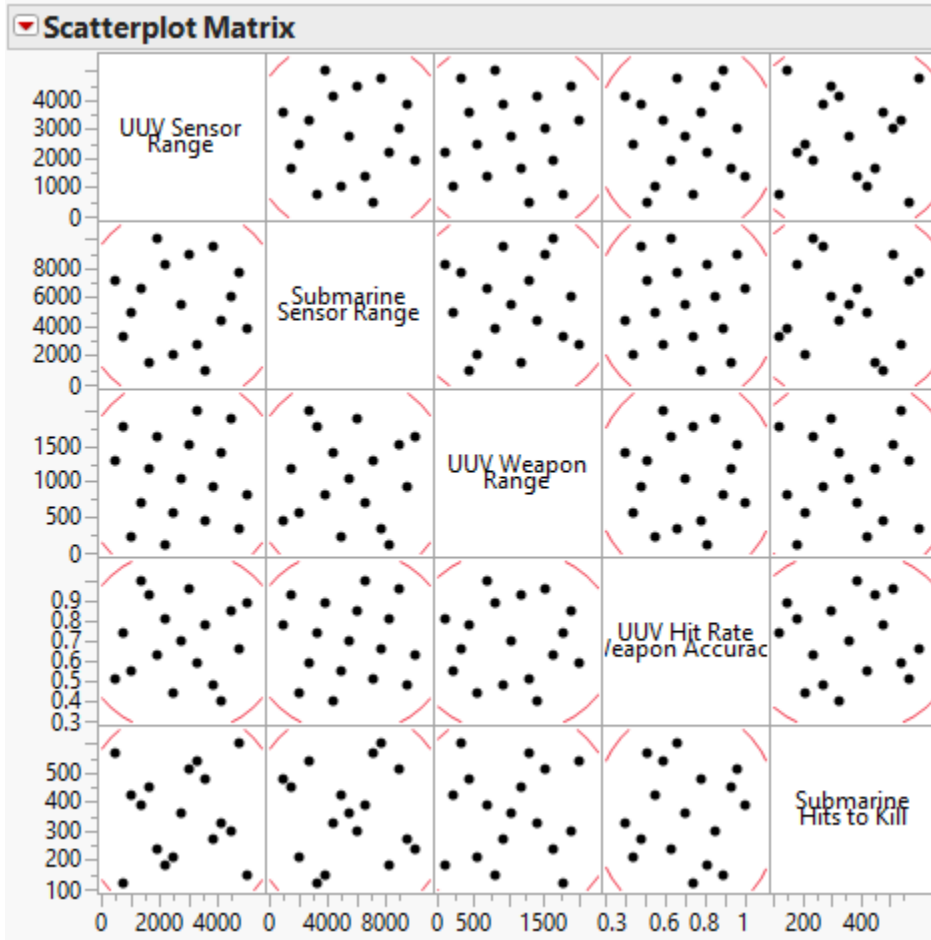
Figure 13.    Scatterplot of the five continuous factors showing
good space filling properties.

# V. DATA ANALYSIS

This chapter discusses the JMP analysis tool and its application to the model output data. Next, we discuss the result of running a set of initial models, before the application of experimental design; followed by analysis of a model that has the design's mean discrete variable values. The final section discusses the impact of the experiment's factors on the selected measures of effectiveness (MOEs).

## A.     JMP

JMP is the primary tool used for analysis of model output. MANA outputs various selected metrics to a spreadsheet set of comma delimited text (.csv) files, and a SEED Center developed post-processor synthesizes and summarizes the output into a single file that can be imported into any statistical tool. JMP is used to analyze the output. The first version of JMP was introduced by a company called SAS in 1989 with the goal of empowering students and scientists to explore data visually [30]. JMP has a series of Graphical User Interfaces (GUIs) that allow for easy and intuitive analysis of data via point and click methods.

JMP enables a wide variety of statistical analysis techniques, including linear and non-linear regression, time series analysis, and partition trees. JMP Pro version 11.2.0 was used for the data analysis in this study. Figure 14 is an example of one of the JMP GUIs.
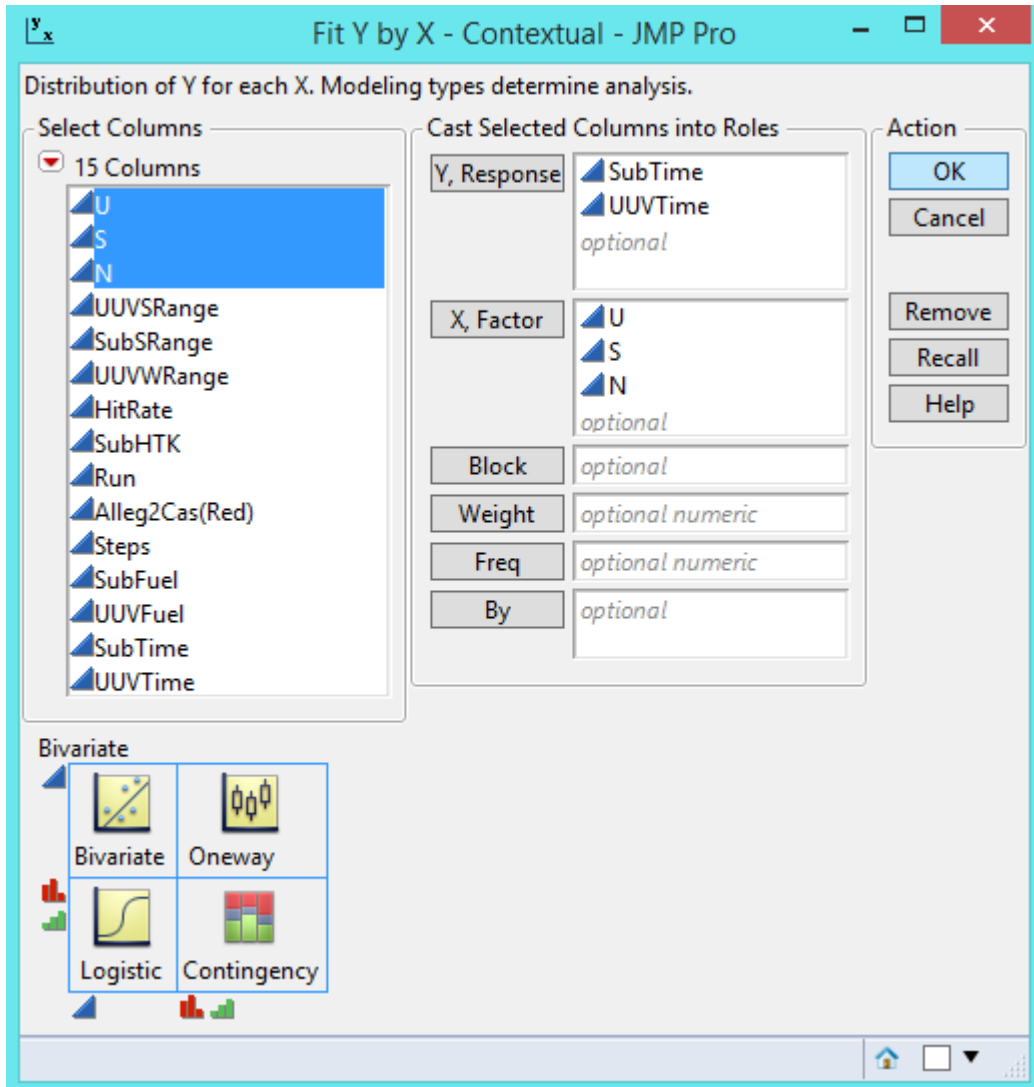
Figure 14.   Example JMP GUI showing out data files for the MANA simulation.

