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Countering piracy with the next generation piracy performance surface model

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MONTEREY, CALIFORNIA

THESIS

COUNTERING PIRACY WITH THE NEXT-GENERATION PIRACY PERFORMANCE SURFACE MODEL

by

Leslie A. Slootmaker

March 2011

Thesis Co-Advisors:	Eva Regnier
	James A. Hansen
Second Reader:	Thomas W. Lucas

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13. ABSTRACT (maximum 200 words)

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This research includes interviews with counter-piracy forces that led to recommended changes in the PPSN model. In addition, using robust and realistic experimental designs, this research identifies the significant intelligence factors of the PPSN model. This gathered information is being used to refine these input variables to achieve maximum performance of the PPSN model. This research also unveiled input variables that are influential in the computing memory requirements and program runtime. This information is being used to focus efforts on setting these variables to realistic levels without sacrificing the model's efficiency and effectiveness. Finally, the results of this thesis allow for quick turnaround of updates to the PPSN model in response to gathered intelligence.

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COUNTERING PIRACY WITH THE NEXT GENERATION PIRACY PERFORMANCE SURFACE MODEL

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Submitted in partial fulfillment of the
requirements for the degree of

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from the

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ABSTRACT

In 2009, the Naval Oceanographic Office was tasked with developing a product that uses forecasted meteorological conditions and historical pirate incidents to predict locations conducive to pirate activity in the Somali Basin Region and the Gulf of Aden. This resulted in the development of the Piracy Performance Surface (PPS) model, whose outputs are briefed daily to the Commander of the United States Naval Forces Central Command and Combined Maritime Forces in Bahrain. The Next-generation PPS (PPSN) model uses simulation to provide as output, a forecast of relative pirate presence probability over time. Effective March 1, 2011, the name of PPSN has been changed to the Pirate Attack Risk Surface (PARS) model.

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LIST OF ACRONYMS AND ABBREVIATIONS

AFRICOM	Africa Command, United States Combatant Command
AFRL DSRC	Air Force Research Laboratory DoD Supercomputing Resource Center
APS	African Partnership Station
BMP3	Best Management Practices 3
CENTCOM	Central Command, United States Combatant Command
CMF	Combined Maritime Forces
CNMOC	Commander, Naval Meteorology and Oceanography Command
COA	Courses of Action
COAMPS	Coupled Ocean / Atmosphere Mesoscale Prediction System model
COCOM	Combatant Command
CONOPS	Concept of Operations
CTF	Combined Task Force
DoD	Department of Defense
DOE	Design of Experiments
EEZ	Economic Exclusive Zone
EU	European Union
FOAM-NEMO	Forecasting Ocean Assimilation Model-Nucleus of European Modeling of the Ocean
GB	Gigabytes
GMT	Greenwich Mean Time
GOA	Gulf of Aden
GPS	Global Positioning System
HOA	Horn of Africa
HPCMP	High Performance Computing Modernization Program

IMB	International Maritime Bureau
INTEL	Intelligence
METOC	Meteorology and Oceanography
MSO	Maritime Security Operations
NOLH	Nearly Orthogonal Latin Hypercube
NATO	North Atlantic Treaty Organization
NAVCENT	Naval Forces Central Command
NAVO	Naval Oceanographic Office
NCOM	Navy Coastal Ocean Model
NGA	National Geospatial-Intelligence Agency
NMS	National Military Strategy
NSS	National Security Strategy
NRL	Naval Research Laboratory
ONI	Office of Naval Intelligence
OOS	Operation Ocean Shield
PAG	Pirate Action Group
PARS	Pirate Attack Risk Surface
PAWW	Piracy Analysis and Warning Weekly
POTUS	President of the United States of America
PPS	Piracy Performance Surface Model
PPSN	Next generation Piracy Performance Surface Model
RPG	Rocket Propelled Grenades
SBR	Somali Basin Region
SEED	Simulation Experiments & Efficient Designs
SME	Subject Matter Expert
SWAN	Shallow Water Near Shore model
TTCP MAR	Technical Cooperation Program Maritime Group

UKGM	United Kingdom Global Model
UNCLOS	United Nations Convention on the Law of the Sea
USMC	United States Marine Corps
USN	United States Navy

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EXECUTIVE SUMMARY

The instability and lack of government in Somalia have caused a rapid increase in pirate activity within the Somali Basin Region (SBR) and the Gulf of Aden (GOA). Due to this increase, maritime security and stability in these regions are severely threatened. Somali pirate attacks have taken the lives of innocent people, held sea-going persons hostage, and cost the world's economy billions of dollars annually (Bowden, Hurlburt, Aloyo, Marts, & Lee, 2010, pp. 12). For this reason, President Barack Obama initiated an executive order on April 12, 2010 to deal with the threat of piracy (Executive Order No. 13,536, 2010). President Obama stated that the collapse of security and the continuation of violence in the Somali region in the form of piracy and armed robbery on the high seas are a threat to the United States' (U.S.) national security and foreign policy of the United States and must be dealt with accordingly.

U.S. Naval Forces Central Command (NAVCENT) Commander Vice Admiral Mark Fox and U.S. Sixth Fleet Commander Vice Admiral Harry Harris, Jr. have been tasked with finding a solution to deter, control, and ultimately eliminate pirating within the GOA and SBR within the U.S. Fifth and Sixth Fleets' operating waters by returning safety, stability, and peace to these regions. Bahrain, being strategically located within the Middle East, has been established as the U.S. Fifth Fleet and Combined Maritime Forces (CMF) Headquarters for the Combined Maritime Forces, the North Atlantic Treaty Organization (NATO), and the European Union (EU); meanwhile, the U.S. Sixth Fleet headquarters resides in Naples, Italy.

To combat the on-going concerns with piracy, Naval Oceanographic Office (NAVO) researchers were tasked by Rear Admiral Titley, Oceanographer and Navigator of the Navy, to assist in the fight against piracy. This tasking occurred just days after the *MV Maersk Alabama*, a U. S.-flagged ship, was hijacked by Somali pirates in the Indian Ocean on April 18, 2009. The Piracy Performance Surface (PPS) model was completed approximately two weeks after this incident, and has undergone a few revisions since its development. The success of the PPS model led to the Naval Meteorology and Oceanography Command leadership to devote efforts to pursue a more advanced anti-piracy model, the Next-generation PPS (PPSN). On March 1, 2011, the PPSN model's name changed to the Pirate Attack Risk Surface (PARS). Dr. James Hansen of the Naval Research Laboratory (NRL) in Monterey, California, was tasked with developing this next generation probabilistic forecasting tool.

The PPSN model is a Monte Carlo probabilistic forecasting tool that takes as input environmental conditions, pirate concept of operations, and gathered intelligence to produce as output the forecast of pirate presence probability as a function of latitude, longitude, and time. The model simulates pirate action groups (PAGs), where a PAG is a group of pirate dhows that are attached to a mother dhow (a larger vessel) that is typically used as a logistical hub for extending distances from land and mission duration. The PPSN outputs a forecast of relative pirate presence probability over a 72-hour forecast time period in 0.2-hour time steps with a probability surface generated at 12-hour time steps (See Figure 1). As of the date of this thesis, the PPSN model is the only known Navy product that couples METOC and INTEL.

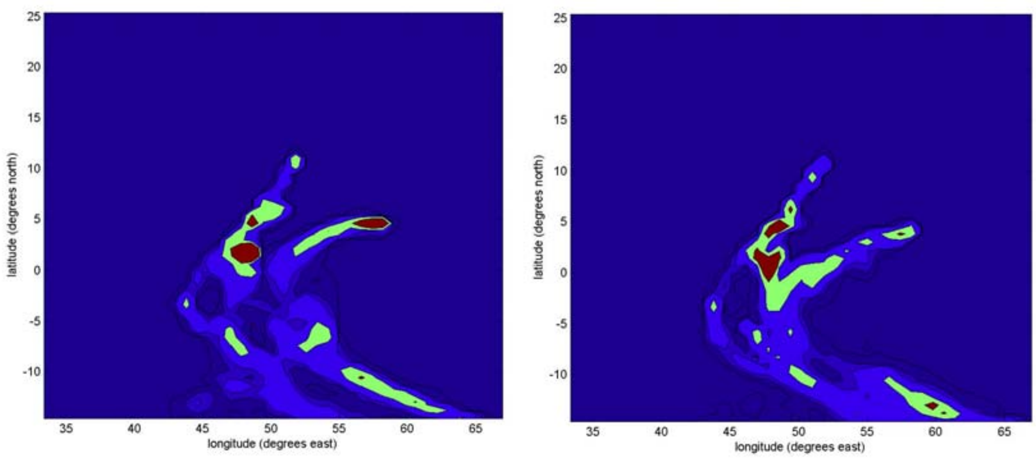

Figure 1. The PPSN model output displaying the forecast of relative pirate presence probability with the 24-hour forecast (left) and the 72-hour forecast (right). Red corresponds to the highest probability forecast of pirate location.

This thesis research includes visits and interviews with users of PPS and other counter-piracy forces to understand the operators' needs and to gain intelligence on the most current pirate CONOPS within the SBR and GOA. This gathered intelligence led to recommended changes in the PPSN code to include the addition of PAG search patterns, the implementation of PAG operating boxes and their mapping, and the understanding of pirate terminology used by military forces combating piracy.

Key findings this research addresses are: (1) which input parameters can be adjusted to decrease run time and computing memory requirements, (2) which input parameters interact most strongly with METOC, (3) which input parameters are the most influential to the PPSN output, and (4) what improvements can be made to enhance the PPSN model.

Three key input parameters that impact the computer memory requirement, which are also highly correlated with runtime, are the PAG's mission length, the number of PAG replications in the simulation, and the number of PAGs. The analysis by the author concludes that the values inputted for each of these variables, in particular, the PAG's mission length, should be considered with the utmost care as their associated values greatly impact the forecast of relative pirate presence probability.

The search pattern the PAGs use when attempting to locate a target vessel of opportunity is the most significant factor in the PPSN model. Operators and military members combating piracy should attempt to acquire intelligence on the specific search pattern that PAGs use in the SBR and GOA.

The probability that PAGs have meteorology and oceanography information prior to leaving their base location is highly influential and interacts with the most important variable, the PAG's search pattern.

In addition, using systematic and robust experimental designs, this research made PPSN more robust and realistic by breaking the code in different ways, resulting in modifications by the developer to make PPSN better and more robust.

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ACKNOWLEDGMENTS

First and foremost, I want to give praise to the Lord for being my light and my salvation.

> The LORD is my shepherd; I shall not want. He makes me to lie down in green pastures. He leads me beside still waters. He restores my soul. He leads me in the paths of righteousness for his name's sake. Even though I walk through the valley of the shadow of death, I will fear no evil, for you are with me; your rod and your staff they comfort me. You prepare a table before me in the presence of my enemies; you anoint my head with oil; my cup overflows. Surely goodness and mercy shall follow me all the days of my life, and I shall dwell in the house of the Lord forever (*English Standard Version*, Psalm 23:1-6).

The Lord has also been graceful in uniting my husband, Matt, and my life together. Without Matt's loving support, my time spent at NPS would not have been fruitful. He has been my rock for the past 27 months. He believed in me when I did not believe in myself and he encouraged me when I became discouraged. He opened my eyes to a world filled with color and for this I am grateful.

I am ever indebted to my advisor, Dr. Eva Regnier, for her continued support and guidance throughout all the trials and tribulations of my thesis. I pray that any future work in this area of study is fruitful and rewarding as she deserves much recognition. For the developer of the PPSN model, Dr. Jim Hansen, I would like to thank him for the wonderful thesis topic and believing in me when I came back from my OR Experience Tour.

I would like to thank the SEED Center staff, specifically, Dr. Tom Lucas, Steve Upton, and Dr. Gary Horne. The insurmountable OR knowledge of Dr. Tom Lucas in design of experiments and simulation analysis proved to be a pillar of knowledge and insight into my thesis. Steve Upton's dedication and perseverance helped me make PPSN data farmable. His patience and positive attitude was a true delight. Lastly, Dr. Gary Horne afforded me the opportunity to present my research in Paris, France, to the NATO Modeling and Simulation Group, which led to a beneficial OR Experience Tour.

I want to thank Dr. Paul Sanchez, Dr. Dashi Singham, and LT Stacey Hall for their pirate analytical enthusiasm during IDFW 20 in Monterey, California. Also, I want to thank Dr. Paul Sanchez, CDR Eric Lednicky, and 1TEN Sofia Miranda for their hard work and dedication during IDFW 21 in Lisbon, Portugal.

I would finally like to thank the NPS OR Professors for their devotion and commitment to teaching me, the military officer, and the world of academia.

My closing thought...*The Man in the Arena* by President Theodore Roosevelt.

I. INTRODUCTION

A. BACKGROUND AND MOTIVATION

The instability and lack of government in Somalia have caused a rapid increase in pirate activity within the Somali Basin Region (SBR) and the Gulf of Aden (GOA). The SBR is the region that lies directly between Somalia and India in the Indian Ocean. The GOA is the body of water located between the Horn of Africa (HOA) and Yemen. Piracy in these regions has not only threatened the stability and safety of ocean-going vessels and their crew members, but has also cost the world's economy over billions of dollars (Bowden, Hurlburt, Aloyo, Marts, & Lee, 2010, pp. 12).[1] For this reason, President Barack Obama initiated Executive Order 13536 on April 12, 2010 to deal with the threat of piracy. President Obama stated that the collapse of security and the continuation of violence in the Somali region in the form of piracy and armed robbery on the high seas is a threat to the United States' national security and foreign policy of the United States and must be dealt with accordingly.

Two U.S. Combatant Commands (COCOMs) are tasked with solving the Somalia piracy problem, U.S. Africa Command (AFRICOM) under General Carter Ham (From http://www.africom.mil), U.S. Army, and Central Command under General James Mattis (From http://www.centcom.mil), U.S. Marine Corps (USMC). Both face an extremely complex situation with combating piracy that originates in the four distinct and independent political regions that make up Somalia (Figure 2), and finishes with hijacking vessels at sea. AFRICOM is currently conducting the African Partnership Station (APS) 2011 with 22 African-partnered nations (LT S. Hall, personal communication, January 31, 2011).[2] CENTCOM is responsible for the waters surrounding the SBR and GOA, and is conducting Maritime Security Operations (MSO)

[1] The costs associated with piracy include ransom costs, insurance increases, re-directing commercial ships, additional security, the use of military vessels, legal jurisdiction for captured pirates, and organizations that help combat piracy.

[2] The author was forwarded this information through LT Stacey Hall. AFRICOM sent LT B. Le to present the African Partnership Station (APS) 2011 on behalf of AFRICOM (Africa Combatant Command) on February 2, 2011.

with Combined Task Force (CTF) 150 and CTF 151. As the reader can see, complexity exists in the Somali region and special attention must be exhibited by the Commanders of the two COCOMs with a partnership for countering piracy operations on land and at sea. An additional layer of complexity exists with a separate U.S. fleet reporting to each COCOM and both fleets sharing the responsibility for the safety and stability of the waters surrounding Africa.

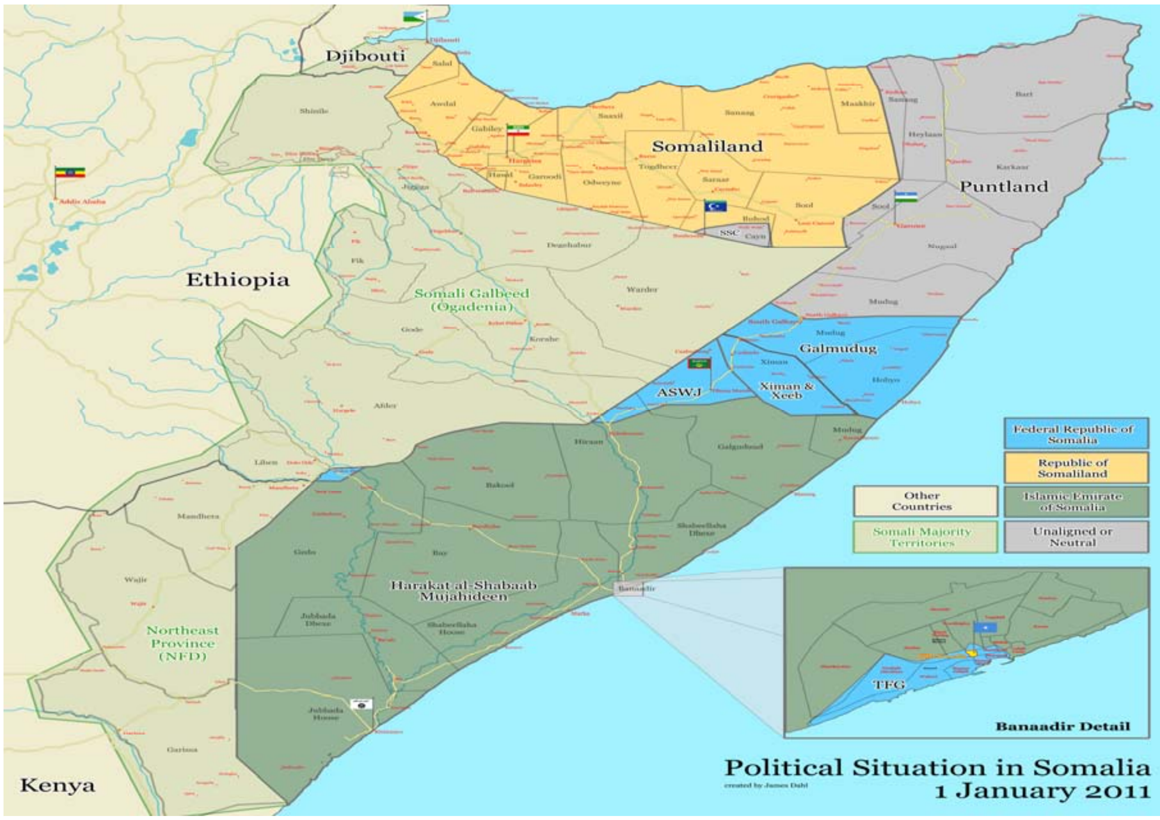

Figure 2. Map of the four political regions of Somalia used by the Combined Maritime Forces assessment team. Region one is defined as Somaliland; region two is defined as Puntland; region three is defined as Galmudug; and region four is Harakat al-Shabaab Mujahideen (From Wikipedia, 2011).

