Design and Experimental Evaluation of an Autonomous Surface Craft to support AUV operations

by

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Abstract

In recent years, there has been a large increase in the use of autonomous underwater vehicles (AUV) for numerous military, commercial, and scientific missions. These include mapping, oceanographic data collection, and search and recovery. The list of the key technologies for AUV research includes communications, power, navigation, design, vehicle tracking and sensor fusion. Despite rapid progress in some of these areas, a number of barriers exists. This thesis offers a novel approach to address these issues by utilizing an Autonomous Surface Craft (ASC) with a wetbay from which to launch an AUV, including a launch capability. This paper also discusses the fusion of sensors required by these two vehicles, including computer resources, sonar images, and power. A new method is described by which an ASC can be tracked through the use of a towed underwater modem increasing the communication range over two kilometers. This thesis describes how an ASC tracks an AUV by configuring two modems together in a short baseline acoustic array. Results of this tracking show less than four meters of error under difficult real-world test conditions. Discussed are the advantages of transmitting the information obtained in the AUV modem transmission via surface communications. A tracking ASC maintaining close proximity to the AUV allows a larger bandwidth of underwater communication, increasing the flow of information. Expanded flow enables multiple assets to communicate over long-ranges. The impact of these contributions will expand the capabilities of autonomous vehicles.

Thesis Supervisor: John Leonard

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Andrew Patrikalakis, was my lab partner and without him testing would not have been possible. He devoted many late nights designing and assembling complex and unique vehicle components. We had many impromptu think tank meetings. He was a great sounding board for me to throw different ideas. His knowledge base and views often differed significantly from mine thus sowing seeds for unique results. One of these results was the use of an array to track vehicles.

Joe Curcio's knowledge and hardware ability were essential during this project. His knowledge helped fabricate and guide me through the development of a new vehicle. His natural ability to adapt and overcome is his strong suit and was used many times during missions to allow testing to continue. His thesis editing effort to help organize my thoughts was invaluable. Joe was able to keep me calm and make me laugh through his never-ending stories of "the trials and tribulations of Joe".

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Table of Contents

List of Figures

List of Equations

1 Introduction

The Office of Naval Research (ONR) has defined five major priorities encompassing the design criteria before autonomous vehicles can be incorporated into the naval fleet for wide use [1, 2]. An autonomous platform must be able to have an autonomous dynamic control during missions, perform 1) reconnaissance, 2) surveillance, 3) target acquisition/ designation, 4) beach survey and 5) battle damage assessment. An Autonomous Surface Craft (ASC) with its complement of sensors, can fulfill a number of these roles due to its diversity and adaptability to the environmental requirements. Additional priorities set forth are a robust package that can operate in multiple environments and conditions. Fusion of the ASC's and Autonomous Underwater Vehicle's (AUV) capabilities allows for a broad range of underwater environments to be reconnoitered. Underwater reconnaissance and surveillance missions are primarily preformed through sonar image processing. The result of these processes gives the manned operator a map specifying the locations of objects of interest in the surveyed area. Surface surveillance can be performed with off-the-shelf visual augmentation packages. Cameras would record beach and hinterland information that can be broadcast real-time through RF communications. The communication package can be a low-power commercial 802.11 Wi-Fi communication link or a more robust low-probability-intercept/low-probability of detections (LPI/LPD) military system. The ability to feed this all through a robust mission-planning package of following waypoints and performing tasks is essential and greatly simplifies the efforts required to operate the system [20].

Technology has necessitated a shortened reaction time for a country if it is to be effective in engaging its military power in defense against an invasion. Deploying ground forces effectively and safely is of great concern. Designing equipment to counter enemy defensive weapons prior to the deployment of ground forces, specifically for an amphibious assault, provides the motivation for this thesis. Hopefully, these efforts will reduce the causalities of our countrymen in future littoral conflicts.