## B.   INITIAL RESULTS

The primary purpose of the early model runs was to ensure that the model was working correctly and to find the lower bound for the continuous factors necessary to ensure a data transfer took place. The process involved manually adjusting the settings for each UUV and submarine agent and running the model 100 times. Each 100 run iteration took approximately five hours on a Toshiba quad core processor laptop computer. In addition, a minimum value of 500 meters was found to be necessary for the data node refuel trigger range. This is the range at which the UUV detects the node and

gets its new data upload. At values less than 500 meters, the randomness added to the UUVs path would occasionally direct the UUV around the data node and it would not get an upload at all. Of course, this range is worth noting—as not linking up could occur in practice.

## C. MODEL USN342 RESULTS

Model USN342 represents the mean of the discrete factors. The model is comprised of three UUVs traveling at four knots and two data nodes. The model was then run 1000 times with all continuous factors set at their mean values. The values for the factor settings are illustrated in Figure 15.

| Factor Name | Level |
|---|---|
| Number of UUVs | 3 |
| Default UUV Speed | 4 |
| Number of Data Nodes | 2 |
|  |  |
| UUV Sensor Range | 2750 |
| Submarine Sensor Range | 5500 |
| UUV Weapon Range | 1050 |
| UUV Hit Rate (Weapon Accuracy) | 0.7 |
| Submarine Hits to Kill | 360 |

Figure 15.    Mean value settings for model USN342.

### 1. USN342 Data Analysis

The two measures of effectiveness (MOEs) in this study are the time it takes for the submarine to receive a download from a UUV once it enters the area and how old that data is (i.e., the time since the UUV last exited the garage or passed a data node). Summary statistics for the 1000 runs of model USN342 are in Figure 16.
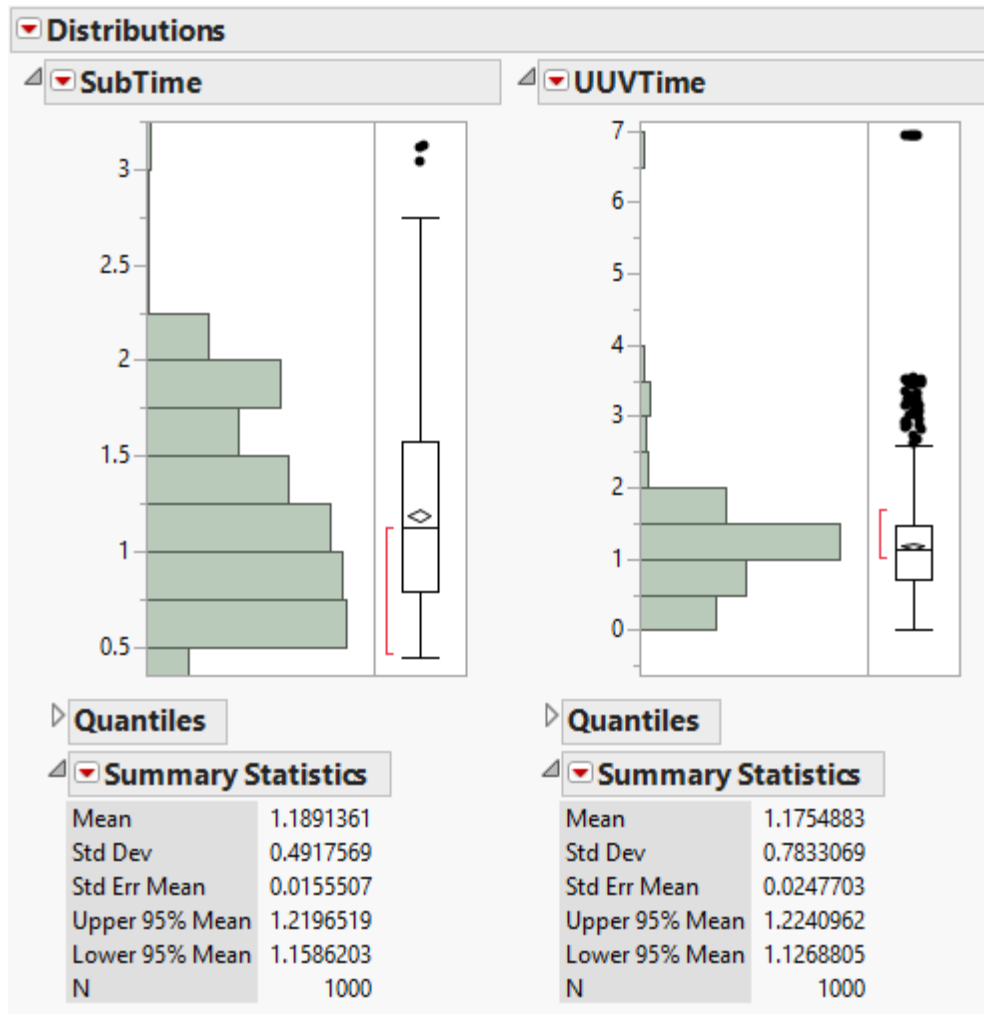
Figure 16.    Model USN342 summary statistics.

The mean time for both MOEs is a little over an hour with absolute maximum times of three hours for the submarine wait time and seven hours for the data latency. The MOEs had standard deviations of roughly 30 and 47 minutes.

## 2.    Outliers

MANA has a feature that tracks the seed value for each model run, allowing the playback of any run with interesting results. There are three cases in which the submarine took approximately three hours to contact a UUV or featured data that was seven hours old. These runs are the result of UUVs that strayed too far off their path and never received a download from a data node. The fuel remaining is used to account for the

elapsed time in the model, but MANA also treats UUVs that have run out of fuel as immobile. The result of the immobile UUV is one that cannot follow the submarine and complete the data transfer. This was unexpected as there were no cases in which the data transfer did not occur in the 100 run initial analysis used to find the minimum continuous factor settings.

## D.    COMBINED MODEL RESULTS

### 1.    NOLH Design Output

The NOLH design used for analysis is discussed in depth in Chapter IV of this study. Five factors of the seven factor spreadsheet were used with values as shown in Figure 17.

| low level | 500 | 1000 | 100 | 0.4 | 120 | 1 | 1 |
|---|---|---|---|---|---|---|---|
| high level | 5000 | 10000 | 2000 | 1 | 600 | 17 | 17 |
| decimals | 0 | 0 | 0 | 2 | 0 | 0 | 0 |
| factor name | UUV Sens | Submarine | UUV Wea | UUV Hit R | Submarine | Hits to Kill | |
| | 1906 | 10000 | 1644 | 0.63 | 240 | 16 | 10 |
| | 781 | 3250 | 1763 | 0.74 | 120 | 6 | 11 |
| | 1063 | 4938 | 219 | 0.55 | 420 | 14 | 17 |
| | 1344 | 6625 | 694 | 1 | 390 | 3 | 13 |
| | 3875 | 9438 | 931 | 0.48 | 270 | 1 | 14 |
| | 5000 | 3813 | 813 | 0.89 | 150 | 13 | 15 |
| | 3313 | 2688 | 2000 | 0.59 | 540 | 8 | 16 |
| | 3031 | 8875 | 1525 | 0.96 | 510 | 11 | 12 |
| | 2750 | 5500 | 1050 | 0.7 | 360 | 9 | 9 |
| | 3594 | 1000 | 456 | 0.78 | 480 | 2 | 8 |
| | 4719 | 7750 | 338 | 0.66 | 600 | 12 | 7 |
| | 4438 | 6063 | 1881 | 0.85 | 300 | 4 | 1 |
| | 4156 | 4375 | 1406 | 0.4 | 330 | 15 | 5 |
| | 1625 | 1563 | 1169 | 0.93 | 450 | 17 | 4 |
| | 500 | 7188 | 1288 | 0.51 | 570 | 5 | 3 |
| | 2188 | 8313 | 100 | 0.81 | 180 | 10 | 2 |
| | 2469 | 2125 | 575 | 0.44 | 210 | 7 | 6 |

Figure 17.    Seven factor NOLH spreadsheet.