U.S. Naval Forces Central Command (NAVCENT); Commander, U.S. Fifth Fleet and Commander, Combined Maritime Forces (CMF), Vice Admiral Mark Fox;[3] and

[3] For detailed information on Admiral Fox and the U.S. Fifth Fleet's mission statement and recent operations visit http://www.cusnc.navy.mil.

Commander, U.S. Sixth Fleet, Vice Admiral Harry Harris, Jr.,[4] have been tasked with finding a solution to deter, control, and ultimately eliminate pirating within the GOA and SBR within the U.S. Fifth and Sixth Fleets' operating waters by returning safety, stability, and peace to approximately two million square miles of ocean water surrounding Somalia.[5] Bahrain, being strategically located within the Middle East, has been established as the U.S. Fifth Fleet and Combined Maritime Forces (CMF) headquarters for the Big Three: Combined Maritime Forces (comprised of 25 nations), the North Atlantic Treaty Organization (NATO), and the European Union (EU); meanwhile, the U.S. Sixth Fleet headquarters resides in Naples, Italy. LCDR K. Lutz[6] (personal communication, June 8, 2010) stated that other nations, such as China and India, are also working to defeat these opportunistic ocean-driven thieves, but these two nations conduct missions not in affiliation with the U.S., NATO, or the EU.

In the 2010 National Security Strategy (NSS), President Obama stated that with the continued threat of unstable nations the U.S. military will constantly be called to provide military security and stability as part of globalization (President of the United States, 2010, pp. 12). Follow-on to the NSS is the 2011 National Military Strategy (NMS) guidance. In this paper, Admiral Mike Mullen, Chairman to the Joint Chiefs of Staff, stated that the Joint Forces will continue to address and combat the violent extremists that have sought a safe haven in the SBR and GOA regions as these extremists (pirates) remain a transnational security threat (CJCS, 2011). Senior military leaders are in a difficult position and General Mattis is a prime example. As CENTCOM Commander, General Mattis must divide his military assets (air, land, and sea) between the instability in the Middle East and the "rash of piracy" in the GOA and SBR (LCDR K. Lutz, personal communication, June 7, 2010). How to properly allocate military forces in order to sustain and ultimately eliminate piracy is a question that leading U.S.

[4] For detailed information on Admiral Harris and U.S. Sixth Fleet's mission statement and recent operations visit http://www.naveur-navaf.navy.mil.

[5] For detailed information on Central Command (CENTCOM) visit http://www.centcom.mil.

[6] LCDR K. Lutz, UK, held the intelligence officer (INTEL officer) position for the CMF assessment team in Bahrain during the author's operations research experience tour.

military and civilian officials are looking to answer. This thesis seeks to support the mission by improving the tools available to decision makers to allocate forces, specifically forces combating piracy.

The first operational piracy prediction model, Piracy Performance Surface (PPS), was developed in 2009 by the Naval Oceanographic Office (NAVO) at Stennis Space Center. The successes of PPS led to follow-on research for the development of a pirate probabilistic tool, the Next-generation PPS model (PPSN).[7] This tool produces as output a forecast of relative pirate presence probability as a function of latitude and longitude over time. This thesis was conducted parallel to the development of the PPSN by the Naval Research Laboratory (NRL) Monterey and NAVO and explores the operational usefulness, product stability, and output consistency of PPSN. In addition, this research includes visits and interviews with users of the PPS model and other counter-piracy forces to understand their needs and pirate tactics, which led to recommended changes in PPSN.

B. RESEARCH QUESTIONS

This thesis addresses the following questions:

1. What improvements can be made to the operational version of the PPSN model that will enhance the product's output?

2. Which PPSN input parameters can be adjusted to decrease computing memory requirements and run time?

3. Which PPSN input parameters interact most strongly with Meteorology and Oceanography (METOC) conditions?

4. Which PPSN input parameters are the most influential in determining the distribution of relative risk of pirate presence in the PPSN?

[7] For continuity in this thesis, the name of the next-generation Piracy Performance Surface model (PPSN) will be used. Effective March 1, 2011 the name of the PPSN model was changed to the Pirate Attack Risk Surface model, PARS.

C. BENEFITS OF THE STUDY

Using carefully designed simulation experiments, this research identifies the most important factors driving the PPSN output. This information can be used for refining intelligence inputs and the PPSN model development efforts to implement the most influential functionality. These results can also be used to optimize parameter selection to allow quick turnaround of updates to the product in response to INTEL, within computational constraints, and without sacrificing product quality. In addition, the information gathered in this thesis will be used to assist the military INTEL community (primarily in affiliation with the Big Three in Bahrain) with PPSN.

D. THESIS ORGANIZATION

Chapter II provides the reader with a literature brief that describes the basis for this thesis research. Chapter III describes the evolution of the efforts of the U.S. in the development of piracy models, and in particular the development of PPSN. Chapter IV defines the choice of independent variables for simulation modeling and the output metrics used to evaluate the forecast of relative pirate presence probability. Chapter V discusses each simulation experimental design. Chapter VI examines the results of the experiments, including multivariate correlation, stepwise regression, sensitivity analysis, and classification and regression trees. Chapter VII draws conclusions and makes follow-on recommendations.

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II. LITERATURE REVIEW

In this chapter, piracy will be defined and the following topics covered: costs and challenges created by piracy, current piracy concept of operations, other nations' potential piracy tools, and the development of experimental designs.

A. DEFINITIONS OF PIRACY

Piracy has plagued the world for thousands of years. However, the U.S. government did not clearly define piracy for many years. In fact, the U.S. Congress did not take an aggressive role in defining piracy for the U.S. judicial system until December 2010 (Mason, 2010). When it finally did, the definition took its origins from the 1982 United Nations Convention on the Law of the Sea (UNCLOS) Article 101 that defines piracy as:

> (a) Any illegal acts of violence or detention, or any act of depredation, committed for private ends by the crew or passengers of a private ship or a private aircraft and directed:
>
> > (i) On the high seas, against another ship or aircraft, or against persons or property on board such ship or aircraft;
> >
> > (ii) Against a ship, aircraft, persons or property in a place outside the jurisdiction of any State;
>
> (b) Any act of voluntary participation in the operation of a ship or of an aircraft with knowledge of facts making it a pirate ship or aircraft;
>
> (c) Any act of inciting or of intentionally facilitating an act described in subparagraph (a) or (b).

Other variations of the definition of piracy include the following: "an act of violence, or the threat of violence, against a ship in international waters (outside a state's geographic sovereignty) with the intent to commit crimes such as theft, hijacking, murder, and kidnapping" (Kline, 2010, pp. 69); and "an act of boarding or attempting to board any ship with the apparent intent to commit theft or any other crime and with the apparent intent or capability to use force in furtherance of that act" (Chalk, 2008, pp. 3).

Many variations of the definition of piracy exist, but the key to combating piracy begins by identifying the root cause of this multi-national threat (Mason, 2010). Two questions have come into the political arena (Goodman, 2009):

(a) Did piracy develop because of illegal fishing in the economic exclusion zone (EEZ) of the SBR?

Or

(b) Did piracy develop from an unstable Somali government?

The former CMF legal officer, CDR David Teasdale, United Kingdom (UK), stated that the UNCLOS has clearly defined piracy, but the real debate surrounding piracy is a “policy debate rather than a legal one" (personal communication, July 10, 2010). The policy debate exists between the U.S., NATO, and the European Union. The UK Ambassador at the Security Council Debate on Somalia Piracy stated, "The United Kingdom believes that the best prospect of sustainable results will come from further enhancing the international community’s efforts to build the capacity of regional states to prosecute and imprison those responsible for acts of piracy" (Grant, 2010, para. 7). Grant (2010) later stated that he believes the root cause of piracy is a direct result of the instability of the Somali government.

B. COSTS AND CHALLENGES CREATED BY PIRACY

Chalk (2008) stated that the International Maritime Bureau (IMB) "estimates that piracy costs the shipping industry anywhere from $1 billion to $16 billion a year” (pp. 16). Paying the ransom money is more cost-effective than implementing protective measurers onboard, but this method is a quick fix to the ultimate problem. A Cooperative Strategy for the 21st Century Seapower recognizes the need for international partnership (Roughead, Conway, & Allen, 2007). “This strategy stresses an approach that integrates seapower with other elements of national power, as well as those of our friends and allies” (Roughead et al., 2007, para. 1). The commercial shipping community as well must continue to practice maritime awareness as modern day pirates are better trained and equipped with semi-automatic machine guns, varieties of rocket propelled grenades, and small arms (Best Management Practices [BMP3], 2010).

C. CURRENT PIRACY CONCEPT OF OPERATIONS

Pirate concept of operations (CONOPS), also known as pirate tactics, has been changing and evolving as the number of successful paid ransoms has increased. In April 2010, Rear Admiral Peter Hudson, British EU Admiral, addressed a new pirate CONOPS swarming tactic that allowed pirate action groups to supersaturate the area once a target of opportunity had been identified (Childs, 2010). Pirates have also extended their operating area to 1,000 nautical miles from the shoreline because commercial vessels are no longer hugging the Kenya and Somali coastline (Figure 3). Admiral Hudson was also quoted in saying (Childs, 2010):

> Five years ago, the maximum range of attacks was 287 km (165 nautical miles). Recently a ship was hijacked 2,037 km (1,100 nautical miles) from the Somali coast - and only 926 km (500 miles) from the coast of India.

Weather conditions also play a significant role in impacting pirate CONOPS. Historical METOC and INTEL reports have shown that pirate activity decreases in the SBR during the biannual monsoon season.[8] This decrease is due to the heightened wind and wave conditions that make the sea states unfavorable for pirating in the SBR. In 2011, though, new pirate CONOPS have enabled the pirate action groups (PAGs) to operate in these adverse weather conditions. Admiral Fox stated (Fellman, 2011):

> The monsoon season once kept pirate skiffs ashore, but mother ships allow for year-round piracy. About eight of these "pirate action groups" are spread throughout the region, he said.

[8] See the Piracy Analysis and Warning Weekly (PAWW) Report (2010) for an example of this report.

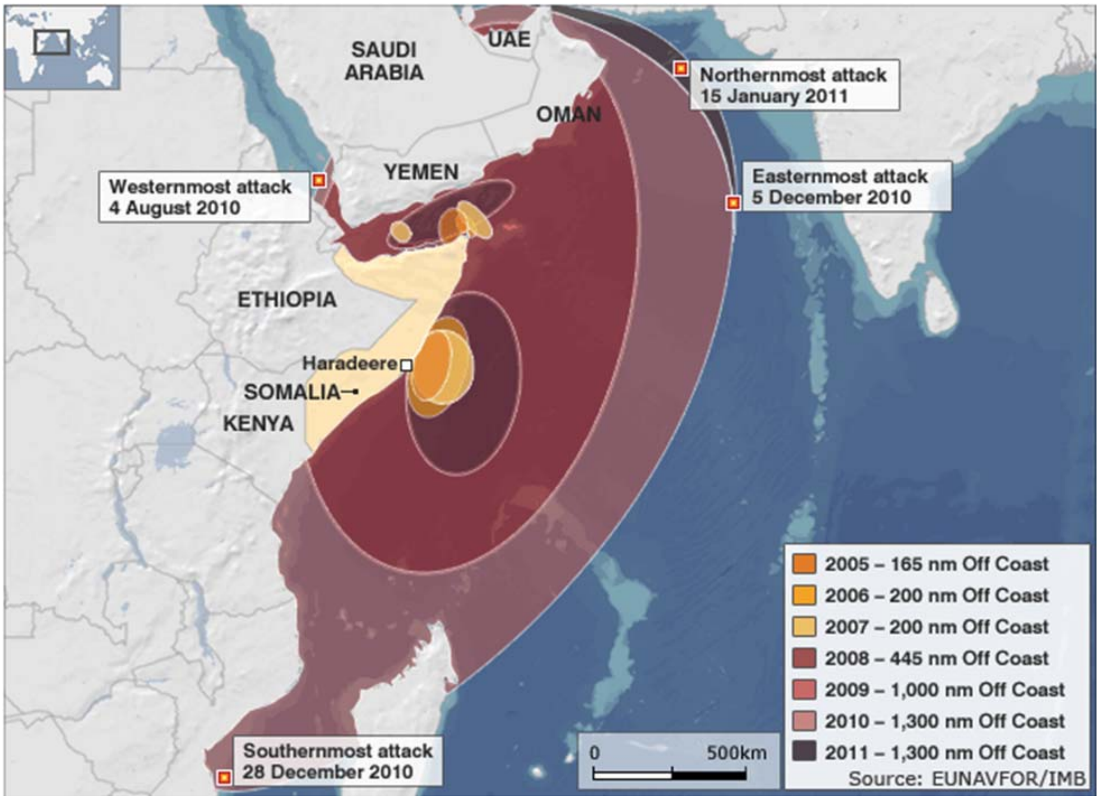

Figure 3. This picture shows the extension of piracy missions from 2005 through 2011. In 2005, pirates were seen operating 165 nautical miles in the SBR and GOA, but in 2011, pirates are operating 1,300 nautical miles from the coastline in these areas (Somalia's states, regions, and districts) (From Childs, 2010).

PAG is the terminology used by the Big Three to refer to a mother dhow and its adjoining pirate dhows. Typically, a mother dhow is a larger vessel, possibly a Boston whaler, used as the logistical hub to extend the longevity in time and distance of the piracy mission. Pirate dhows are often attached to the mother dhow with the boarding ladder, which is an aluminum ladder (Figure 4) (Agence France Presse [AFP], 2009). When pirates have located a vessel of opportunity, the pirates will use marine equipment such as grappling hooks to board the vessel. Pirates onboard can be equipped with satellite phones, global positioning system (GPS), rocket-propelled grenade launchers with warheads (RPGs), and AK-47s (Houreld, 2010). Commercial vessels traveling at slow speeds and having low freeboards are typically easier targets of opportunity.

Figure 4. Picture on the left is a mother dhow for logistical support at sea and three pirate dhows attached for the attacking of a commercial vessel (From Operation Ocean Shield, 2010). The picture on the right is a pirate dhow and pirates (From Ocean Shield, 2010).

In the past, pirates have not been known to kill the crew of the pirated vessel. On February 22, 2011, pirates captured and killed four Americans onboard the Quest, a 58-foot yacht (Wadhams, 2011). These killings sparked questions about the effectiveness of the military in deterring piracy. Hillary Clinton, U.S. Secretary of State, stated, "We've got to have a more effective approach to maintaining security on the seas, in the ocean lanes that are so essential to commerce and travel" (Wadhams, 2011).

D. OTHER POTENTIAL PIRACY TOOLS

1. United Kingdom Global Model

As part of the Big Three, the UK has its own forecasting model, the UK Global Model (UKGM), for "ease of maneuver and to optimize precision weapons" (Ritchie, 2010). This model is run four times per day and provides as output a forecast for the following six days. Wave Watch III provides the wave characteristics and the Forecasting Ocean Assimilation Model-Nucleus of European Modeling of the Ocean (FOAM-NEMO) provides environmental information such as salinity and sea temperature for the model. The UKGM, with inputs from other systems, can be used to provide advice for likely enemy courses of action (COAs), but this model does not incorporate the INTEL about PAG CONOPS.