1.1 Application

The idea of using autonomous vehicles to search a given area and to return disclosed information has existed for many years. The United States Department of Defense has many remotely operated vehicles. Landbased remotely operated vehicles, such as Talon, can be manually driven to objects of interest and, by using visual camera technology, can record images allowing an operator to classify objects of interest after the mission [3]. Many airborne assets exist, such as the Predator and Global Hawk, which have extensive sensor payload for tracking and prosecuting targets [3]. They also have an ordnance payload and can operate as the sole source for an offensive engagement. The Navy uses the Super Scorpio for salvage operations in deep water, and recently has used a Semi-Autonomous Hydrographic Reconnaissance Vehicle (SAHRV or the civilian version REMUS) for clearance operations in Al-Basrah Port, Iraq [11]. These are all important advancements toward fully autonomous operations but they are labor intensive. They require an extensive infrastructure to operate. In contrast, operation of an autonomous vehicle reduces the manpower needed to prosecute the same mission by requiring minimal configuration and is designed for no user interaction once initiated. As robots evolve into autonomous vehicles, their abilities to calculate the correct path must expand exponentially. They are limited by the ability of the programmer to ensure that all environments they can enter are accounted for in the operating software. This configuration for environmental information would be uploaded as to what course to follow to fulfill the mission requirements. The autonomous vehicle then determines the correct path to complete the mission.

1.2 Problem

The Autonomous Operations for Future Naval Capabilities (AOFNC), a recent research program of the Office of Naval Research (ONR), addresses autonomous operation gaps in the ability of the United States Navy Forces to conduct successful autonomous missions. The vision of AOFNC is to dramatically increase the autonomy, performance, and affordability of the autonomous vehicle systems. To meet this charter, four major vehicle categorizes were determined to cover all current autonomous realms: Unmanned Aerial Vehicles (UAV), UAV Propulsion, Unmanned Undersea Vehicle (UUV/AUV) Technology and Unmanned Ground Vehicle (UGV) Technology [2]. The AOFNC-designed products, both hardware and software, are to be capable of transition into the fleet operation forces with minimal effort.

Of these categories, the AUV technology project addresses the capability to perform missions with AUV assets allowing United States Navy Forces to expand their sphere of influence and to mitigate the inherent risk of operating in littoral waters. The Navy AUV's Master Plan [1] identifies seven key missions that can be fulfilled by autonomous programs: 1) Intelligence/Surveillance/Reconnaissance (ISR), 2) mine countermeasures (MCM), 3) oceanography, 4) communications/navigation aid (C/NA), 5) anti-submarine warfare, 6) weapon platform engagement, and 7) logistics supply. This paper will discuss four of these missions: ISR, MCM, oceanography, and C/NA. The goal of ISR is to provide the ability to rapidly survey selected areas using networks of small AUV's, performing functions such as mine hunting/neutralization, underwater object location and recovery, and hydrographic/bathymetric surveys [2]. Locating mines in littoral waters is the primary purpose of sonar equipment. Oceanography, such as depth, temperature, wave height and duration information is also recorded. The surface C/NA is to provide a communication/navigation relay for other underwater vehicles operating in the immediate area and is expected to serve as a gateway for an autonomous underwater communication network. This is also the root of the research performed in this thesis, with respect to localization of an underwater vehicle from a single surface asset. Sensor fusion between two waterborne autonomous vehicles to increase the capability of both is advantageous. This combination is force multiplier, where the abilities of each vehicle are far surpassed by those of the union of both vehicles operating towards a common goal.

1.3 Example Mission

An example of how an ASC used during a tactical situation is; imagine a U.S. ground assault force aboard ships located over the horizon, off the coast of a terrorist-supporting country. To initiate a predawn amphibious assault, the ships launch a group of autonomous surface vehicles at dusk. Each of the ASC's travels at five knots to a unique target, determined from a-priori reconnaissance maps. As ASC's navigate toward shore, they employ on a small motor with an electrical alternator to keep their batteries fully charged. Prior this infiltration, the motor is shutdown to minimized noise and batteries maintain power to operate the ASC's and AUV's systems. The ASC sends a real-time surface Forward-Looking Infrared (FLIR) imaging system, along with wave period and wave height information from gyro rate calculations to the command and control ship through a SATCOM/Iridium communication package. This combined with the forward-looking sonar image from the AUV payload forms a substantial situational awareness for those in control and can assist in their formulation of a plan of attack for the follow-on beach assault.