The 17 design points from the five-factor NOLH were run for each of the 36 discrete factor models, resulting in 612 total design points. Each design point was run 40 times for a total of 24,480 simulated missions. The SEED-developed post-processor

gathered and summarized the output of all models in one file—which allowed for easier data analysis in JMP. This dataset is further summarized by the mean of each design point, and it is this data that is used as the basis for the regressions and partition trees described in this chapter.

## 2. One-Way ANOVA

One-way analysis of variance (ANOVA) is a reliable method of inference that can be used when these three assumptions are met [31]:

- All observations are independent of one another.

- The individual error terms are normally distributed.

- The variance of the individual errors is the same across treatment groups.

In Figure 18, it is shown that variances are not quite equal overall, but are relatively consistent within groups of the same number of UUVs.
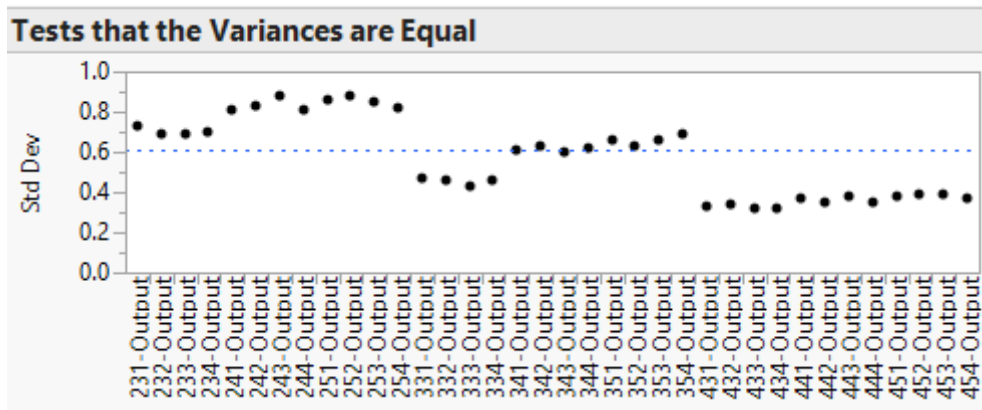


Figure 18.    Test for equal variances.

One-way ANOVA analysis conducted on the whole data set reveals a *p-value* of < 0.0001. The *p-value* is the probability that differences this large would be observed by chance if in fact all the variances are equal. This means the null hypothesis that each model produces the same results is strongly rejected. Results of the ANOVA analysis are included in Figure 19. Note: since the variances are not quite equal, and the residuals show some non-normality, the *p-values* should be viewed as approximations rather than

exact results. Fortunately, in our case, the differences are large enough to be considered statistically significant.
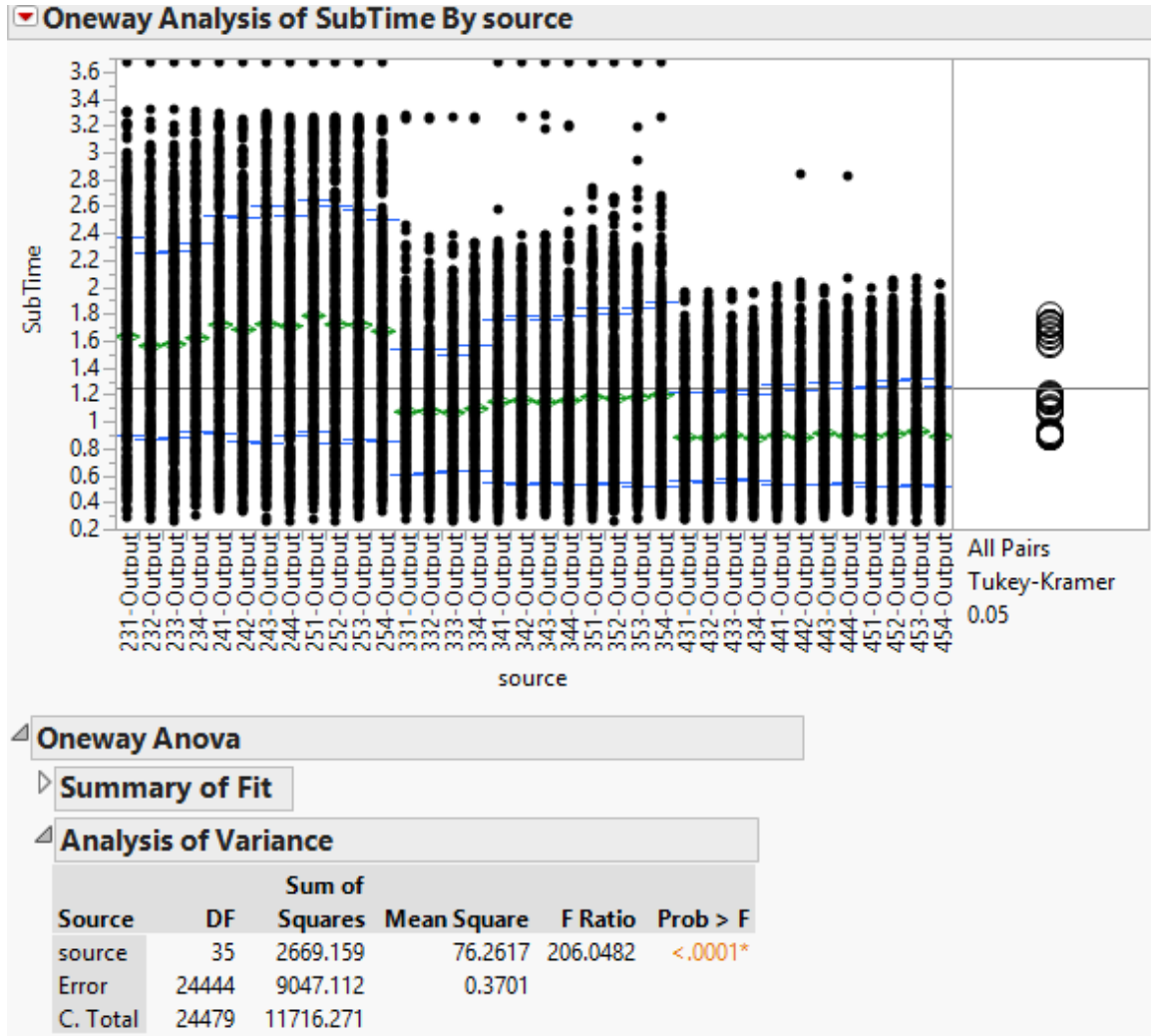


Figure 19.    Submarine wait time ANOVA output.