2. Technical Cooperation Program Maritime Group

In October 2008, Australia, Canada, New Zealand, the UK, and the U.S. agreed to develop a piracy-based toolset that would support the efforts to counter the increasing threat of piracy with specific attention paid to the HOA. This toolset is the Technical Cooperation Program Maritime Group (TTCP MAR). Discussions held during a TTCP MAR meeting in September 2009 in Halifax, Canada, addressed the desire to "conduct a Red Teaming Exercise to help predict how pirate tactics and strategies may adapt and evolve as their current operations are impacted by coalition interdiction efforts" (D. DaSilva, personal communication, June 11, 2010).[9] The developers of the TTCP MAR were interested in learning about the author's research and how it could enhance TTCP MAR's development.

E. EXPERIMENTAL DESIGNS

1. Design of Experiments

Design of experiments (DOE) has an extensive background and a variety of applications in the operations research and simulation community. Sanchez (2005) describes DOE as the ability of "the analysts to examine many more factors than would otherwise be possible, while providing insights that could not be gleaned from trial-and-error approaches or by sampling factors one at a time" (pp. 69). DOE can be thought of as an enabler that when properly implemented helps to reduce correlation among input variables while providing a robust design that eliminates duplication in the data analysis, which leads to greater statistical power.

As described by Kleijnen, Sanchez, Lucas, and Cioppa (2005), DOE provides effective and efficient results without using a "trial-by-error approach" (pp. 263). Kleijnen et al. (2005) defines basic objectives analysts should have in developing their

[9] TTCP MAR information was provided by D. DaSilva (UK civilian contractor for the CMF assessment team) to the author as a result of the author's operations research experience tour to the CMF in Bahrain on June 11, 2010.

DOE prior to formulating the meta-model. Kleijnen et al. (2005) recommends that the DOE must be an integral part in the developmental stages of multivariate polynomial modeling and should continue thereafter:

> DOE can uncover detailed insight into the model's behavior, cause the modeling team to discuss in detail the implications of various model assumptions, help frame questions when the analysts may not know ahead of time what questions should be asked, challenge or confirm expectations about the direction and relative important of factor effects, and even uncover problems in the program logic. (pp. 266)

When analyzing the output, analysts should be aware of nonlinear effects, discontinuous effects, chaotic behavior, and a simulation spin-up period (Kleijnen et al., 2005). These model effects can lead to the wrong analytical result.

2. Nearly Orthogonal Latin Hypercubes

Depending on the question(s) to be answered, the modeler may be focused on orthogonality of input factors. Orthogonality means the model's factors are uncorrelated—the cross product of any two input vectors in the model's space is equal to zero. If there is multicolinearity among input factors, then the differences in standard error compared to the best-fit model may be extremely large and lead to inconclusive analytical results (Kleijnen et al., 2005).

To provide a good DOE for many applications, Cioppa and Lucas (2007) develop an algorithm to provide nearly orthogonal Latin hypercube (NOLH) experimental designs. Cioppa and Lucas start with the goal of estimating simple yet common first-order effects in a model. In general, to estimate such a model, the number of simulation runs increases significantly with the number of factors, which may be prohibitive. Cioppa and Lucas define two objectives, ρ_{max} and the condition number, cond ($X^T X$), that indicate how well the NOLH performs with respect to correlation:

> One measure, ρ_{max}, gives the worst correlation between design matrix columns, whereas the other measure, cond ($X^T X$), assesses the overall degree of nonorthogonality of the design matrix. A design matrix will be classified as *nearly orthogonal* if it has a maximum pairwise correlation no greater than .03 and a condition number no greater than 1.13. (pp. 47)

Other operations research studies that use DOE and the NOLH include Bodden (2010), who studies the survivability of the transformable craft; Abel (2009), who studies the effectiveness of frigate defensive measures in pirated waters; Wegner (2007), who studies system reliability and capabilities within a joint environment; and Joshua (2006), who studies the expansion of the NOLH as used in computer-based simulations.

3. Design Points

In modeling, specifically in DOE, input factors will affect the results generated by the simulation. An experimental design can be considered a $m \times n$ matrix where m defines the columns and n defines the rows of the matrix. The m columns will correspond to the input factors and the n rows will correspond to the factor settings during the number of runs. Each row represents a combination of factor-levels and is called a design point (Sanchez, 2006). In general, a proper DOE specifies a set of design points that efficiently enables the analysis after the experimental results are obtained.

III. U.S. PIRACY MODELS

In this chapter, the first generation Piracy Performance Surface (PPS) and the Next generation Piracy Performance Surface (PPSN) models are discussed, as well as how the PPS model is being used by the U.S. and allied nations' militaries, and the differences between the two piracy models. This chapter also includes interviews with operators and users of the PPS model.

A. FIRST GENERATION PIRACY PERFORMANCE SURFACE MODEL

Just days after the *MV Maersk Alabama*, a U.S.-flagged ship, was hijacked by Somali pirates in the Indian Ocean on April 8, 2009, NAVO researchers were tasked by Rear Admiral David Titley, Oceanographer and Navigator of the Navy, to assist in the fight against piracy (B. Lingsch, personal communication, May 19, 2010).[10] Admiral Titley wanted his staff to define how meteorologists could play a vital role in countering piracy operations, having knowledge of the limited military assets available to use and the impact of environmental conditions on the success of pirate activity.[11] The PPS product was completed approximately two weeks after the *Maersk* incident, and has undergone a few revisions since its development.

The primary purpose of PPS is to be used as a piracy-forward warning tool for military and commercial vessels. The model depicts the predicted pirate threat in SBR and GOA. Figure 5 shows the color coded output to the model. Red represents forecasts of high piracy threat against neutral vessels. Areas displayed in green have a lower piracy threat level. The Sixth Fleet Admiral and his staff are comfortable with the PPS convention in which red is indicative of areas more favorable for pirate activity.[12]

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[10] B. Lingsch is head of the INTEL Department at the Commander, Naval Meteorology and Oceanography Command (CNMOC) at Stennis Space Center in Mississippi. He is also the sponsor of the author's thesis research.

[11] Dr. James Hansen and Mr. Bill Lingsch in a presentation to the Battlespace Atmospheric and Cloud Impacts on Military Operations (BACIMO) and Weather Impacts Decision Aids (WIDA) Conference on April 13–15, 2010.

[12] This information was gathered during the author's operations research experience tour on May 20, 2010. The author was given a presentation by NAVO civilian contract Nathan Hooper.

The model's index is a weighted combination of forecast environmental suitability for pirate activity and historical observed pirate activity with weights determined by the Office of Naval Intelligence (ONI), of 90% and 10% respectively (N. Hooper, personal communication, May 20, 2010).[13] The environmental suitability is forecast using a wave model called the Shallow Water Near Shore model (SWAN).

When a pirate event in the form of a boarding, attempted boarding, or suspected boarding occurs, an area surrounding the location is highlighted to represent a high-risk area in the PPS surface for the next forty-eight hours, then slowly dissipates over the next seven days. Such pirate events are reflected by the red dots in Figure 5. Historical attacks provided by ONI are also factored into the pirate activity index with a lesser contribution than the recent pirate activity.

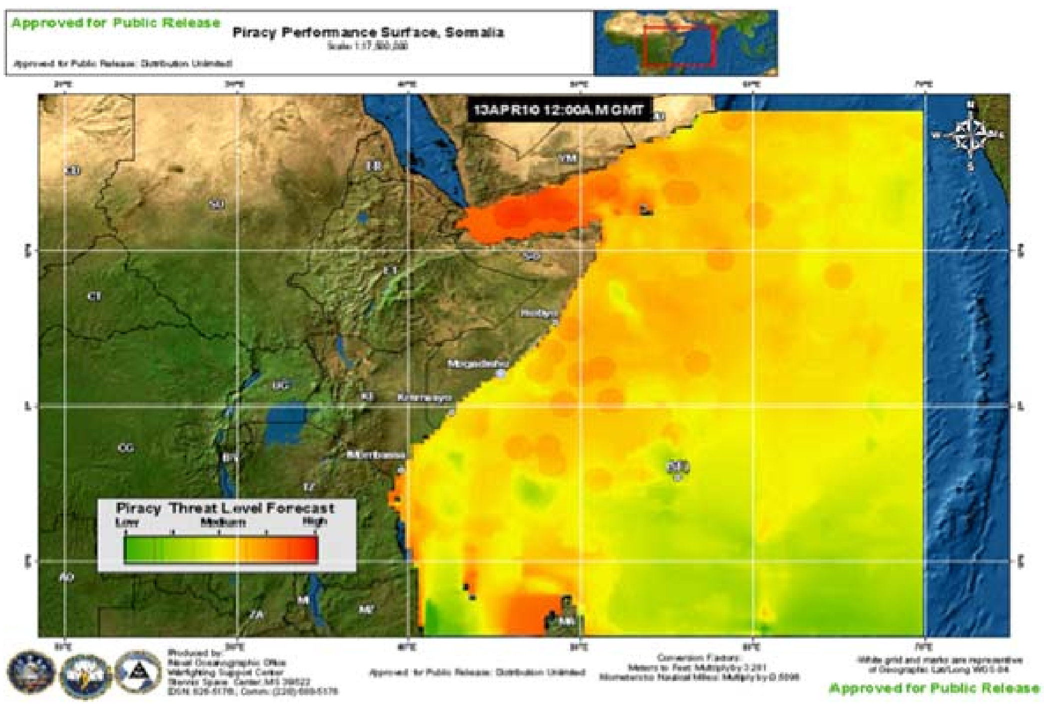

Figure 5. PPS model output provided to the CMF assessment team that was based on April 12, 2010 at 1200 a.m. GMT. The areas encircled in red and annotated 'high' are areas that are more prone to pirate attacks, and thus should be areas avoided by neutral vessels and monitored by forces combating piracy in the SBR and GOA (From N. Hooper, personal communication, 2010).

[13] This information was gathered during the author's operations research experience tour on May 20, 2010. The author was given a presentation by NAVO civilian contractor Nathan Hooper.

B. MILITARY APPLICATION

As of this writing, the 1200 Greenwich Mean Time (GMT) PPS snapshot is briefed to the Commander of NAVCENT at the Combined Maritime Forces Headquarters' daily meeting.[14] This snapshot of PPS is used to inform the chain of command of the current day’s relative pirate threat index. This 1200 GMT snapshot is also provided to the military forces deployed to the GOA and SBR in support of Operation Ocean Shield (OOS) and European Union Naval Force Somalia - Operation Atalanta. At the end of March 2011, PPSN will be briefed at this meeting. On March 1, 2011, the name referencing the next-generation piracy model is the Pirate Attack Risk Surface (PARS).

C. THE NEXT GENERATION PIRACY PERFORMANCE SURFACE MODEL

The success of the PPS model led the Naval Meteorology and Oceanography Command (CNMOC) leadership to devote efforts to pursue a more advanced anti-piracy model, PPSN. Dr. James Hansen, Naval Research Laboratory (NRL) Monterey, was tasked with developing this next generation probabilistic forecasting tool.

PPSN simulates pirate behavior within the METOC environment over a 72-hour forecast time period in 0.2-hour time steps with a probability surface generated at 12-hour time steps. The simulated behavior depends on intelligence parameters such as the PAG's camp location, the PAG's operating area, and the PAG's mission length. Figure 6 displays the PPSN output, i.e. the relative forecast of pirate presence probability as a function of latitude, longitude, and time.

The early version of the PPSN model simulated pirates from randomly generated starting locations. The pirates motored to a pre-determined location while being affected by environmental conditions (waves, winds, and currents), then drifted until the pirates ran out of simulated food, water, and/or khat, and then motored back to their beginning location. The output from the simulation was the relative probability that a pirate would

[14] This information was gathered on June 8, 2010 during the author's operations research experience tour.

be at a given latitude, longitude and time. PPSN represented probabilities with color coding, with the highest probabilities in red and the lowest probabilities in dark blue.

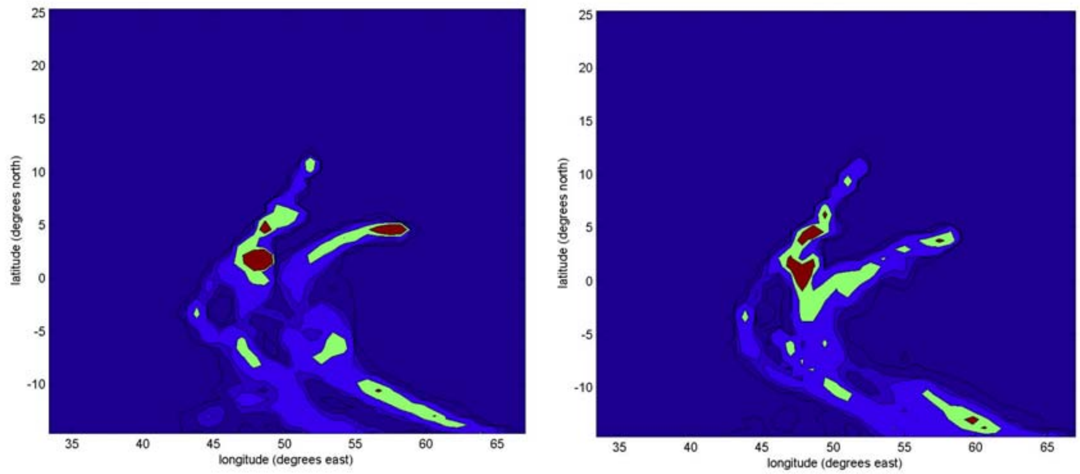

Figure 6. The PPSN model output displaying the relative forecast of pirate presence probability as a function of latitude, longitude, and time. The two pictures displayed are the 24-hour forecast (left) and the 72-hour forecast (right) of relative pirate presence probability. Red corresponds to the highest probability forecast of pirate location.

1. Modeling Differences Between PPS and PPSN

Table 1 describes the modeling differences between the PPS and PPSN models.

Model	***PPS***	***PPSN***
1	Overlay of waves, currents and INTEL about pirate activity.	Simulation of pirate behavior.
2	Uses METOC forecasts of waves and currents.	Uses METOC forecasts of winds, waves and currents.
3	Assumptions about environmental suitability based on a 9-foot skiff.	Incorporates additional INTEL to include pirate METOC knowledge, pirate skiff movement patterns, and pirate skiff speed.
4	Updated every three hours unless pirate activity occurs.	In addition to updates if pirate activity occurs, the model takes operator inputs that drive the model to include pirate operating locations, length of time a pirate can operate, pirate camp locations, and observed pirate activity.
5	Provides a snapshot forecast of environmental suitability for pirate activity.	Time-integrates environment with pirate CONOPS to produce relative forecast of pirate presence probability.

Table 1. Model comparisons between PPS and PPSN.

D. INTERVIEWS WITH OPERATORS AND USERS

The author traveled to AFRICOM in Stuttgart, Germany, and met with the CMF assessment team in Bahrain to brief them on the PPS model and preliminary experiments using the MATLAB version of the PPSN model. The author met with users and operators to learn about their use of the PPS model, their needs, and about pirate tactics.

In Bahrain, the operators, NATO and U.S. Intelligence officers, subject matter experts (SME), and high ranking military officers provided insight and direction that led the author to make recommendations to modify the PPSN model of pirate behavior. Based on these recommendations, several changes were incorporated in the new version (Python) of the PPSN model. Changes that were based on the author's recommendations included:[15]

- Defining factors in the PPSN model that INTEL and users justified as being significantly important in PAG CONOPS.
- Implementation of different PAG search patterns (described below).
- Redefining the factor definitions used in the model to assimilate the terminology being used by the U.S. and allied military operators.
- Implementation of mapping PAG from their base location to their operating waypoint location.
- Extending the run time of the model to weeks and months rather than days to reflect longer PAG CONOPS.

[15] A trip report of the author’s operations research experience tour is included in Appendix A of this thesis.

E. POST EXPERIENCE TOUR DESCRIPTION OF THE REDEVELOPED PPSN

PPSN is a Monte Carlo probabilistic forecasting tool that takes as input environmental conditions, pirate CONOPS and gathered INTEL to produce as output the relative forecast of pirate presence probability as a function of latitude, longitude and time. PPSN is written in Python (x,y) version 2.6.5.1 (Python 2.6.2). The Python version of PPSN has been continually in development since June 2010, and later experiments were conducted with an updated version, finalized in October 2010, which is similar (but not identical) to the current operational version.

As of the date of this thesis, PPSN is the only known operational Navy product that couples METOC and INTEL. It is used by the U.S. and allied forces to combat piracy in the SBR and GOA.

1. Meteorology and Oceanography Conditions

The METOC forecast used in the PPSN model is provided by NAVO oceanographic models.

a. Oceanographic Models

The Shallow Water Near Shore model (SWAN) provides the waves.

The Coupled Ocean/Atmospheric Mesoscale Prediction System model (COAMPS) provides the currents.