The same analysis was then conducted on UUV data age. Again the *p-value* was < 0.0001, so the hypothesis that the output is the same from model to model is also strongly rejected. UUV data age ANOVA output is included in Figure 20.
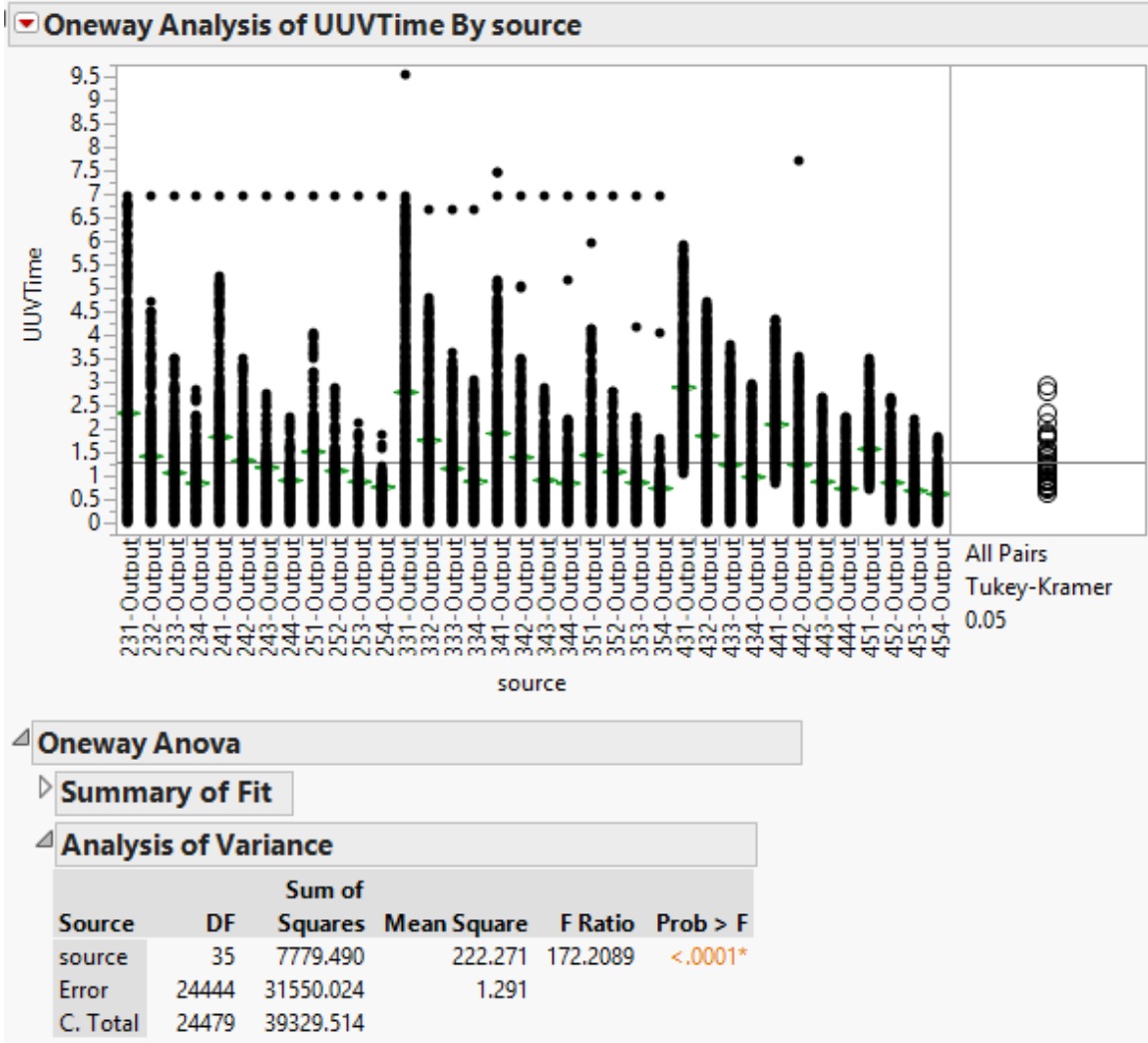
Figure 20.    UUV data age ANOVA output.

### 3.    Linear Regression

Linear regression is used to estimate a mathematical relationship between response variables and input factors. Linear models assume the regression function is linear or that the linear model is an acceptable approximation [32]. The linear model is stated by the following equation:

$$f(X) = \left( \beta_0 + \sum_{j=1}^{p} X_j \beta_j \right)$$

(1)

In the equation, $\beta_0$ is the value of the $y$ intercept and $\beta_j$ is the calculated coefficient of the regressor variable $X_j$. Each regressor is independent and the value of each regressor coefficient is approximated by JMP. The first model fit was a simple main effects model on both the submarine wait time and UUV data age MOEs. The main effects models for submarine wait time is in Figure 21 and UUV data age is in Figure 22.
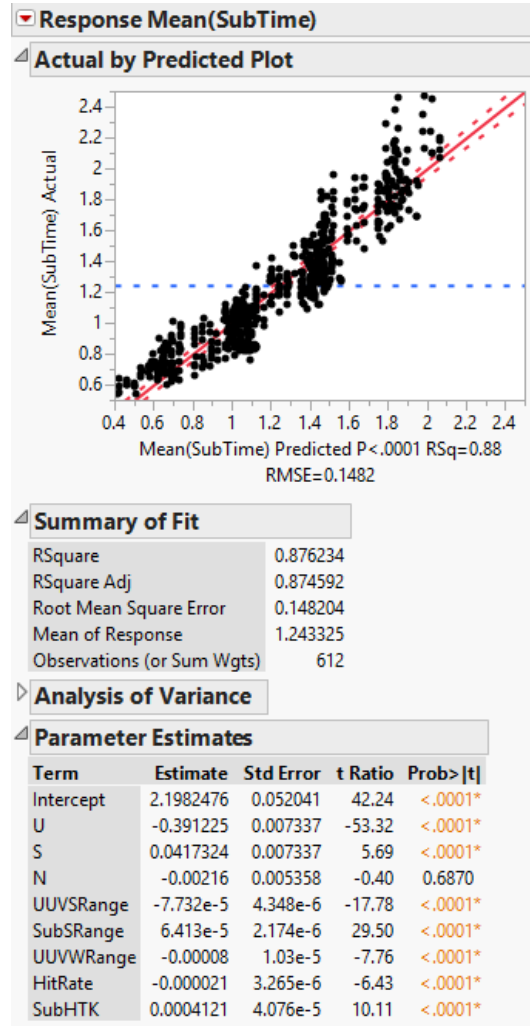


Figure 21.    Main effects model for submarine wait time.
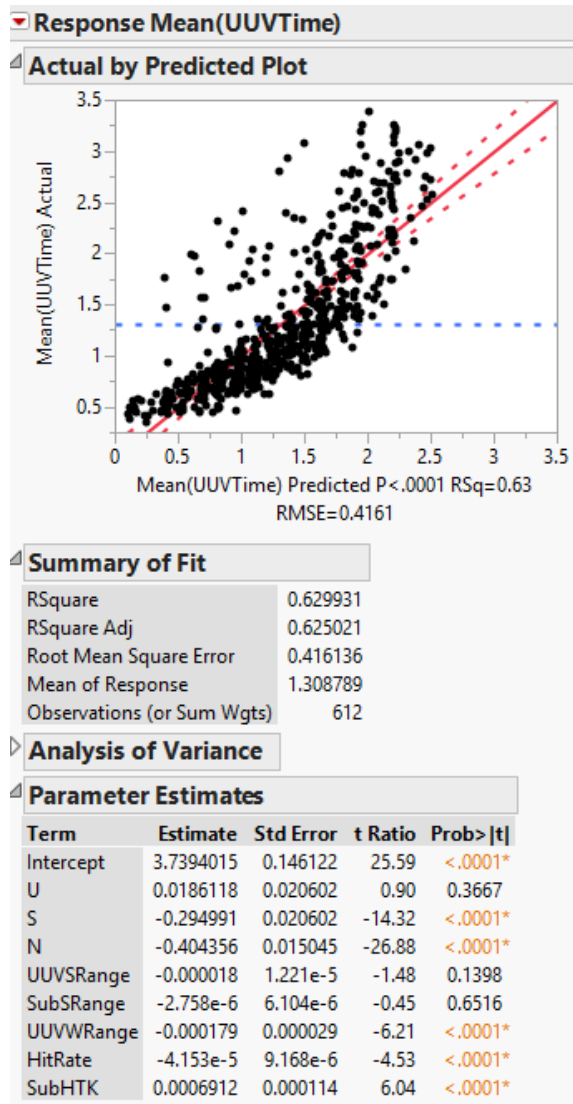
Figure 22.    Main effects model for UUV data age.

The linear regression for the submarine wait time shows strong evidence that all of the factors except the number of data nodes affect the wait time. The regression for the UUV data age suggests that the number of UUVs and the range of both the UUVs and submarine's sensors have little impact on the age of the data.

An improved model (found using stepwise regression) for the submarine wait time MOE includes six factors from the previous model (all but number of data nodes and UUV speed), as well as a two-way interaction term and a quadratic term. The updated model is shown in Figure 23.

**Actual by Predicted Plot**
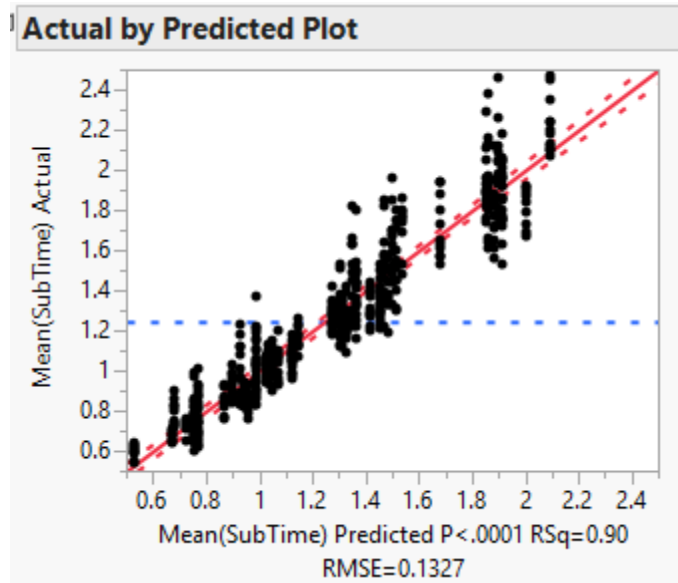
**Summary of Fit**

| | |
|---|---|
| RSquare | 0.900748 |
| RSquare Adj | 0.899431 |
| Root Mean Square Error | 0.132718 |
| Mean of Response | 1.243325 |
| Observations (or Sum Wgts) | 612 |

▷ **Analysis of Variance**

▷ **Lack Of Fit**

**Parameter Estimates**

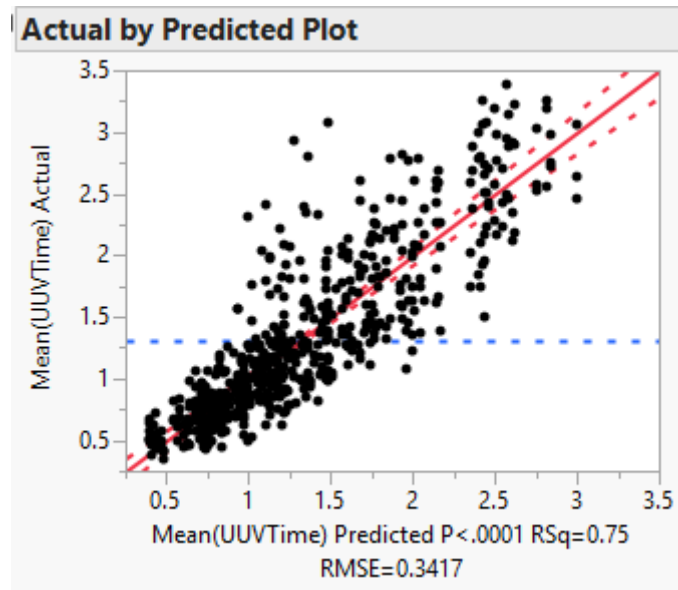| Term | Estimate | Std Error | t Ratio | Prob>\|t\| |
|---|---|---|---|---|
| Intercept | 2.2610566 | 0.037346 | 60.54 | <.0001* |
| U | -0.391225 | 0.006571 | -59.54 | <.0001* |
| UUVSRange | -7.732e-5 | 3.894e-6 | -19.86 | <.0001* |
| SubSRange | 6.413e-5 | 1.947e-6 | 32.94 | <.0001* |
| UUVWRange | -0.00008 | 9.222e-6 | -8.67 | <.0001* |
| HitRate | -0.000021 | 2.924e-6 | -7.18 | <.0001* |
| SubHTK | 0.0004121 | 3.65e-5 | 11.29 | <.0001* |
| (U-3)*(SubSRange-5500.24) | -1.071e-5 | 2.384e-6 | -4.49 | <.0001* |
| (U-3)*(U-3) | 0.1480816 | 0.01138 | 13.01 | <.0001* |

Figure 23.    Improved regression model for submarine wait time MOE.

Again, the improved model for the UUV data age MOE includes several main effects as well as a two-way interaction term and a quadratic term. The updated model for the second MOE is shown in Figure 24. The interaction terms account for some of the non-linearity seen in Figure 22 and increased the R squared value from 0.63 to 0.75 with only nine terms (one more than the main effects model).

37

Figure 24. Improved regression model for UUV data age MOE.

## 4. Regression Tree Analysis

Complementing the use of regression to understand the result of a designed experiment, recursive partitioning is a nonparametric technique used to identify the parameters that best predict the dependent variable of interest. Variations of recursive

partitioning are referred to by many names, including decision trees, partition trees, and Classification and Regression Trees (CART). The partitioning technique iteratively splits the data at optimum points, in order to maximize the difference in the values of the response variables between the two groups formed by the split. The result is a tree that classifies each observation into a group, and shows the factors and key threshold values that best explain the groups [33].

The results for the first five splits of the submarine wait time MOE are presented in Figure 25.
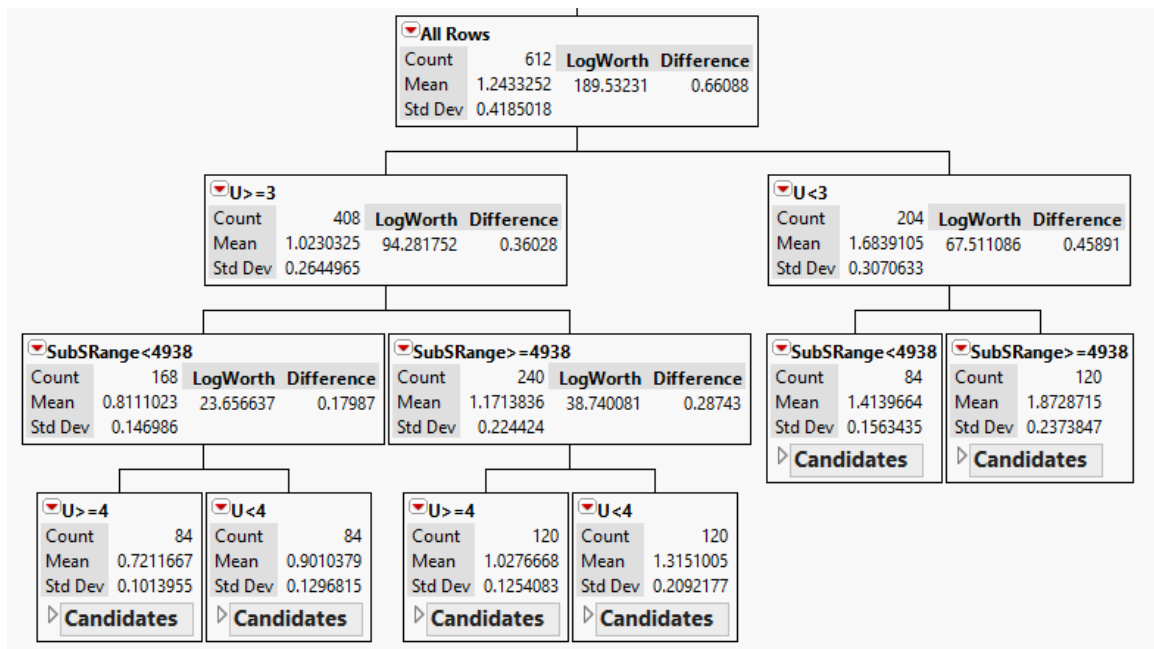


Figure 25.    Submarine wait time MOE regression tree.