The Navy Coastal Ocean model (NCOM) provides the surface winds.

b. METOC Parameters Provided by the User

Input parameters describing the effect of METOC on PAGs are provided by the operators that drive PPSN. Typically, this information will be provided by the U.S. or the SMEs of the allied forces. These parameters affect the PAG's movement during transit from a base (camp) location to a waypoint location and when the PAG is conducting CONOPS in the waypoint operating area. The input parameters listed below are defined in more detail in Chapter IV of this thesis.

The factor by which the currents impact the PAG.

The factor by which the winds impact the PAG.

The threshold below which the PAG can operate under certain surface wind conditions.
The wave height threshold below which the PAG can operate (analogous to wind threshold).

Whether the PAG had knowledge of METOC conditions before leaving its base location.

2. Pirate Action Group Mapping

a. Base Mapping

The PPSN model simulates PAGs, which is a group of pirate dhows that are attached to a mother dhow (a larger vessel) that is typically used as a logistical hub for extending distances from land and mission length. PAGs are given a specific beginning location (base) that can be a single point or a box, and may be a land-based camp or an origin point at a mother dhow at sea. Each base has a longitude and latitude, and a longitudinal and latitudinal size of the box, and an associated weight. The weight is normalized in the code and defines the likelihood that the PAG will use one base over another base in PPSN.

b. Waypoint Mapping

From the PAG's base, the PAG is mapped to a hunting area known as the waypoint location. The waypoint location can be a defined by a single point or a box. The waypoint location is given a longitude and latitude, and a longitudinal and latitudinal size of the box and a weight. The user can define the base and waypoint to be the same longitude and latitude. This could potentially be beneficial when mapping PAGs at distances 1,000 nautical miles from campsites. This technique was used in this thesis.

c. PAG Mapping Demonstration

Figure 7 displays an example of the overall mapping of PAGs from base locations to their respective operating waypoints (annotated by the arrow). Each simulated PAG begins its mission at a location randomly sampled from the base distribution. For example, consider the third yellow box in Puntland off the HOA. This small yellow box is the starting base location that the operator may choose to model as the PAG's beginning location. The second yellow area labeled Distro2 may be the PAG's waypoint. The PPSN code requires the lower left-hand corner of each base and waypoint to be the longitude and latitude of a base or waypoint. The author used Google Earth to build the inputs for the mapping necessary for the PPSN model.

When establishing Distro2, the user will define this box by longitude and latitude in degrees, $\left(6.14^{\circ} N, 64.86^{\circ} E\right)$. The associated longitude and latitude size of the box is equal to five in this case. A size of five for a box means approximately a 300×300 mile box. In this thesis, the author used a size of 0.01 for the base boxes and 0.1 for the size of the waypoints boxes.

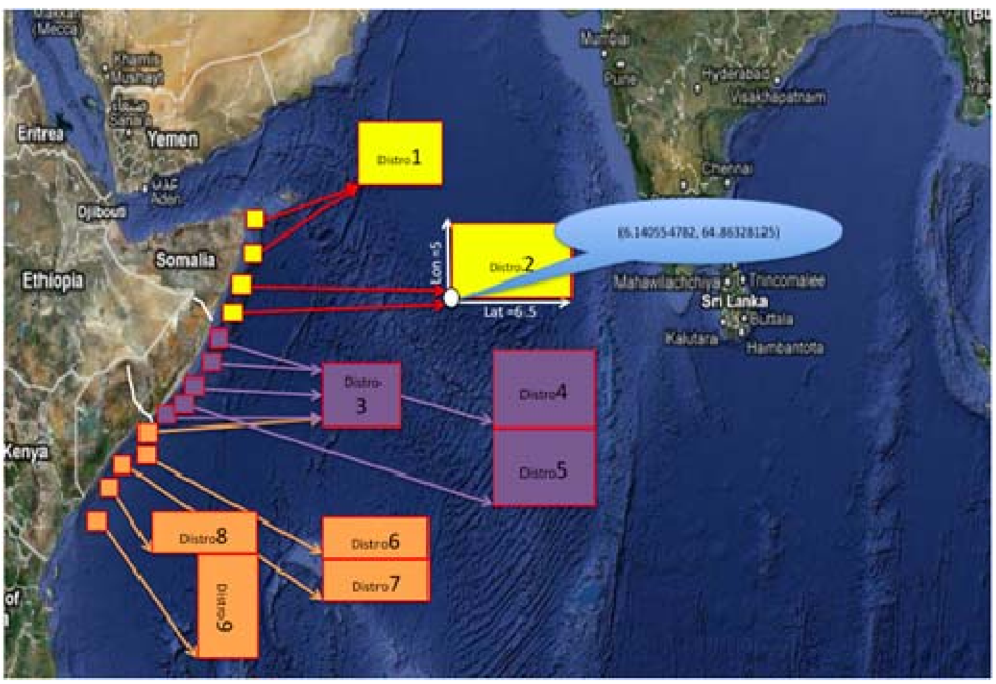

Figure 7. Representation of the base and waypoint locations inputted by the user into the PPSN model for the appropriate mapping of each PAG.

3. PAG Search Patterns

This factor defines the movement pattern that the PAG will use once it has reached its waypoint longitude and latitude and begins the hunting phase (described in Phase 2 below). The PAGs can be given any of the following search patterns:

- 0 (drift) - This value represents the PAG drifting as a function of the environmental conditions while searching for vessels of opportunity.
- 1 (random walk) - This value represents the PAG randomly walking within the defined longitude and latitude waypoint while searching for vessels of opportunity.
- 2 (zig-zag) - This value represents the PAG zig-zagging within the defined longitude and latitude waypoint. The zig-zag search pattern resembles the PAG moving across a known shipping transit lane while searching for vessels of opportunity.
- 3 (transit) - This represents the PAG hunting only within the defined longitude and latitude waypoint.

4. Three Phases of PPSN

Three typical PPSN PAG CONOPS phases are as follows:

1. Phase 1 is the PAG's transit from its base to its waypoint. During the transit, the PAG will be impacted by winds, currents, and wind and wave threshold. The PAG will continue to the defined waypoint until it gets within a tolerance (distance) or the PAG's mission length (defined in Chapter IV) has been exceeded.
2. Phase 2 is the PAG’s hunting phase. During this phase, the PAG will be impacted by winds, currents, and wind and wave threshold. The PAG will hunt using one of the described search patterns until the PAG's remaining mission length is equal to the time it took the PAG to get to its waypoint location (transit time). If the transit time is greater than half the PAG's mission length, then the PAG will immediately return to its base.
3. Phase 3 is the transit back to its base. During this phase, the PAG will be impacted by winds and currents, but will not be impacted by wind threshold and wave thresholds.

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IV. VARIABLE DEFINITIONS

This chapter describes the independent and dependent variables modeled in each design of experiments (DOE) in this thesis to analyze the PPSN model.

A. INDEPENDENT VARIABLES

The impacts of the following variables were studied using a NOLH design to produce a robust and space-filling DOE. A brief description of each of the independent variables is as follows:

1. Number of pirate action groups (npi): This discrete factor represents the number of simulated PAGs, defined by the user, in the simulation. This factor must be an integer greater than zero.
2. Number of bases ($nbase$): This discrete factor represents the number of distinct base locations the PAGs will originate in and must be an integer greater than zero. In this thesis, $nbase$ represents the total number of land and sea bases.
3. Mission length ($t\_mission$): This discrete factor represents the mean length of time in hours that PAGs remain active in the simulation.
4. Number of PAG replications ($numtracks$): This discrete factor represents the number of times the model is replicated for every PAG in a given 24-hour period. For example, if $numtracks$ equals 1,028 then the model will be run 1,028 times per PAG for each 24-hour period to generate the forecast of relative pirate presence probability.
5. METOC knowledge ($iweather$): This continuous factor represents the probability, $iweather \in [0,1]$, that PAGs have METOC knowledge prior to leaving their base.
6. Skiff speed ($skiff\_speed$): This continuous factor represents the speed that a given PAG is expected to sustain during the transit and searching patterns. This factor is measured in knots and must be a positive real number.
7. Drift current ($drift\_curr$): This continuous factor represents the factor by which the currents impact skiff movement, $drift\_curr \in [0,1]$.
8. Drift wind ($drift\_wind$): This continuous factor represents the factor by which the winds impact skiff movement, $drift\_wind \in [0,1]$.

9. Wind threshold $(wind\_thresh)$: This continuous factor represents the threshold below which PAGs can operate. If winds exceed a PAG's threshold, the PAG can no longer operate. The PAG will either return to its base or remain at its base if the PAG has not left. This factor is measured in knots and is a positive real number.

10. Wave threshold $(wave\_thresh)$: This continuous factor represents the threshold below which PAGs can operate. If waves exceed a PAG's threshold, the PAG can no longer operate. The PAG will either return to its base or remain at its base if the PAG has not left. This factor is measured in knots and is a positive real number.

11. Pirate search pattern $(search\_pattern)$: This categorical factor is an integer from zero to three that describes how the PAGs will conduct their search once they reach their waypoint operating areas. Table 2 describes the possible PAG search patterns.

Search Pattern	**Description**
0 (drift)	PAG movement is determined by winds and currents only.
1 (random walk)	PAGs will be moving at the defined $skiff\_speed$ in a random walk, plus a component due to winds and currents.
2 (zig-zag)	PAGs will be moving at the defined $skiff\_speed$ in a zig-zag pattern. This pattern represents PAGs moving in a strategic motion east to west and west to east across a southerly to northerly transit lane. The zig-zag pattern will also be impacted by winds and currents.
3 (transit)	PAGs will be transiting at the defined $skiff\_speed$ and will be impacted by winds and currents.

Table 2. Descriptions of the four PAG search patterns. These patterns take effect when the PAGs reach their waypoint destination and begin to search for a vessel of opportunity.

B. DEPENDENT VARIABLES

Summarizing and quantifying the output from the PPSN model was a challenge. Each simulation run produced a pirate density in each cell at multiple forecast leads (usually 12, 24, 36, 48, 60, and 72 hours). Therefore, the results in 43×51 cells at multiple forecast leads must be summarized.

In addition, it was impossible to use historical pirate incidents to verify PPSN's performance because historical METOC conditions and available INTEL corresponding to observed pirate activity have not been archived. In addition, there is insufficient INTEL gathered from historical pirate incidents within the SBR and GOA. Therefore, for any experiment conducted during this thesis, there is no definitive ground truth against which to compare results.

Each simulation run in this thesis was summarized and compared usefully with the results from other design points to identify the variables that are most influential and have the greatest interaction with METOC conditions. Within each simulation, differences across the forecast lead times reflected sensitivity and interactions with METOC conditions. Differences in the probability fields across design points reflected the influence of the experimental variables.

A brief description of each of the dependent variables is given below.

τ = forecast lead where $\tau = 0, 6, 12, \ldots, \tau_{\max}$

$\tau_{\max}$ = longest forecast lead provided for the PPSN METOC

x_i = i^{th} indexed longitude, where $i = 1, \ldots, 43$ and $x_1 = 33°E$ and $x_{i+1} - x_i = 0.8°$

y_j = j^{th} indexed latitude, where $j = 1, \ldots, 51$ and $y_1 = -15°N$ $\left(15° S\right)$ and $y_{j+1} - y_j = 0.8°$

dp = design point number from the DOE

r = replication number of each dp

$pirate\_prob(dp, \tau, i, j)$ = PPSN-forecast of relative pirate presence probability as output, $\in [0,1]$

R = the set of comparable design points

$$mean\_pirate\_prob(\tau,i,j,R) = \frac{1}{|R|}\sum_{dp\in R} pirate\_prob(dp,\tau,i,j) \quad \in [0,1]$$

$RMSD$ and $MAXVAL$ are both output measurements used to measure the difference between the forecast of relative pirate presence probability for each design point and the mean pirate probability that is generated by the simulation.

(1) Root mean squared difference $\left(RMSD(dp,\tau,R)\right)$ is the mean square root of the squared difference between the cell-by-cell relative pirate probability $pirate\_prob(dp,\tau,i,j)$, and the mean forecast of relative pirate presence probability, $mean\_pirate\_prob(\tau,i,j,R)$, for the set of comparables R.

$$RMSD(dp,\tau,R) = \sqrt{\frac{1}{43\cdot 51}\sum_{i=1}^{43}\sum_{j=1}^{51}(pirate\_prob(dp,\tau,i,j) - mean\_pirate\_prob(\tau,i,j,R))^2}$$

(2) Maximum value $\left(MAXVAL(dp,\tau,R)\right)$ is the cellwise maximum absolute value of the difference between the relative pirate probability, $pirate\_prob(dp,\tau,i,j)$, and the mean forecast of relative pirate presence probability, $mean\_pirate\_prob(\tau,i,j,R)$.

$$MAXVAL(dp,\tau,R) = \max_{i=1,\ldots,43,\, j=1,\ldots,51}\left|pirate\_prob(dp,\tau,i,j) - mean\_pirate\_prob(\tau,i,j,R)\right|$$

These inner variants measure the differences across forecasted relative pirate presence at different lead times within the same design point. The following equations will define the inner variants of $RMSD$ and $MAXVAL$.

$$inner\_mean\_prob(dp,i,j,\tau_{\max}) = \frac{1}{\frac{\tau_{\max}}{12}}\sum_{t=1}^{\frac{\tau_{\max}}{12}} pirate\_prob(dp,12\cdot t,i,j)$$

The inner variants are designed to capture the sensitivity of a given design point's probability field to METOC conditions, using the forecasts at different lead times as a proxy for changing METOC conditions.

(3) The inner variant of $RMSD$ $\left(iRMSD(dp,\tau_{\max})\right)$ is the square root of the maximum squared difference between the cell-by-cell relative pirate probability, $pirate\_prob(dp,\tau,i,j)$, and the inner mean relative pirate probability, $inner\_mean\_prob(dp,i,j,\tau_{\max})$, of each design point over available forecast leads $\left(\tau's\right)$.

$$iRMSD\left(dp,\tau_{MAX}\right)=\sqrt{\frac{1}{43\cdot 51}\sum_{i=1}^{43}\sum_{j=1}^{51}\max_{\tau\le\tau_{MAX}}\left(pirate\_prob\left(dp,\tau,i,j\right)-inner\_mean\_prob\left(dp,i,j,\tau_{MAX}\right)\right)^{2}}$$

(4) The inner variant of $MAXVAL$ $\left(iMAXVAL(dp,\tau_{MAX})\right)$ is the maximum cellwise absolute difference between a probability field and the inner mean relative pirate probability, $inner\_mean\_prob(dp,i,j,\tau_{\max})$, of each design point over available forecast leads.

$$iMAXVAL(dp,\tau_{\max})=\max_{\tau<\tau_{MAX}}|\,pirate\_prob(dp,\tau,j,i)-inner\_mean\_prob(dp,j,i,\tau_{\max})\,|$$

Smoothed variants of $RMSD$, $MAXVAL$, $iRMSD$, and $iMAVAL$ were also used. In the smoothed variants, each cell's value $(pirate\_prob)$ was replaced by the average of the value plus the eighth adjacent cell's values $(smoothed\_pirate\_prob)$.

$$smoothed\_pirate\_prob(dp,\tau,i,j)=\frac{1}{9}\sum_{k=i-1}^{i+1}\sum_{m=j-1}^{j+1}pirate\_prob(dp,\tau,k,m)$$

Two other measures were also calculated. Mean 50th percentile ($MAREA$) is the average area containing 50% of the relative forecast of pirate presence probability density. $MAREA$ and the smoothed variant ($MAREAs$) were not used in the analysis as discussed in Chapter VI, Section B.

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V. SIMULATION EXPERIMENTAL DESIGNS

This chapter describes the PPSN experiments used in this thesis: (A) computer memory requirements, (B) significant factors, and (C) variability across design points.

This thesis uses the Air Force Research Laboratory Department of Defense Supercomputing Resource Center (AFRL DSRC) High Performance Computing (HPC) system, hawk, to perform the PPSN simulation runs. The AFRL DSRC HPC is located at Wright-Patterson Air Force Base in Ohio. The SGI Altix 4700 (hawk) consists of 18 computer nodes with each computer node having 512 processors, all running a variant of the the Linux operating system (AFRL DSRC, 2010). Each of 16 computer nodes has 1.5 GB of useable available memory while two computer nodes have 3.5 GB of useable memory (S. Upton, personal communication, February 24, 2011). [16]

This memory limitation significantly impacted the number of design point runs that were completed. Steve Upton (personal communication, February 24, 2011) calculated that 24,000 computer-hours were used to complete this thesis on hawk. Upton (2011) stated,

> This may seem inflated; in order to use the large memory nodes this thesis needed to "reserve" eight processors even though the PPSN model was using one processor in each of the jobs. In addition, jobs that did not complete in the allotted time were still charged with that amount of computer time. There were also a few trial and error missteps by the hawk user.