The regression tree agrees with the linear regression model in that the first division is on number of UUVs and that is the most significant regression factor. The next two divisions take place on the submarine sensor range. The divisions are both split on a submarine sensor range of 4,938 meters and show that detecting the UUV further out negatively impacts the submarine's wait time. Upon review of the models, this is largely due to the submarine slowing down to five knots too early. This means that the UUV will take longer to reach the submarine and suggests that the submarine should slow down

later by procedure or the range of the UUV sensor should be increased to minimize the submarines wait time. The regression tree for the UUV data age is shown in Figure 26.
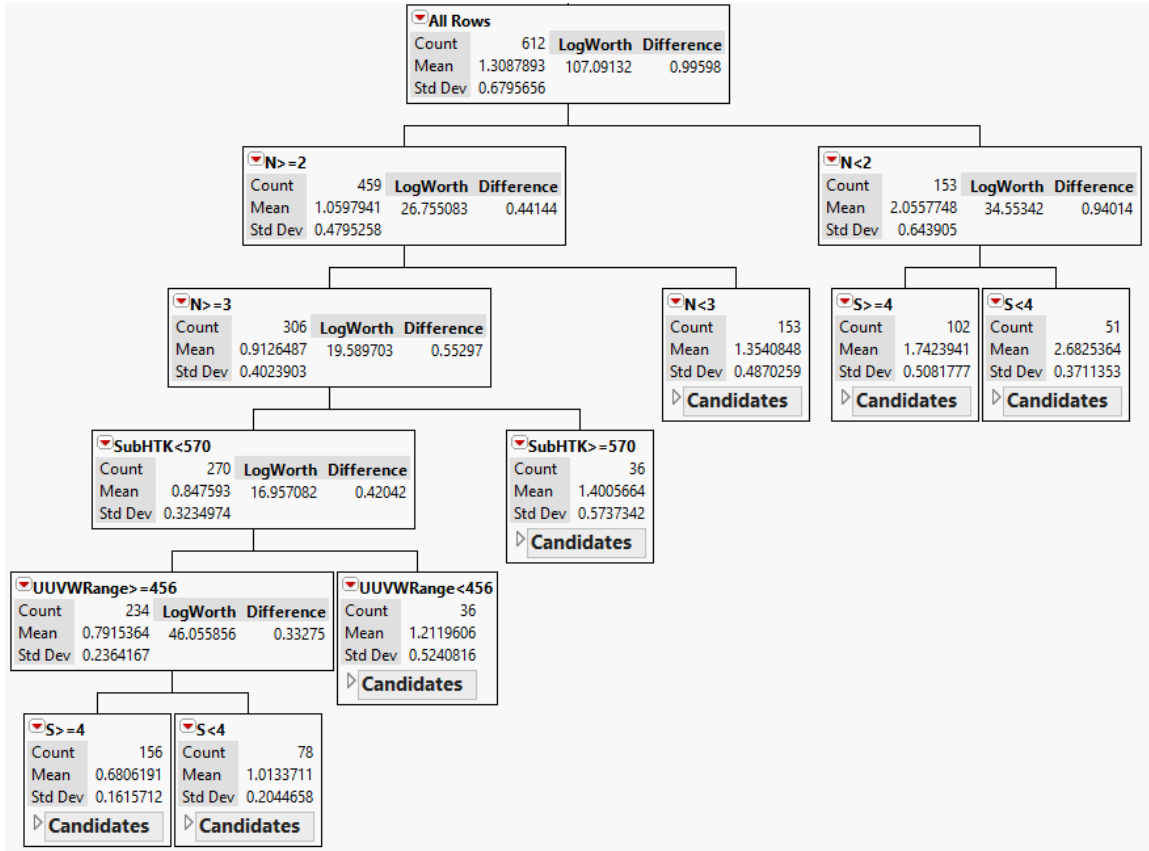


Figure 26.    UUV data age MOE regression tree.

The regression tree for the UUV data age shows more interesting results. As expected, the first two splits occur based on the number of data nodes, but the next split is based on the UUV speed. Upon review of several models using a UUV speed of four knots, the split is partly due to a mismatch in UUV and submarine speed while the UUV is traveling away from the submarine (UUV is heading back to the garage). In some cases, the submarine detects the UUV, slows down and the UUV continues at four knots until another UUV traveling the opposite direction detects the submarine. This factor is mitigated in the five knot UUV models due to the larger area covered by the faster-traveling UUVs. Higher submarine hits-to-kill means it simply takes longer for the data

transfer to take place, and the higher UUV weapon range means the UUV engages the submarine earlier.

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# VI. CONCLUSION

The main purpose of the study is to explore the feasibility of using UUVs and the blue-green laser to find if they can be used to replace submarine trips to periscope depth. The relationship between different submarine and UUV operating characteristics and patterns was also investigated.

There is a strong relationship between the number of UUVs operating and the time it takes for the submarine to get service as well as between the number of data nodes and the age of the data provided. Sensor detection ranges for both the UUVs and the submarine dictate when the UUV should speed up and the submarine should slow down.

Stepwise linear regression and partition trees are used to study the mean time it takes for the submarine to interface with a UUV once it enters the operating area and the age of the data carried by the UUV.

## A. FINDINGS

To summarize, this research concludes that:

- Agent-based models are a powerful tool for modeling a variety of scenarios in a relatively short time period.

- Data farming using NOLHs enables the efficient investigation of models that have multiple factors.

- UUVs equipped with the blue-green laser are a feasible option to replace or aid submarine periscope depth communications, as modeled.

- UUVs' internal navigation needs to be sufficient to pass within 500 meters of a data node to ensure that communication will take place.

- Ranges at which a UUV and a submarine detect one another are very important. Due to the disparity in detection ranges, once the submarine has detected the UUV, it should wait until it has closed distance to slow down and the UUV should speed up immediately to minimize the submarine wait time.

- Combination of four UUVs traveling at five knots and four data nodes resulted in a mean submarine wait time of about 54 minutes and a mean UUV data age of 38 minutes.

- Addition of one UUV to a system reduces the submarine wait time by 23 minutes, on average.

- Addition of one data node to a system reduces the UUV data age by 24 minutes, on average.

## B. FUTURE RESEARCH

This thesis suggests many topics for follow-up studies. The infancy of both UUV and blue-green laser technologies means that there are many applications that have not yet been considered. The following is a list of possible future topics:

- Use a different type of modeling software to analyze the same problem.

- Expand the number of data nodes or use nodes arranged in different patterns to cover a wider area.

- Increase the number of UUVs and have them operate in different patterns.

- Use UUVs instead to search out submarines and pass them one time data transfers while they are in a communication denied environment.

- Use explosive equipped UUVs to hunt enemy submarines.

- Apply a similar UUV and submarine interface model to acoustic communications rather than the blue-green laser interface.

- Conduct a classified study using exact current values for UUV and blue-green laser ranges and data transfer rates.