A. MEMORY REQUIREMENT DESIGN OF EXPERIMENTS

In attempts to run the PPSN model, the computing memory requirements were often exceeded resulting in failed design point runs. Preliminary experiments revealed that increasing $t\_mission$, $numtracks$, and npi significantly increased the computer memory requirements of the PPSN runs, and high memory requirements could cause

[16] This information was provided by Steve Upton, SEED Center for Data Farming research associate.

early termination of the simulation. Therefore, an experiment was designed to analyze each of the three memory-driving independent variables separately to determine their influence on the PPSN output.

1. Mathematical Calculation Used to Determine the Computer Memory Requirements

Close examination of the code showed that the following equation approximates the required memory for each design point (S. Upton, personal communication, February 24, 2011).[17]

$$memory\_estimate = \left(pirate\_location\_size + METOC\_array\_size\right) \div 2.5$$

The division by 2.5 in the equation above is indicative of the compression ratio on Microsoft Windows software.

$ntaus$ = the number of forecasts

$$hrs = \left\lfloor \frac{\max(t\_mission)}{6} \right\rfloor + ntaus$$

$$nw = \left\lceil \frac{2 * \max(t\_mission)}{24} \right\rceil$$

$$METOC\_array\_size = \left(3 * 201 * 171 * 2 * hrs\right) + \left(2 * 321 * 273 * 2 * hrs\right)$$

The values 171, 201, 273, and 321 are fixed array sizes based on the array size of the provided METOC data.

$$pirate\_location\_size = npi \times \left(npi\left(nw\left(numtracks+1\right)\right) * \left[\left(\frac{24*2}{dt}\right) * \left(\frac{\left(ntaus-1\right)*6}{t\_mission}\right) + \left(24*\left(nw+1\right)\right)\right]\right)$$

Using this memory calculation allowed the author to create design of experiments that could be run in a reasonable operational time and produce relevant output results with less than the approximately 24 GB $\left(16 * 1.5GB\right)$ of memory available.

[17] This formula was provided by Mr. Steve Upton, research associate for the SEED Center for Data Farming.

2. Description of Three Independent Variables That Increase Computer Memory Requirements

The memory capacity of about 24 GB precluded using a space-filling design that varied $t\_mission$, $numtracks$, and npi throughout realistic ranges.

Appendix B displays the values given to each design point. This appendix also shows the three cases modeled in this DOE. Design point one is used as the base case design point for this DOE (refer to Appendix B). Design point one will remain constant through the simulations and when analyzing the three memory requirements variables. Design point one has the following values associated with each variable: $t\_mission = 36$, $numtracks = 128$, and $npi = 4$. The computer memory requirement for this base case was less than 1 GB.

a. The Number of PAG Replications

The first sub-design, design points 1 and 2-16, varies $numtracks$ while holding $t\_mission$ and npi constant. The input values given to $numtracks$ vary between 128 and 2,048 PAG replications per 24-hour period in increments of 128 PAG replicates. This variable is used in the PPSN model to produce the forecast of relative pirate presence probability. This variable is not reflective of gathered INTEL from the military assets countering piracy in the SBR and GOA. It is solely used for modeling purposes.

b. Mission Length

The second sub-design, design points 1 and 17-35, varies $t\_mission$ while $numtracks$ and npi are held constant. The input values given to $t\_mission$ vary between 24 and 336 hours in increments of 6, 12, and 24 hours, respectively (refer to Appendix B). Despite 336 hours being the longest $t\_mission$ in this DOE, the CMF assessment team INTEL officer, LCDR K. Lutz, (personal communication, June 8, 2010) stated that the increase in pirate capabilities has enabled the PAGs to sustain pirating missions for longer than 336 hours; thus, 336 hours is a moderately low mission length for advanced PAG CONOPS.

c. The Number of PAGs

The third sub-design, design points 1 and 36-46, varies *npi* while $t\_mission$ and *numtracks* are held constant. The input values given to *npi* vary between 4 and 48 in increments of four PAGs. The current operational testing being conducted on PPSN has injected real-time INTEL reflecting the value associated with this variable.

B. SIGNIFICANT FACTORS DESIGN OF EXPERIMENTS

The following DOE with 33 design points investigates which PPSN input parameters are the most influential in determining the distribution of relative risk of pirate presence in PPSN and which PPSN input parameters interact most strongly with METOC conditions and INTEL parameters.

Table 3 shows the variables modeled and the ranges of values given to each of the variables discussed in Chapter IV. With the exception of $t\_mission$, these values are realistic according to information gained during the author's operations research experience tour.

Independent Variables	**Minimum Value**	**Maximum Value**
npi	10	30
$t\_mission$	72	240
numtracks	85	888
$skiff\_speed$	5	35
$drift\_curr$	0.5	1.0
$drift\_wind$	0.4	0.8
$wind\_thresh$	20	30
$wave\_thresh$	3	9
$iweather(probability)$	0	1
$search\_pattern(categorical)$	---	0,1,2,3

Table 3. NOLH maximum and minimum values for the ten independent variables used in the significant factors design of experiments.

In addition, $skiff\_speed$ standard deviation was set to 20% of each design point's $skiff\_speed$. The $wave\_thresh$ standard deviation was set to a NOLH design variable with values ranging from 0.1 to 0.9 multiplied by the value of $wave\_thresh$.

Since npi ranges from 10 to 30, the PAGs are assigned to the six bases randomly. One-third are assigned to land bases, which are sampled without replacement until all land-base positions have been used at least once, and then with replacement until all PAGS have been assigned a base. Each land base is paired with a hunting waypoint. The remaining sea-based PAGs are also assigned to the three sea bases in the same way. For sea-based pirates, their base is identical to their hunting waypoint.

A NOLH was used to achieve near-orthogonality and a good space-filling design for the 10 independent variables. Appendix C provides the full NOLH design of the 33 design points. Due to the memory and runtime requirements, a rotational design, or other larger designs, was not feasible for this experiment. The runs which completed indicated that runtime was highly correlated with memory requirements in GB (refer to Figures 8 and 9).

Figure 8 represents the original DOE where the memory requirements for the 16 design points that did not complete (level zero) ranged from 0.7 to 15.8 GB. These design points are 3, 5, 6, 11, 12, 14, 15, 16, 17, 18, 21, 24, 25, 26, 27 and 30. Design point 18 has the highest total memory requirement, 15.79 GB. This design point also has a drifting $search\_pattern$. For the design points that completed (level one), design points 1 and 2 are the outliers with memory requirements of 14.7 GB and 14.3 GB, respectively. This difference between these two design points and design point 18 is their $search\_pattern$. Design points 1 and 2 had a transit only $search\_pattern$.

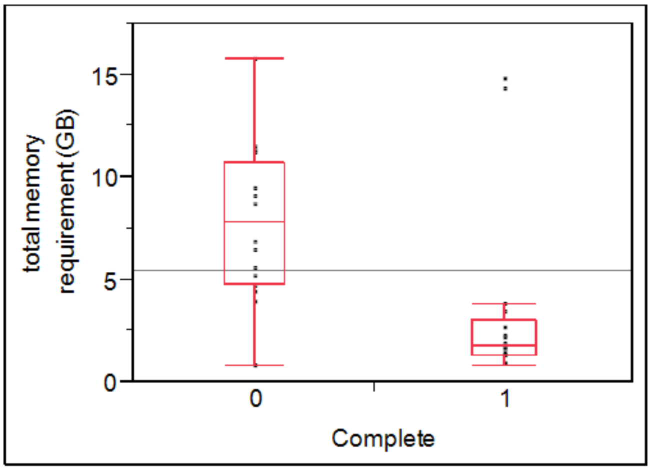

Figure 8. Original DOE with 33 design points. A level of one indicates design points That ran to completion and zero indicates design points that failed to complete.

In order for the remaining 16 design points to run to completion, the DOE was modified (Figure 9). The length of $t\_mission$ was decreased by 20% of its original value, $numtracks$ was decreased by 60% of its original value, and the allotted runtime was increased from 30 hours to 60 hours. Decreasing $t\_mission$ and $numtracks$ reduced the remaining design points' memory requirements to less than 9.5 GB.

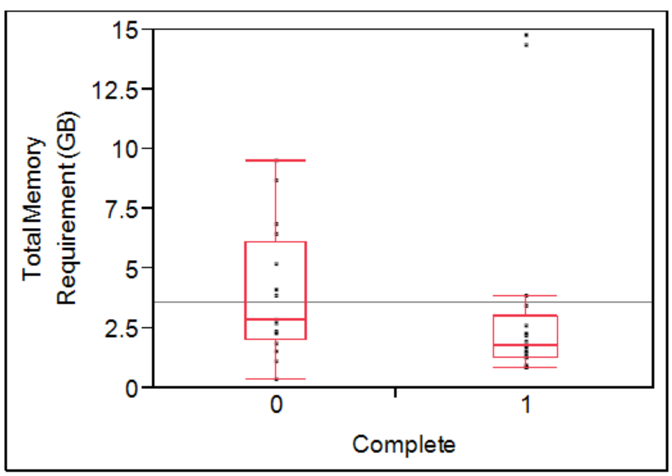

Figure 9. Modified DOE with 33 design points. The design points that did not complete (level 0) had a reduction in $t\_mission$ and $numtracks$.

The scatterplot matrix (Figure 10) shows that the 10 independent variables used in the significant factors DOE have nearly linear independence, even after the modification of the DOE. The correlation between the variables is less than 0.3.

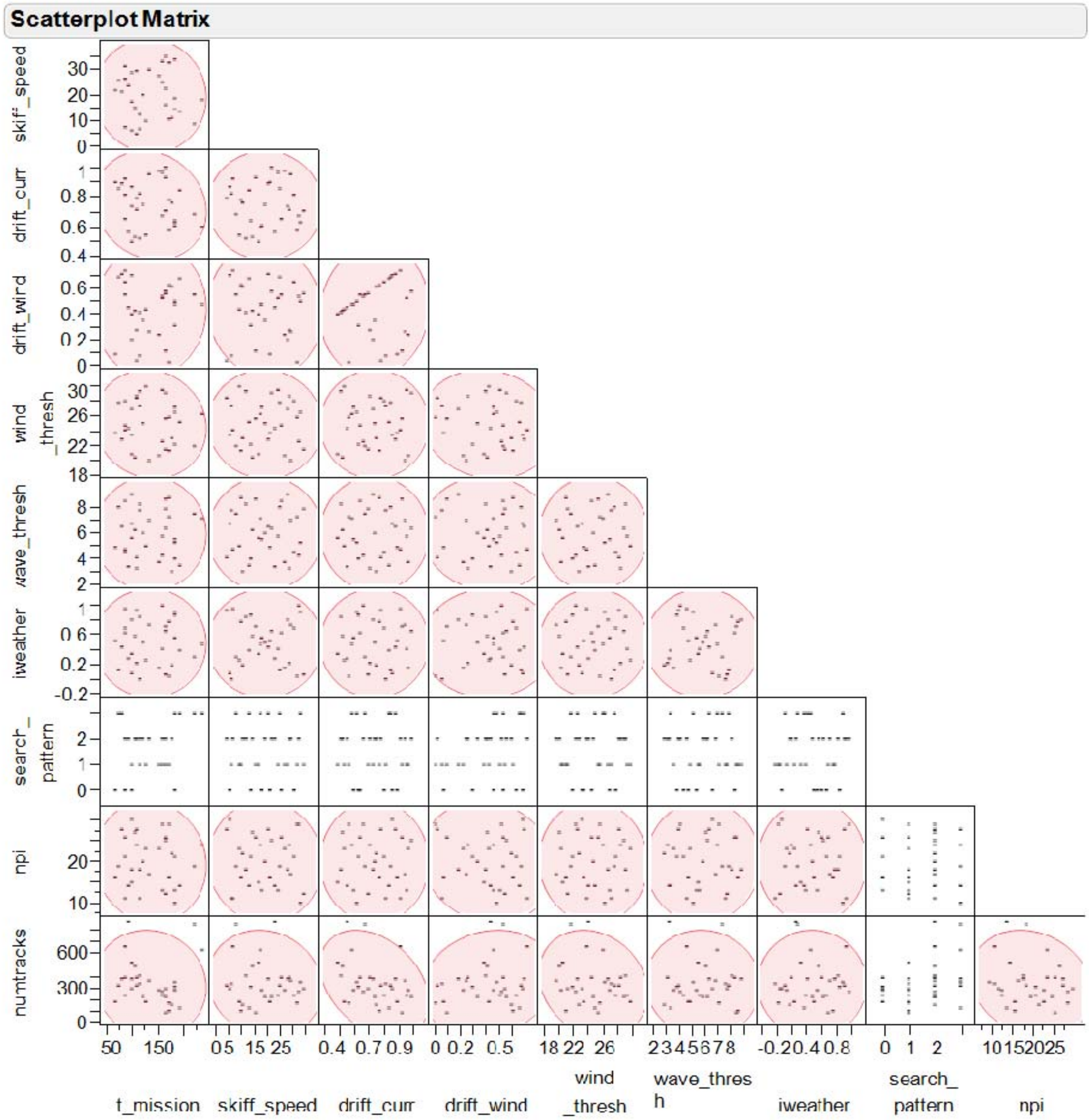

Figure 10. Scatterplot matrix of the significant factors DOE.

C. VARIABILITY ACROSS DESIGN POINTS

Long runtimes prevented conducting a larger experiment with many replications; hence, a small experiment was conducted to evaluate the variability inherent in the PPSN model. The question that this experiment addresses is how much variation is there for a single design point due to the stochastic variation in the model. A single design point from the significant factors DOE is chosen—design point 13. This design point is chosen because it is not an outlier and its memory requirement is less than 3.5 GB, 0.9 GB to be precise. Design point 13 is replicated 23 times with the variable values as defined in Table 4.

Independent variables	**Value**
npi	16
t_mission	172
numtracks	100
skiff_speed	10.63
drift_curr	0.78
drift_wind	0.62
wind_thresh	21.25
wave_thresh	8.81
iweather	0.78
search_pattern	1

Table 4. Design point 13 values for the variability across design points DOE.

VI. DATA ANALYSIS

The previous five chapters discussed the problems of piracy, the two piracy performance surface models, the independent and dependent variables used in this thesis, and the simulation DOEs.

In this chapter, the results from each of the experiments are analyzed. The conclusions drawn from this analysis are used for refining INTEL inputs and PPSN developmental efforts.

A. METHODOLOGY AND TOOLS

For each forecast lead time and design point, a picture in the form of a jpeg file is produced, which shows the forecast of relative pirate presence probability (see Figure 6 for examples in Chapter III, Section C).

1. Analytical Tool

JMP is used as the statistical analysis software in this thesis.[18] JMP's robust tool sets allow for the use of one software program to apply the following analytical methods used here: (1) partition trees, (2) stepwise regression methods, (3) sensitivity analysis, and (4) multivariate correlation.

2. Linear Regression Analysis

This thesis will use the following multivariate regression equation for determining the "best" fit model:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{i,i} x_i^2 + \sum_{j=1}^{k} \sum_{i=1}^{j} \beta_{i,j} x_i x_j + \varepsilon ,$$

where $\varepsilon = error$.

Montgomery, Peck, and Vining (2006) discuss three stepwise-type procedures for analyzing data. These broad categories include forward selection, backward elimination, and stepwise regression. This thesis uses forward selection which assumes no

[18] JMP^R , Version 9. SAS Institute Incorporated, Cary, N.C. Retrieved from http://www.jmp.com.

independent variables are initially in the model. The first variable to be included in the model is the independent variable with the greatest correlation to the dependent variable. Additional independent variables are added in the model if their partial correlation is significant after adjusting for the effects of the included independent variables.

The significance levels for variables to enter and exit the regression model are $P_{ENTER} = 0.05$ and $P_{EXIT} = 0.10$. Devore (2009) states the

> P-value (*observed significance level*) is the smallest level of significance at which H_0 would be rejected when a specified test procedure is used on a given data set. Once the P-value has been determined, the conclusion at any particular level α results from comparing the P-value to α:
>
> 1. $P-value \le \alpha \Rightarrow$ reject H_0 at level α.
>
> 2. $P-value > \alpha \Rightarrow$ do not reject H_0 at level α (pp. 313).

The null hypothesis, H_0, is the hypothesis assumed to be true, and the test procedures are an attempt to disprove the null hypothesis. Devore (2009) states "the two possible conclusions from a hypothesis-testing analysis are then reject H_0 or fail to reject H_0" (pp. 285).

The coefficient of determination, R^2, is used as one of the key measures of model effectiveness (Montgomery et al., 2006). R^2 is the proportion of total variance explained by the model. A R^2 value close to 1 means most of the variation in the dependent variable is explained by the regression equation.

3. Classification and Regression Trees

The use of classification and regression trees can be a powerful tool for understanding results graphically. The tree methods explain the variation of the output variable (dependent variable) by splitting or partitioning on the data recursively, creating homogeneous branches until a stopping criterion is met. The stopping criteria for this thesis use the sum of squares for continuous variables and the log-likelihood chi-squared for discrete and categorical variables.[19] A regression tree is used for this thesis to show clear-cut partitions for the influences of the independent variables modeled in PPSN.