# APPENDIX A. STATISTICAL RESULTS OF THE SUBMARINE WAIT TIME MOE

Presented here are the summary statistics and sorted parameter estimates for the submarine wait time measure of effectiveness exploring all two-way interactions:

## Actual by Predicted Plot



Mean(SubTime) Predicted P<.0001 RSq=0.93
RMSE=0.1129

## Summary of Fit

| | |
|---|---|
| RSquare | 0.929019 |
| RSquare Adj | 0.927233 |
| Root Mean Square Error | 0.112892 |
| Mean of Response | 1.243325 |
| Observations (or Sum Wgts) | 612 |

## Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|
| Model | 15 | 99.41699 | 6.62780 | 520.0432 |
| Error | 596 | 7.59585 | 0.01274 | Prob > F |
| C. Total | 611 | 107.01283 | | <.0001* |
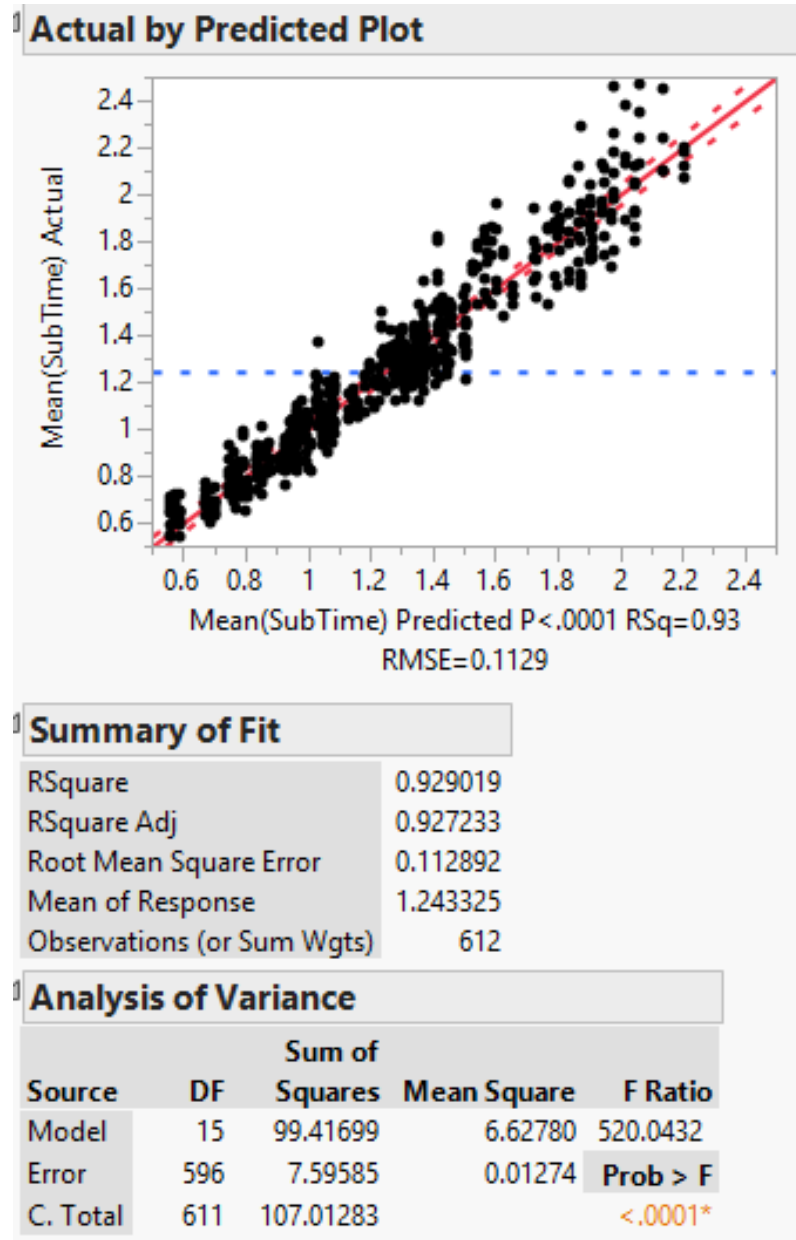
## Sorted Parameter Estimates

| Term | Estimate | Std Error | t Ratio | | Prob>|t| |
|------|---------:|----------:|--------:|---|---------:|
| U | -0.391225 | 0.005589 | -70.00 | | <.0001* |
| SubSRange | 6.4018e-5 | 1.656e-6 | 38.65 | | <.0001* |
| UUVSRange | -7.731e-5 | 3.312e-6 | -23.34 | | <.0001* |
| (U-3)*(U-3) | 0.1480816 | 0.00968 | 15.30 | | <.0001* |
| SubHTK | 0.0004114 | 0.000031 | 13.25 | | <.0001* |
| UUVWRange | -0.00008 | 7.845e-6 | -10.21 | | <.0001* |
| HitRate | -2.066e-5 | 2.487e-6 | -8.31 | | <.0001* |
| S | 0.0417324 | 0.005589 | 7.47 | | <.0001* |
| (SubSRange-5500.24)*(SubSRange-5500.24) | -5.32e-9 | 8.07e-10 | -6.59 | | <.0001* |
| (HitRate-7011.76)*(SubHTK-360) | -1.456e-7 | 2.732e-8 | -5.33 | | <.0001* |
| (U-3)*(SubSRange-5500.24) | -1.071e-5 | 2.028e-6 | -5.28 | | <.0001* |
| (U-3)*(S-4) | -0.027261 | 0.006845 | -3.98 | | <.0001* |
| (U-3)*(UUVWRange-1050.12) | 3.7342e-5 | 9.608e-6 | 3.89 | | 0.0001* |
| (UUVSRange-2750.12)*(SubHTK-360) | 5.6516e-8 | 1.99e-8 | 2.84 | | 0.0047* |
| (UUVWRange-1050.12)*(HitRate-7011.76) | 7.185e-9 | 6.236e-9 | 1.15 | | 0.2497 |

# APPENDIX B. STATISTICAL RESULTS OF THE UUV DATA AGE MOE

Presented here are the summary statistics and sorted parameter estimates for the UUV data age measure of effectiveness exploring all two-way interactions:
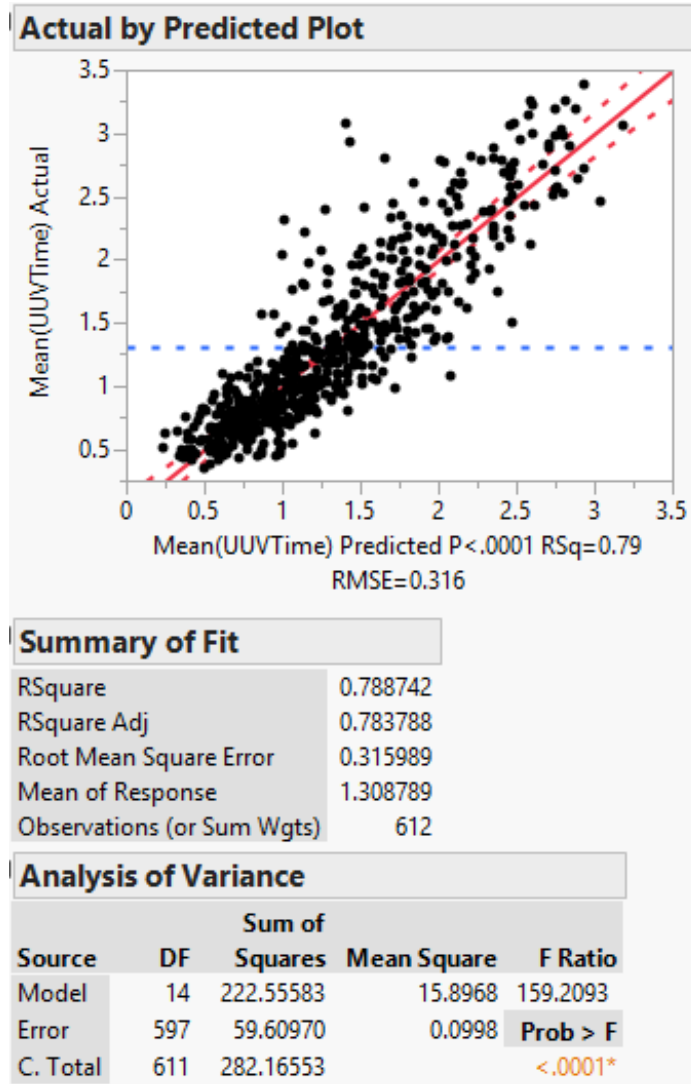
**Actual by Predicted Plot**