B. MULTIVARIATE CORRELATION

Chapter IV described each of the ten output metrics. The multivariate correlation scatterplot, depicted in Table 5, shows the pairwise correlations among the dependent variables resulting from the significant factors experiment. The high correlation among $RMSD$, $MAXVAL$ and their smoothed versions indicates that only one of these four dependent variables needs to be used in the analysis of this thesis. Thus, $RMSD$ is the first dependent variable used in the analysis. Furthermore, high correlation exists among $iRMSD$ and $iMAXVAL$ and their respective smoothed versions. Therefore, $iRMSD$ is the second dependent variable used in the analysis.

Table 5 also shows that $MAREA$ and $MAREAs$ are negatively correlated to each of the other eight dependent variables and positively correlated to each other. However, these dependent variables did not significantly depend on any of the DOE input variables. Therefore, these output variables are not used in this thesis.

[19] Details on how JMP calculates the $p-$value using partition tree analysis can be found at http://www.jmp.com/blind/whitepapers/wp_montecarlo_cal.pdf.

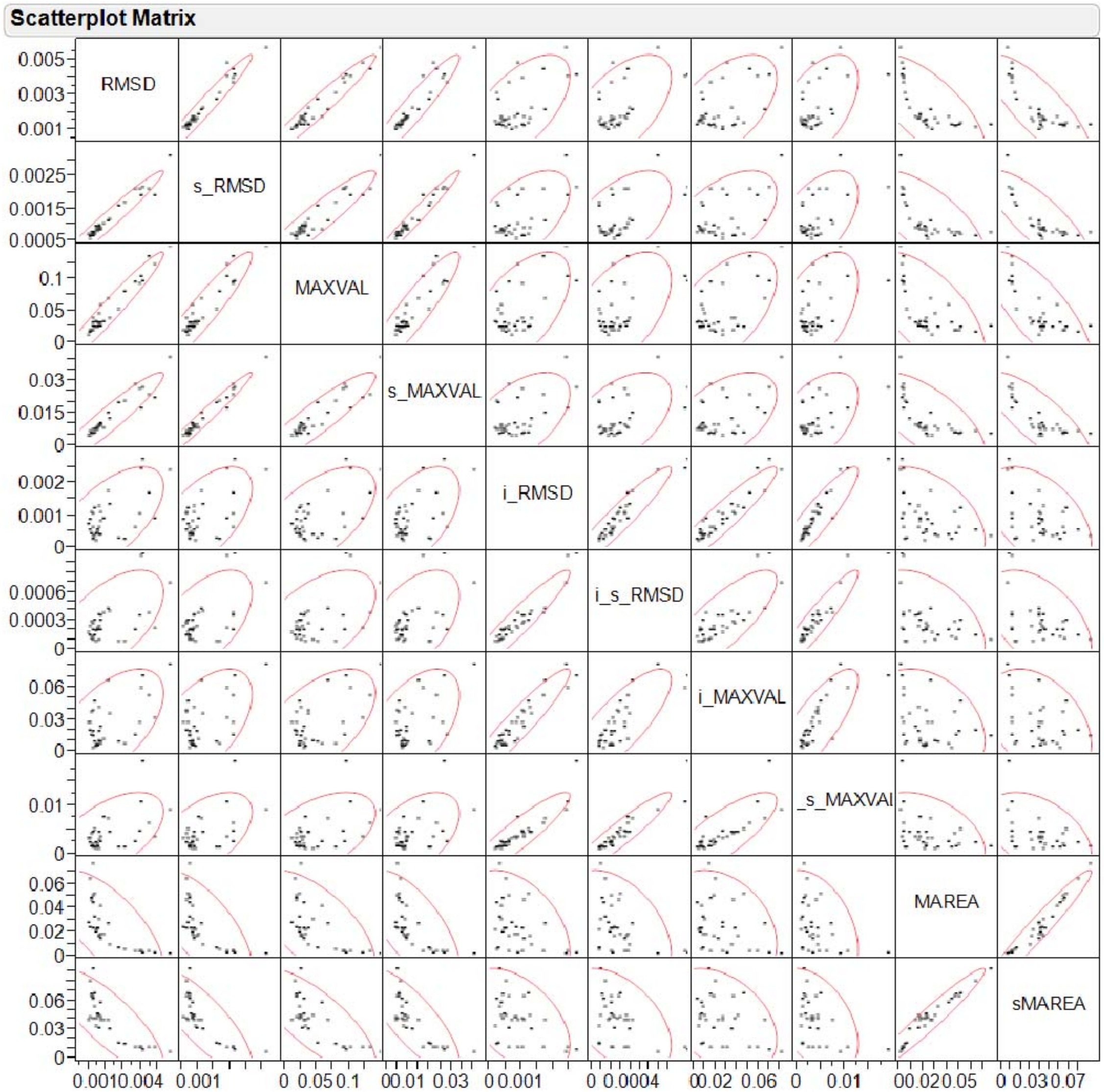

Table 5. Multivariate correlation scatterplot matrix of the output statistics for the 24-hour forecast from the significant factors experiment with 33 design points. This experiment was used to test the correlation between the output metrics. $RMSD$ and $iRMSD$ are the two dependent variables used in this thesis.

C. RESULTS

1. Computer Memory Requirement Experiment

The computer memory requirement experiment analyzes the three memory variables, $t\_mission$, $numtracks$, and npi, to pinpoint how these variables affect the

PPSN output. The underlying question that this experiment answers is whether the value given to these variables alters the forecast of relative pirate presence probability. The information gathered from this experiment is important for the operational testing being conducted on PPSN.[20]

a. Mission Length

The modelers are using a mission length of seven days (168 hours) in operational testing being conducted on PPSN. D. Laleijini[21] stated, "We want to keep the PAGs in the model for as long as we reasonably can based on processing time and memory requirements" (personal communication, February 7, 2011). The following $t\_mission$ analysis will show why special precautions should be taken when decreasing $t\_mission$ to meet operational objectives.

Figure 11 shows the results of varying $t\_mission$ values together with the best fit quadratic equation and reveals that $t\_mission$ does matter. What Figure 11 does not show is what specific values of $t\_mission$ should be used. It may appear that the knee of the curve lies between a $t\_mission$ value of 150 and 225 hours. This is an incorrect assumption. These results do not show that values of $t\_mission$ produce the best results. These results show that small values of $t\_mission$ will produce very different results than increased values. A $t\_mission$ value that reflects true PAG CONOPS should be used rather than a $t\_mission$ that gives PPSN a shorter run time.

The military operator conducting missions in the SBR requires an accurate portrayal of the relative pirate presence probability. Unlike PPS, PPSN provides better information that focuses the military's surface assets to a specific area within the SBR. Since the SBR covers millions of square miles using realistic CONOPS for simulated PAGs is important. Decreasing a PAG's mission length will produce very different PPSN output results.

---

[20] Effective March 1, 2011, the name of the next-generation Piracy Performance Surface model, PPSN, was changed to the Pirate Attack Risk Surface model, PARS.

[21] D. Lalejini is a civilian researcher for NRL-Stennis Space Center in Mississippi.

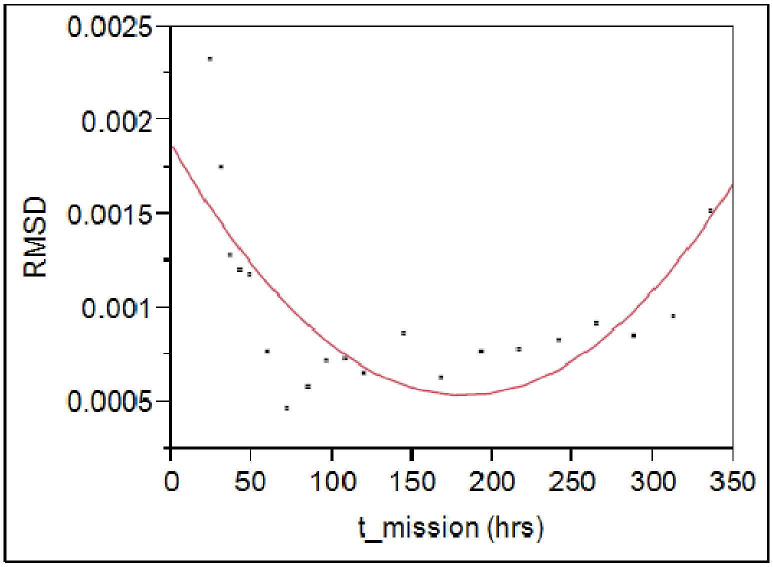

Figure 11. Effect of varying *t_mission* on *RMSD* for the 72-hour forecast probability field together with the best fit quadratic model. The model's R^2 is 0.57.

b. Number of Pirate Action Group Replications

The number of PAG replications, *numtracks*, is another variable that significantly impacts computer memory requirements. The variable *numtracks* determines how many times the PPSN model is replicated with the same input variables to produce the pirate probability fields.

Figure 12 shows the result of varying *numtracks*. A smaller value of *numtracks* produces a larger difference between each design point and the mean probability. Figure 12 shows that *RMSD* is influenced by *numtracks* over the entire experimental range from 128 to 2048.

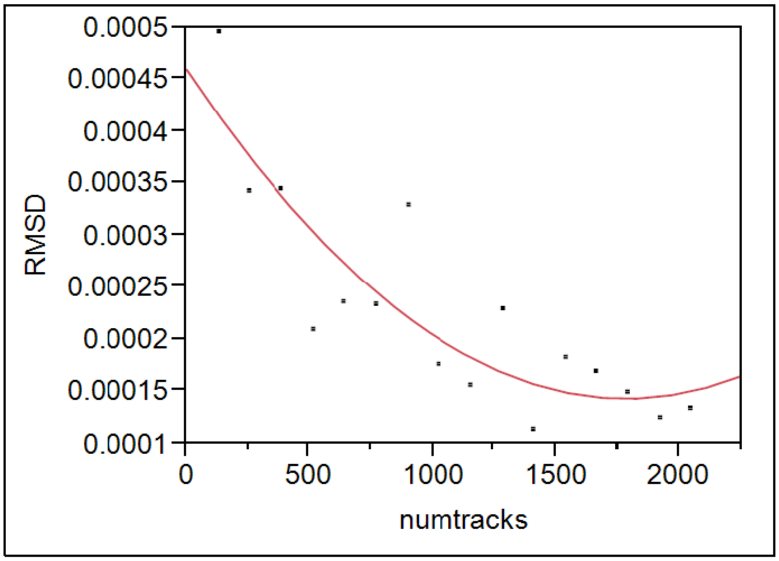

Figure 12. Effect of varying *numtracks* on *RMSD* for the 72-hour forecast probability field together with the best fit quadratic model. The model's R^2 is 0.757.

Initially, the operational testing being conducted on PPSN was using *numtracks* equal to 512. After a discussion with the developer and modelers, *numtracks* was increased to 1024 replications.

In closing, this variable should be hard-coded into the PPSN model rather than letting the operator set the value since it is influential but it is not impacted by changing METOC or INTEL.

c. *Number of Pirate Action Groups*

The current operational testing being conducted on PPSN uses a value of *npi* that is based on recent anti-shipping activity messages from the National Geospatial-Intelligence Agency (NGA) indicating when a PAG location has been reported (D. Lalejini, personal communication, February 7, 2011). The observed PAGs remain in the PPSN model for a maximum of six days. A typical value is $npi = 6$, which is lower than most values used in the significant factors experiment of this thesis. Those conducting the operational testing include only reported PAGs, but they are currently unable to acquire the most accurate and real-time intelligence on current PAG activity in the SBR and GOA. The true number of PAGs operating at one time is believed to be greater.

Figure 13 shows *npi* ranging between 8 and 48 PAGs. The author's operations research experience tour interviews reveal that limited knowledge is available on the exact number of PAGs operating within (on the high seas) the SBR and GOA and along the coastline at camp sites. For this reason, a wide range of scenarios for *npi* should be considered. Figure 13 shows that PPSN output is sensitive to the value of *npi* throughout the experimental range, but the effect of *npi* diminishes substantially around $npi = 30$. At this point, it should be noted that for all design points in this thesis experiment, the same four bases and four hunting waypoints are used for all values of *npi*, so differences across design points are due to the number of PAGs, not the number or locations of bases and hunting waypoints.

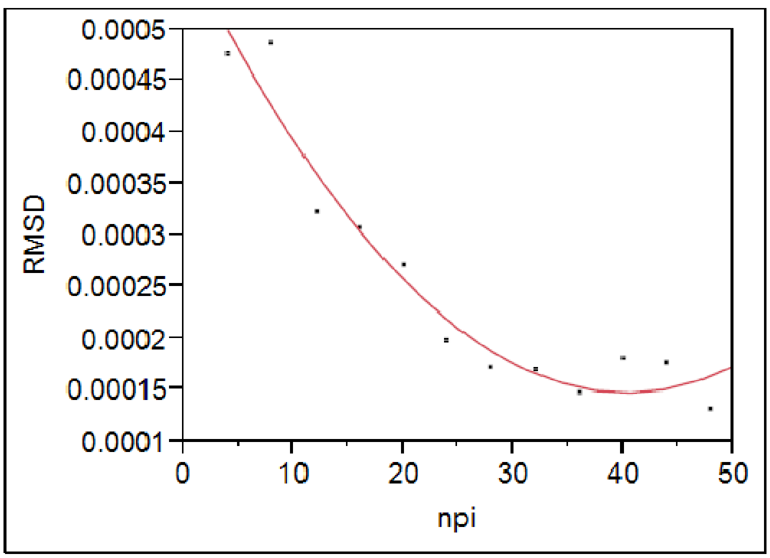

Figure 13. Effect of varying *npi* on *RMSD* for the 72-hour forecast probability field together with the best fit quadratic model. The model's R^2 is 0.944.

In conclusion, this variable should be controlled by the operator. Specific intelligence should be gathered as to provide realistic values for this variable.

2. Significant Factors Experiment

The significant factors experiment is analyzed using partition trees and linear regression. The ten independent variables this DOE uses were selected based on information collected during the author's operations research experience tour to the Combined Maritime Force's headquarters in Bahrain.

The DOE answers the following two questions:

1. Which PPSN input parameters are the most influential in determining the distribution of relative risk of pirate presence in the PPSN?

2. Which PPSN input parameters interact most strongly with METOC conditions and INTEL parameters?

Information gathered from this DOE will help the developer, modelers, and operators in focusing their efforts towards a more direct, systematic approach when using PPSN and gathering INTEL on PAG CONOPS.

a. *Significant Factors Using Partition Trees*

In a partition tree, the splits indicate the best predictors of the output metrics. The partition tree for $RMSD$ shows which METOC and INTEL variables have the greatest effect on the PPSN output, while the $iRMSD$ partition tree shows how variables interact with METOC changes across the forecast leads.

Figure 14 shows that the majority of the variation in $RMSD$ is explained by $search\_pattern$. Recall, the following $search\_pattern$ definitions:

- 0 (drift)
- 1 (random walk)
- 2 (zig-zag)
- 3 (transit)

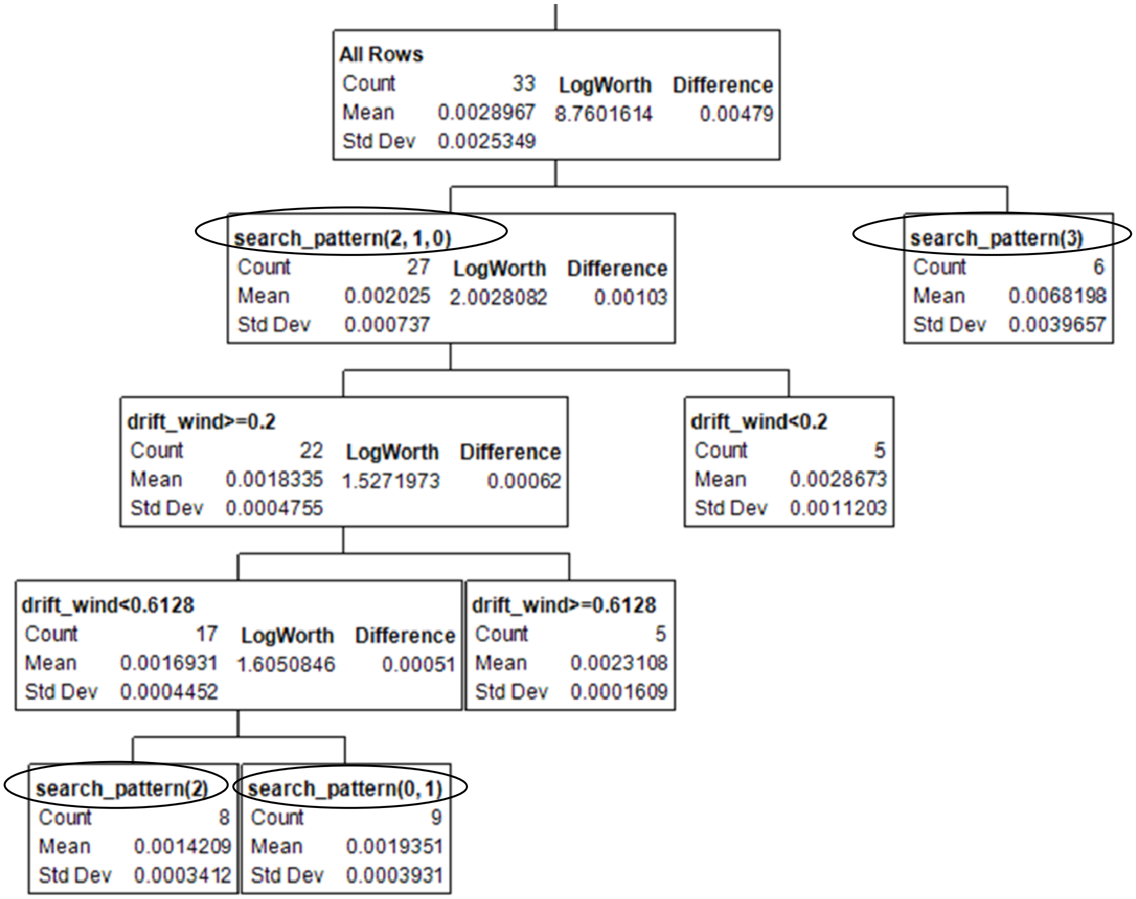

Figure 14. Partition tree displaying a R^2 value of 0.58. The dependent variable is $RMSD$ where $\tau = 72$ hours

One of the important results of the author's operations experience tour was the addition of $search\_pattern$ in the PPSN code. The developer initially only had the drifting search pattern; three additional search patterns were implemented. Figure 14 shows that $search\_pattern$ is highly significant in influencing the PPSN output. The INTEL community should concentrate their efforts on determining PAG search behavior. This knowledge will prove to be beneficial for the PPSN output.

The variability chart for $RMSD$ at 72 hours (Figure 15) shows $search\_pattern$ equal to 3 (transit only) and reflects the greatest difference in variability in the PPSN model. This means that a PAG modeled with a transit only searching pattern has the greatest difference in pirate probability fields compared to the mean pirate probabilities. As stated previously, specific INTEL should be gathered to determine if PAGs use a transit only searching pattern when looking for a target vessel.

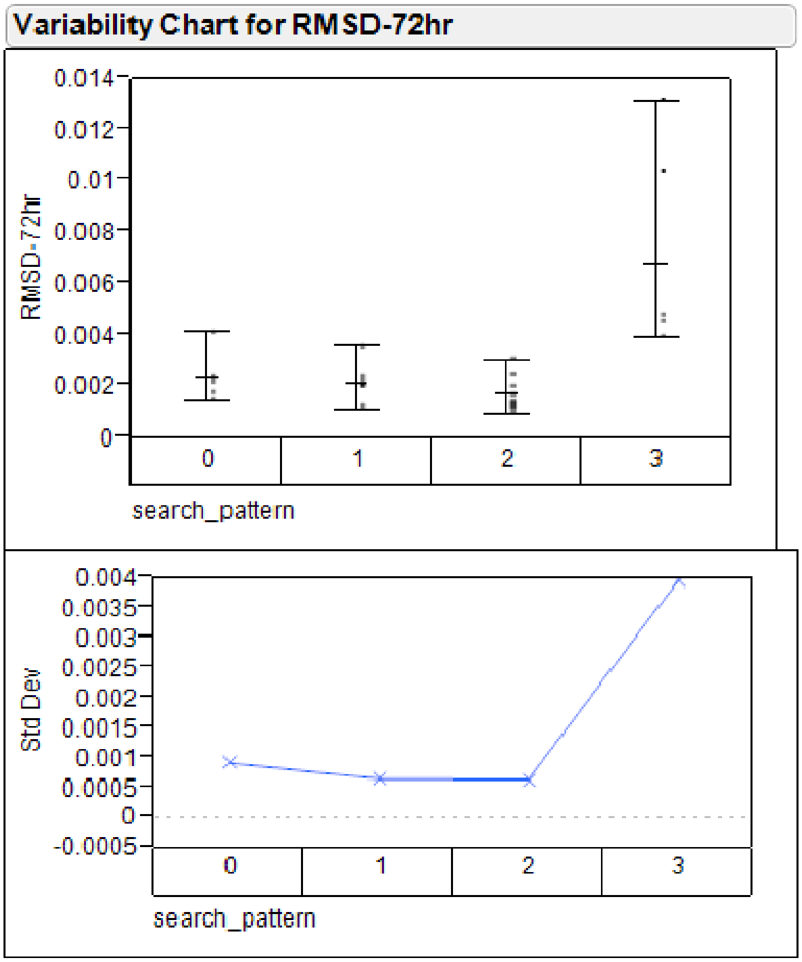

Figure 15. Variability chart for *RMSD* at 72 hours

The second partition occurs on $drift\_wind$ at 0.2. Recall that $drift\_wind$ is a continuous variable between 0 and 1 that represents the factor by which winds impact the PAGs' movement. Another way to look at this is that it is important to know how much of PAGs' movement is affected by surface winds in order to predict the relative distribution of pirate presence probability. The third partition in Figure 14 also occurs on $drift\_wind$. This time the split occurs on a factor of 0.6128. This result means that $drift\_wind$ above 0.2 and below 0.6128 leads to output similar to the mean pirate probability fields, but $drift\_wind$ below 0.2 or above 0.6128 produces results different from the mean pirate probability fields.

The inner metric, $iRMSD$, captures the sensitivity of the probability field within each design point to a change in the forecast leads. Figure 16 shows a partition tree using $iRMSD$ as the dependent variable. The first and second splits occur on $search\_pattern$ indicating that a search pattern of 3 (transit) or 0 (drift) makes the design point more sensitive to METOC. The third split occurs on $wind\_thresh$. Recall that $wind\_thresh$ is a continuous factor that represents the wind speed threshold below which PAGs can operate. If winds exceed a PAG's threshold, the PAG will either return to its base or remain at its base if it has not left.

INTEL should be gathered for this specific variable depending on the change in the METOC across each season. Since this variable describes much of the variability in $RMSD$, associating a realistic value is important. A recommendation is to have the modelers at ONI input the wind threshold and standard deviation.

The final split occurs on npi, the number of PAGs simulated in PPSN. As described previously in Section C.1 of this chapter, better intelligence should be gathered on the value given to this variable.

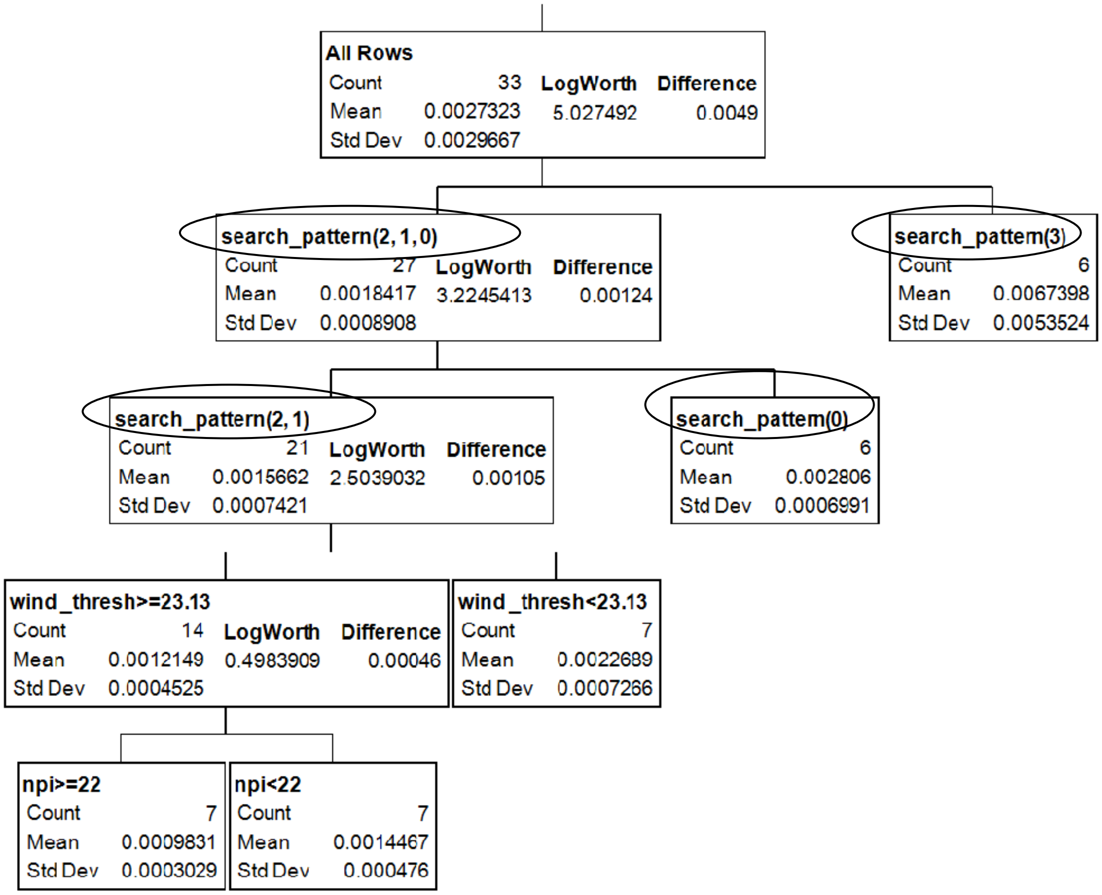

Figure 16. Partition tree displaying a R^2 value of 0.47. The dependent variable is $iRMSD$.

b. Significant Factors Using Linear Regression

Linear regression is the second way this experiment's results are analyzed. This thesis uses linear and quadratic terms, and first-order interaction terms as shown in Chapter VI, Section A.2 in the linear regression equation.

(1) *RMSD* as a Measure of Output. The linear regression model's summary of fit (Figure 17) shows that the model generated by the stepwise regression has a R^2 value of 98.4 percent. This R^2 is nearly 1, meaning that most of the variation in the model is explained by the regression equation.

Summary of Fit

RSquare	0.983951
RSquare Adj	0.97297
Root Mean Square Error	0.000417
Mean of Response	0.002897
Observations (or Sum Wgts)	33

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	13	0.00020232	0.000016	89.6068
Error	19	0.00000330	1.737e-7	**Prob > F**
C. Total	32	0.00020562		<.0001*

Figure 17. Summary of fit and analysis of variance for the linear regression analysis for $RMSD$.

Figure 18 shows that seven of the ten independent variables modeled in this DOE are significant in determining $RMSD$ for a forecast lead of 72 hours. Notice that unlike the partition tree, $drift\_wind$ is not included in the linear regression model. This result is a product of the partition tree recursively splitting on homogeneous groups while the linear model uses a regression equation.

Also, take note of the interaction between $search\_pattern$ and $iweather$. Recall, $iweather$ is the probability that PAGs have METOC knowledge prior to leaving on a mission. This result is interesting because PAGs are given a specific $search\_pattern$ and $iweather$ probability before the simulation spin-up. Both of these variables are highly influential. Therefore, operators should focus their efforts on getting valid INTEL about these two variables. A PAG having knowledge of METOC is going to mitigate the effect of the PAG's search pattern on the forecast of relative pirate presence probability.

In Figure 18, the two terms with quadratic effects are $t\_mission$ and $iweather$. These two squared terms show that these two variables have a nonlinear effect. The variable $iweather$ should be estimated based on intelligence gathered of the sophistication at each camp site. This variable does interact with $search\_pattern$, the variable that was shown in the partition tree to describe most of the variability in the model.

Another interesting aspect of Figure 18 is that the three computer memory requirement variables discussed earlier in this chapter are significant. As discussed previously, care must be taken when selecting values for these three variables as they are highly influential.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
(iweather-0.50061)*(search_pattern{0&1&2-3}-0.63636)	-0.007244	0.000426	-17.01	<.0001*
search_pattern{0&1&2-3}	-0.002174	0.000137	-15.83	<.0001*
iweather	0.0023018	0.000253	9.10	<.0001*
(wind _thresh-25.0012)*(search_pattern{0&1&2-3}-0.63636)	-0.000463	5.612e-5	-8.24	<.0001*
wind _thresh	0.0001575	2.786e-5	5.65	<.0001*
(search_pattern{0&1&2-3}-0.63636)*(numtracks-345.424)	-3.728e-6	6.653e-7	-5.60	<.0001*
(t_mission-139.697)*(t_mission-139.697)	3.5577e-7	7.052e-8	5.05	<.0001*
t_mission	-0.00001	2.183e-6	-4.57	0.0002*
(skiff_speed-20.0012)*(wind _thresh-25.0012)	-9.844e-6	2.958e-6	-3.33	0.0035*
skiff_speed	-2.622e-5	8.848e-6	-2.96	0.0080*
npi	-3.658e-5	1.36e-5	-2.69	0.0145*
numtracks	-1.343e-6	5.031e-7	-2.67	0.0151*
(iweather-0.50061)*(iweather-0.50061)	0.002382	0.001055	2.26	0.0360*

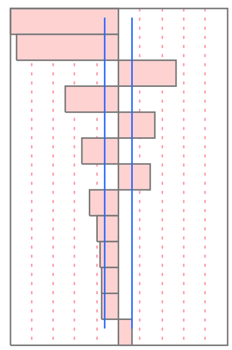

Figure 18. Model parameter estimates overview for $RMSD$ at 72 hours.

(2) $iRMSD$ as a Measure of Output. The output metric, $iRMSD$, captures the sensitivity of a given design point to METOC conditions, using the forecasts at different lead times as a proxy for changing METOC conditions. Figure 19 provides the sorted parameter estimates; this reveals the independent variables that are significant and influential.

One interaction term that has not been seen in any of the previous analyses is $skiff\_speed$ and $wind\_thresh$. Interactions among variables can often be difficult to interpret. When analyzing interactions, one area of focus is each variable's parameter or β. The β value allows the analyst to determine the effect of each variable and their interaction on the model.

For example, this linear model includes the following terms:

$$\beta_{wind\_thresh}x_{wind\_thresh} + \beta_{skiff\_speed}x_{skiff\_speed} + \beta_{wind\_thresh:skiff\_speed}x_{wind\_thresh}x_{skiff\_speed}$$

This equation implies that the effect of a change in $skiff\_speed$ is dependent on the value of $wind\_thresh$. Likewise, the effect of a change in $wind\_thresh$ is dependent on the value of $skiff\_speed$.

Figure 19 shows that $t\_mission$ appears as the only nonlinear term (other than interaction terms). As stated previously, the value of $t\_mission$ is important when modeling PAG CONOPS in the PPSN model.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
(iweather-0.50061)*(search_pattern{0&1&2-3}-0.63636)	-0.010013	0.000375	-26.71	<.0001*
iweather	0.0031655	0.00021	15.06	<.0001*
(t_mission-139.697)*(t_mission-139.697)	6.9561e-7	5.845e-8	11.90	<.0001*
search_pattern{0&1&2-3}	-0.001473	0.000138	-10.65	<.0001*
(wind_thresh-25.0012)*(search_pattern{0&1&2-3}-0.63636)	-0.00043	4.887e-5	-8.79	<.0001*
(skiff_speed-20.0012)*(wind_thresh-25.0012)	-0.000017	2.721e-6	-6.21	<.0001*
(search_pattern{0&1&2-3}-0.63636)*(npi-20.0606)	-8.066e-5	0.000018	-4.47	0.0004*
(t_mission-139.697)*(iweather-0.50061)	0.0000316	7.184e-6	4.40	0.0004*
(npi-20.0606)*(numtracks-345.424)	3.2898e-7	7.597e-8	4.33	0.0005*
wind_thresh	9.5219e-5	2.371e-5	4.02	0.0010*
skiff_speed	2.6788e-5	7.412e-6	3.61	0.0023*
npi	0.0000324	0.000011	2.94	0.0095*
(skiff_speed-20.0012)*(numtracks-345.424)	-1.559e-7	5.698e-8	-2.74	0.0147*
drift_wind	0.0007921	0.000339	2.34	0.0328*
t_mission	3.6294e-6	1.645e-6	2.21	0.0424*
numtracks	1.048e-6	4.84e-7	2.17	0.0458*

Figure 19. Significant factors sorted model parameter estimates. $R^2 = 0.99$.