Mean(UUVTime) Predicted P<.0001 RSq=0.79
RMSE=0.316

**Summary of Fit**

| | |
|---|---|
| RSquare | 0.788742 |
| RSquare Adj | 0.783788 |
| Root Mean Square Error | 0.315989 |
| Mean of Response | 1.308789 |
| Observations (or Sum Wgts) | 612 |

**Analysis of Variance**

| Source | DF | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|
| Model | 14 | 222.55583 | 15.8968 | 159.2093 |
| Error | 597 | 59.60970 | 0.0998 | Prob > F |
| C. Total | 611 | 282.16553 | | <.0001* |

**Sorted Parameter Estimates**

| Term | Estimate | Std Error | t Ratio | | Prob>\|t\| |
|------|----------|-----------|---------|---|---------|
| N | -0.404356 | 0.011425 | -35.39 | | <.0001* |
| S | -0.294991 | 0.015644 | -18.86 | | <.0001* |
| (S-4)*(N-2.5) | 0.1594694 | 0.013992 | 11.40 | | <.0001* |
| (N-2.5)*(N-2.5) | 0.1322367 | 0.012773 | 10.35 | | <.0001* |
| (HitRate-7011.76)*(SubHTK-360) | -5.117e-7 | 5.712e-8 | -8.96 | | <.0001* |
| UUVWRange | -0.00018 | 0.000022 | -8.20 | | <.0001* |
| SubHTK | 0.0006884 | 0.000087 | 7.92 | | <.0001* |
| (U-3)*(UUVSRange-2750.12) | 6.9744e-5 | 1.135e-5 | 6.14 | | <.0001* |
| (U-3)*(S-4) | -0.113511 | 0.01916 | -5.92 | | <.0001* |
| HitRate | -0.000041 | 6.961e-6 | -5.89 | | <.0001* |
| (S-4)*(UUVWRange-1050.12) | -0.000147 | 2.689e-5 | -5.47 | | <.0001* |
| (U-3)*(SubHTK-360) | -0.000574 | 0.000106 | -5.39 | | <.0001* |
| UUVSRange | -0.000018 | 9.27e-6 | -1.95 | | 0.0519 |
| U | 0.0186118 | 0.015644 | 1.19 | | 0.2346 |

# APPENDIX C. SUMMARY STATISTICS FOR MODEL 454

Summary statistics are included for the most complicated scenario, which used four UUVs traveling at five knots and four data nodes. This analysis is conducted on the 40 run design point from the NOLH design output.



| SubTime Summary Statistics | |
|---|---|
| Mean | 0.8952588 |
| Std Dev | 0.3708146 |
| Std Err Mean | 0.0142201 |
| Upper 95% Mean | 0.9231795 |
| Lower 95% Mean | 0.8673382 |
| N | 680 |

| UUVTime Summary Statistics | |
|---|---|
| Mean | 0.6304429 |
| Std Dev | 0.3258425 |
| Std Err Mean | 0.0124955 |
| Upper 95% Mean | 0.6549774 |
| Lower 95% Mean | 0.6059085 |
| N | 680 |
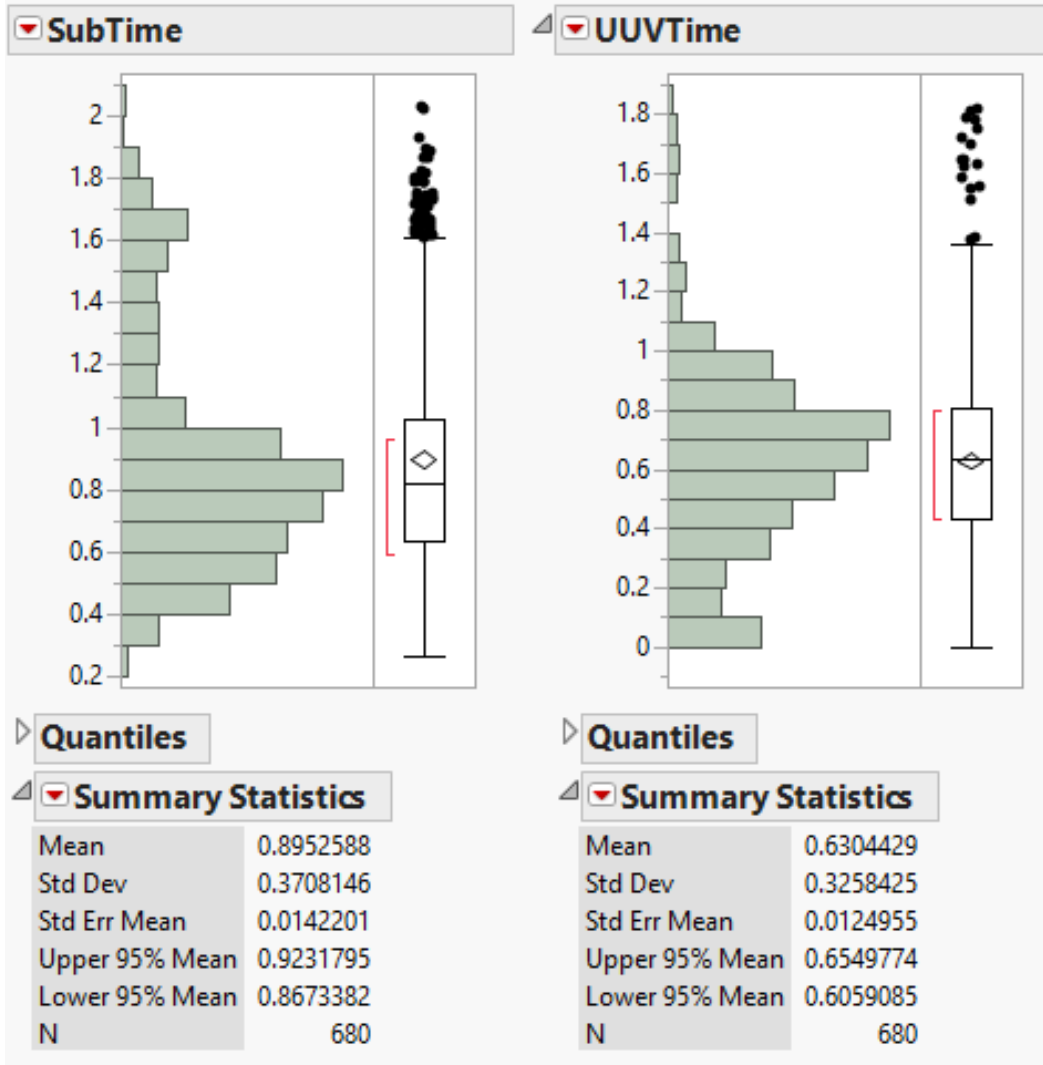
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