3. Variability Experiment

The variability experiment is designed to see how the variability for a single design (design point 13) point replicated 23 times compares with the variability across design points in the significant factors experiment. Table 6 shows the ratio of the standard deviation of $RMSD$ for the variability experiment (σ_{VAR}) to the standard deviation of $RMSD$ for the significant factors experiment $(\sigma_{SIG\_FACTORS})$ for three forecast leads. For each forecast lead, the ratio is less than 16%. This metric provides evidence that the variation in the significant factors experiment is primarily due to the variable settings in the DOE, rather than the variation created within the PPSN simulation. So, for example, if one operator were to run the simulation with the same input variables and values more than once, the operator should achieve similar forecasts of relative pirate presence probability.

	$\frac{\sigma_{VAR}}{\sigma_{SIG\_FACTORS}}$
24 hour *RMSD*	0.157
48 hour *RMSD*	0.109
72 hour *RMSD*	0.070

Table 6. The ratio between the standard deviation of design point 13 from the significant factors experiment and the 33 design point significant factors experiment. The output measurement is *RMSD* for forecast leads of 24, 48, and 72 hours.

The results of three carefully designed simulation experiments identify the most important drivers of the PPSN output and their significance. The results of this thesis have also provided insights that have been and can be used to improve parameter selection for operational implementation of the PPSN model to allow quick turnaround of updates to the product in response to new intelligence, within memory constraints, and without sacrificing product quality.

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VII. CONCLUSION AND RECOMMENDATIONS

A. RESEARCH SUMMARY

This thesis research includes visits and interviews with users of PPS and other counter-piracy forces to understand the operators' needs and to gain intelligence on the most current pirate CONOPS within the SBR and GOA. This gathered intelligence led to recommended changes in the PPSN[22] code. In addition, using robust experimental designs, this research identifies the most significant INTEL factors driving the PPSN output. This gathered information is being used by the developer and modelers for the refining of these input variables and choosing the best functionality for enhancements to the PPSN model. This research also unveils input variables that are influential in the computing memory requirement and runtime. This information is being used to focus efforts on setting these variables at realistic levels, without sacrificing the model's efficiency and effectiveness, to allow for quick turnaround of updates to the PPSN model in response to gathered INTEL.

B. RESEARCH QUESTIONS

This thesis addresses the following questions:

1. What improvements can be made to the operational version of the PPSN model that will enhance the product's output?

2. Which PPSN input parameters can be adjusted to decrease computing memory requirements and run time?

3. Which PPSN input parameters interact most strongly with METOC conditions?

4. Which PPSN input parameters are the most influential in determining the distribution of relative risk of pirate presence in the PPSN?

[22] Effective March 1, 2011, the name of the next-generation Piracy Performance Surface model, PPSN, was changed to the Pirate Attack Risk Surface model, PARS.

To answer Questions 2, 3, and 4 above, a systematic approach, not a trial-by-error approach, to experimental designs is used. The DOE use a robust design and use a realistic model of PAG CONOPS that conveys operators' knowledge about current pirate behavior as seen in the SBR and GOA.

The memory requirement findings in this thesis identify the three key input parameters that impact computer memory requirement, which is also highly correlated with runtime. These variables are the PAG's mission length, the number of PAG replications in the simulation, and the number of PAGs. The analysis by the author concludes that the values inputted for each of these variables should be considered with the utmost care as their associated values greatly impact the forecast of relative pirate presence probability. For the PAG's mission length, the value associated with this input variable should be based on current PAG CONOPS and not based on computing constraints; for example, if a PAG has the ability to be at sea for up to four weeks, then the mission length should be set accordingly. Setting the input value to anything less will sacrifice validity in the PPSN output. It is recommended that the number of PAG replications be controlled by the modelers as this input variable is not indicative of gathered INTEL or METOC, but rather, specific to the PPSN code. The last variable, the number of PAGs, should be modeled based on INTEL, but in the event that insufficient INTEL is available then the operator should input postulated PAGs into locations of typically high pirate activity.

The search pattern the PAG uses when attempting to locate a target vessel of opportunity is the most significant factor in the PPSN model. This variable was introduced into the PPSN code because the author gained intelligence on this variable and informed the developer of its significance. Operators and military members combating piracy should attempt to acquire INTEL on the specific search pattern that PAGs use in the SBR and GOA.

Another significant variable that is driving the simulation is the factor by which the wind impacts the PAG's movement. The author recommends that this variable be controlled in the model by METOC and piracy subject matter experts in the SBR and GOA as they have a greater knowledge in this area. The value given to this factor does impact the output.

An interesting input variable in this thesis research is the probability that PAGs have METOC information prior to leaving their base location. In the linear regression model, this variable is significant and shows a strong interaction with the PAGs' search patterns and the PAGs' mission lengths when analyzing the sensitivity of the design points to a change in METOC across the forecast lead times. Proper INTEL should be gathered on the specific sophistication of PAG camp sites. The value given to this variable is highly influential and interacts with the most important variable, $search\_pattern$.

The results of this thesis did not come at an easy cost. The code was broken in different ways, resulting in modifications by the developer to make PPSN better and more robust, which delayed the completion of experiments for several months. The software required to run the PPSN model was not available on the Hamming shared cluster at the Naval Postgraduate School, thus, this thesis required the use of high performance computing power using the hawk from Wright-Patterson Air Force Base in Ohio. During the simulation runs of this thesis, some design points would require longer than 60 hours of computing time, and there were even times when this runtime was exceeded, which led to a failed design point run. Computer memory calculations show that design points that were typically below 3.5 GB ran to completion in 30 hours. To ensure that all the design points ran to completion, this thesis required a reduction in the PAG mission lengths and the number of PAG replications.

C. RECOMMENDATIONS

The following recommendations from this thesis research are as follows:

1. The PAGs’ mission lengths and the number of PAGs should be given realistic values despite their impact on computing memory requirements and runtime. Altering these values to unrealistically low values will have a detrimental impact on the model.

2. The PAGs' search patterns are highly influential and interact most strongly with METOC conditions, so INTEL should focus on accurately understanding PAGs' search strategies.

3. Better INTEL on the number of PAGs needs to be provided to the modelers. This information will result in improved forecasts of relative pirate presence probability.

D. THESIS IMPACT

The author's experience tour resulted in a complete overhaul of the PPSN code by the developer. The author's sponsor, Bill Lingsch, who is head of the INTEL Department at CNMOC, stated,

> Piracy in the Somalia over the last two years has dramatically increased impacting worldwide commercial shipping. As good practices are implemented by mariners to minimize the piracy threat the pirates tactics, techniques, and procedures (TTPs) are evolving. In the past there has been anecdotal evidence of how and when pirates would attack. The thesis work done under [the author] applies the much needed scientific rigor to understand what variables really matter in attempting to predict where and when pirates are most likely to attack. These results are huge as Navy moves forward in building a forecast model for areas of highest probability of attacks. Task Force Commanders can then use this product to determine where to allocate limited assets in a vast area to deter and/or interdict pirates. [The author's] thesis work provides the groundwork for both the operational product and where to focus follow on research. Her engagement throughout the operational and scientific community to address piracy has truly accelerated support to the operational Navy in addressing this growing problem. (personal communication, March 4, 2011)

The after action report provided by the author resulted in changes made to the existing PPSN model. While this research was being conducted the PPSN code was being reworked and altered. This created an intense working environment and a challenge to the forward progress necessary for this research.

After a year of dedicated hard work on helping to provide the military leaders and operators with a piracy tool, the author is receiving a master's degree from the Naval Postgraduate School in Operations Research a week after the PPSN model becomes operational. This is a landmark in the history of military analysis as it is the first operational prediction product that couple METOC and INTEL.

E. FUTURE RESEARCH

Since this thesis was the first systematic exploration of the PPSN simulation, an abundant amount of follow-on research exists. Some of the future research relating to piracy can extend to the following areas:

1. Differentiating between neutral vessels and PAGs.
2. Providing an operational risk management matrix for military assets.
3. Guidance for the proper allocation of resources (ships, air, unmanned systems) to cover a large body of water.
4. Extension to the issues surrounding drug trafficking on the high seas.
5. Using PPSN to reduce uncertainty about the location of camp sites once a vessel has been pirated.
6. Game theory approach to optimize the PAG's best course of action and responses.
7. Finding the means to validate the model against historical data.

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APPENDIX A. AUTHOR'S OR EXPERIENCE TOUR

The Naval Postgraduate School operations research experience tour occurs during the last six weeks of the 5th quarter. During this time, the operations research student takes time out of the rigors of the previous four quarters to gain information in the form of intelligence but more commonly, data, to be used for their thesis research. The author of this thesis was afforded a very unique experience tour. The author traveled to Stennis Space Center in Mississippi; Paris, France; Stuttgart, Germany; Bahrain and finished back in Monterey.

The first stop in the author's experience tour was to Stennis Space Center along the Mississippi Gulf Coast where the author briefed the sponsor, the Naval Meteorology and Oceanography Command. During this time, the author was provided invaluable information on the PPS model and its background.

Paris, France, was the next stop in the author's experience tour. The author presented and participated in the NATO Modeling and Simulation Group (MSG-088) conference. The lead U.S. Chairman for this group is Dr. Gary Horne[23], Naval Postgraduate School Operations Research professor. Dr. G. Horne stated,

> The context of the Task Group is to work on NATO related issues. The Task Group will look to use Data Farming in the 6 realms: High Performance Computing, Visualization of simulation data output, Rapid prototyping of scenarios, Design of experiments, Collaborative processes, and Model Development. Each of the members that have participated in the MSG will be a subgroup to help solve the designated problem. (personal communication, May 26, 2010)

At the MSG-088 conference, the author did not gather information on piracy, but was able to gain information on different techniques used by other countries to solve sophisticated problems.

The third stop in the author's operations research experience tour was to the United States African Command headquarters in Stuttgart, Germany. This visit was vital

[23] Dr. G. Horne is also a professor in the Operations Research Department at the Naval Postgraduate School in Monterey, CA.

for the sharing of information on the current PPS model and the future PPSN model, along with describing how the author's thesis research would impact and enhance the development of the PPSN model. At the time of the author's experience tour, AFRICOM had little to no partnership with Naval Postgraduate School. As a result of the author's experience tour, a new relationship was formed between this command and the Naval Postgraduate School, specifically with the Operations Research department.

After the author's presentation, Lieutenant Commander Netherlands Navy (OF 3) J. Bertelink[24] provided positive feedback and recognized the possible benefits of using the PPSN model for anti-piracy operations conducted by the Netherlands Navy. Lieutenant Commander Bertelink (personal communication, September 7, 2010) stated,

> One of my duties is to organize and (if possible) improve the METOC support to the NLD navy units. As you probably know the NLD navy plays an active roll (siz) in the NATO Operation Ocean Shield and the EU Operation Atalanta, both anti piracy operations in the Somalia basin. Therefore your presentation about the PPS-next model looked very interesting to me and I would like to ask you some questions about it.

The final stop of the author's experience tour was to the Combined Maritime Forces (CMF) headquarters in Bahrain. The briefing room reserved for the author was filled with a multitude of high-ranking NATO and EU military members who were concerned with the increase in pirate activity within their area of concern, the SBR and GOA. They were familiar with the PPS model, but skeptical and yet intrigued by the PPSN model that would supersede PPS. The presentation was filled with questions that helped the author understand what tools the operators were requesting. During the remainder of the author's time with the CMF Assessment Team, the author was able to gain important intelligence on current military operations and pirate definitions, as well as CONOPS that occur within the SBR and GOA.

The author, now equipped with a wealth of knowledge from the previous stops of the experience tour, returned to the Naval Postgraduate School in Monterey for the final stop. The author briefed the findings of the experience tour to the developer, modelers,

[24] Lieutenant Commander Netherlands Navy J. Bertelink is head of the Royal Netherlands Navy Command, Hydrographic Office.

and sponsor, which led to the redevelopment of the PPSN model. This version of the PPSN model written in Python (x,y) will be the operational model used in combating pirate activity in the SBR and GOA.

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APPENDIX B. MEMORY REQUIREMENT DOE

Appendix B shows the variables values according to each design point and their respective base to waypoint mapping input values.

t_mission	varies	according to design point
npi	varies	according to design point
numtracks	varies	according to design point
nbase	4	See below
skiff_speed	12	See below
drift_curr	1	
drift_wind	0.3	
wind_thresh (mean)	13.0	See below
wave_thresh (mean)	4.8	
iweather (mean)	0.5	See below
search_pattern (categorical)	0,1,2,3	

Bases:	lon	lat	lon_size	lat_size	weight
	50.10528	6.316111	0.01	0.01	1
	46.92722	2.361111	0.01	0.01	1
	58.41361	4.258333	2	2	1
	46.29083	-5.00556	2	2	1

Waypoints	lon	lat	lon_size	lat_size	weight
	55.14861	2.415556	1	1	1
	43.40861	-2.53222	1	1	1
	58.41361	4.258333	2	2	1
	46.29083	-5.00556	2	2	1

Skiff Speed	mean
	10
	10
	12
	10

iweather	
	0
	1
	0
	1

METOC Thresholds	wind	wave
	15	4
	10	5
	12	6
	15	4

search_pattern	
	0
	1
	2
	3

DP	npi	numtracks	t_mission
1	4	128	36
2	4	256	36
3	4	384	36
4	4	512	36
5	4	640	36
6	4	768	36
7	4	896	36
8	4	1024	36
9	4	1152	36
10	4	1280	36
11	4	1408	36
12	4	1536	36
13	4	1664	36
14	4	1792	36
15	4	1920	36
16	4	2048	36
17	4	128	24
18	4	128	30
19	4	128	42
20	4	128	48
21	4	128	60
22	4	128	72
23	4	128	84
24	4	128	96
25	4	128	108
26	4	128	120
27	4	128	144
28	4	128	168
29	4	128	192
30	4	128	216
31	4	128	240
32	4	128	264
33	4	128	288
34	4	128	312
35	4	128	336
36	8	128	36
37	12	128	36
38	16	128	36
39	20	128	36
40	24	128	36
41	28	128	36
42	32	128	36
43	36	128	36
44	40	128	36
45	44	128	36
46	48	128	36

APPENDIX C. SIGNIFICANT FACTORS DOE

design point	t_mission	skiff speed	drift curr	drift wind	wind threshold	wave threshold	iweather	search pattern	npi	numtracks
1	240	18.13	0.59	0.48	26.25	7.13	0.47	3	24	634
2	224	8.75	0.69	0.55	21.88	7.5	0.31	3	19	859
3	219	32.19	0.58	0.46	25.94	7.31	0.03	1	29	438
4	167	35.00	0.70	0.56	21.56	7.88	0.06	1	12	297
5	230	19.06	0.61	0.49	27.19	5.44	0.56	0	13	719
6	235	14.38	0.64	0.51	22.19	3.94	0.88	0	21	775
7	188	34.06	0.63	0.50	26.56	5.25	0.91	3	10	353
8	161	33.13	0.67	0.54	22.5	4.31	1	2	29	269
9	182	11.56	0.77	0.61	23.13	3	0.19	2	22	156
10	198	13.44	0.84	0.68	25.31	3.56	0.38	3	14	128
11	193	27.50	0.98	0.79	20.63	3.75	0.16	1	23	691
12	203	24.69	0.97	0.78	29.69	5.81	0.41	1	13	606
13	172	10.63	0.78	0.62	21.25	8.81	0.78	1	16	100
14	214	16.25	0.94	0.75	25.63	8.63	0.72	1	26	213
15	177	30.31	0.95	0.76	20	6.94	0.75	2	17	916
16	209	22.81	1.00	0.80	29.06	6.38	0.66	2	25	578
17	156	20.00	0.75	0.60	25	6	0.5	2	20	550
18	72	21.88	0.91	0.72	23.75	4.88	0.53	0	16	466
19	88	31.25	0.81	0.65	28.13	4.5	0.69	0	21	241
20	93	7.81	0.92	0.74	24.06	4.69	0.97	2	11	663
21	146	5.00	0.80	0.64	28.44	4.13	0.94	2	28	803
22	83	20.94	0.89	0.71	22.81	6.56	0.44	3	28	381
23	77	25.63	0.86	0.69	27.81	8.06	0.13	3	19	325
24	125	5.94	0.88	0.70	23.44	6.75	0.09	0	30	747
25	151	6.88	0.83	0.66	27.5	7.69	0	1	11	831
26	130	28.44	0.73	0.59	26.88	9	0.81	1	18	944
27	114	26.56	0.66	0.52	24.69	8.44	0.63	0	26	972
28	119	12.50	0.52	0.41	29.38	8.25	0.84	2	18	409
29	109	15.31	0.53	0.42	20.31	6.19	0.59	2	27	494
30	140	29.38	0.72	0.58	28.75	3.19	0.22	2	24	1000
31	98	23.75	0.56	0.45	24.38	3.38	0.28	2	14	888
32	135	9.69	0.55	0.44	30	5.06	0.25	1	23	184
33	104	17.19	0.50	0.40	20.94	5.63	0.34	1	15	522

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