The ASC utilizes the sonar of the AUV mounted in its wetbay to determine its position in reference to an uploaded reconnaissance map of the underwater domain. From this result, the ASC can adaptively vectoring itself to its pre-designated target. It begins to flood ballast tanks decreasing its surface signature. As a specific target comes within range, the AUV receives a final surface navigation fix and launches from the ASC. The un-tethered AUV dives on a target intercept course, followed by the ASC navigating a shadow course. A communication conduit is maintained between the two autonomous vehicles using underwater acoustic communications (ACOMMS). As the AUV makes its way toward the target, it transmits a unique ACOMMS signal, which is received by the ASC along an acoustic array. The ASC calculates the position of the AUV from the ACOMMS signal. If the AUV course exceeds an error corridor toward the target, the ASC will transmit an error correction for the AUV to amend any underwater navigation error, thus enabling the AUV to properly proceeed toward the target. Once the AUV sonar acquires the target, its terminal guidance code is enabled.

With the AUV at the target, it begins a detailed transmission of the ten most recent sonar images to the ASC. The ASC uses this transmission to accurately determine the AUV's final position. The ASC transmits to the command and control, the location and final images used for target acquisition, and classification. The command and control can then identify, and verify the target as necessary . If the command and control deems a change of target is required, the new mission would be relayed through the ASC to the AUV. When the AUV mission is complete and remains with the target, the ASC returns over the horizon for reuse if required.

1.4 Layout

This thesis discusses the initial steps toward the realization of a new paradigm for an ASC and an AUV to interact cooperatively while performing a mapping and surveillance mission. The following chapters will define how four of the seven missions as outlined by ONR vision of the future for Naval work with AUVs. Intelligence/Surveillance/Reconnaissance (ISR) gathering is accomplished using low cost forward-looking sonar underwater. Through sonar image detections, objects that meet predefined MCM criteria can be located. Oceanography characteristics can be determined from both autonomous platforms using sensors to determine wave height, wave period, water temperature, and other data. The Communication/ Navigation Aid (C/NA) is where the true fusion of sensors takes place. It is important for the two vehicles not only for maintaining an accurate position of the AUV but for also sending terminal AUV guidance and returning final images to planners for detailed real-time analysis for future missions.

The structure of the remainder of the thesis is as follows:

Chapter Two discusses the history of amphibious warfare as it pertains to methods used for clearing a safe passage which will allow troops to penetrate from the ocean onto the shore. Discussed are current techniques used by the US military to clear a beach of underwater threats. The capabilities of past and current vehicles are discussed: can they operate as efficiently? In addition, this chapter discusses the manned assets which are available today; and the Navy's is interest in replacing them with autonomous vehicles to fulfill the requirements.

Chapter Three presents a novel approach for docking an AUV into an ASC with a launch capability. We present the design of the RUSSO (Remote Underwater Surveillance and Support) ASC, a robotic surface craft designed for autonomous deployment and operation of AUVs. The design has been instantiated as an extension of the Scout ASC developed by Curcio *et al.* at MIT [7], [12]. We use the Nekton Ranger as the target host AUV[6]. This chapter also reviews the hardware design and provides details of key subsystems, including autonomous launch, modular bay, and hull modifications.

Chapter Four focuses on the sensor fusion of the design, interaction of sensors including the power and communication between vehicles systems. In addition, this chapter describes extensive field trials using a Scout ASC equipped with a Blazed Array Forward Looking Sonar (FLS) for mapping experiments.

Chapter Five addresses the cooperative ASC/AUV navigation problem, presenting a new approach to tracking an AUV from the surface, using standard Woods Hole Oceanographic Institute (WHOI) Micro Modems in a short baseline configuration [8]. Extensive experimental results are reported. (This algorithm has been implemented in close collaboration with MIT EECS Ph.D. candidate Jacques Leedekerken.)

Finally, Chapter Six summarizes the contributions of this thesis and suggest directions for future research. Exciting possibilities for further extending the RUSSO/Scout ASC concept including surface concealment, satellite communications, launch of a swarm of sensors, and creation of long duration mobile gateway.

2 History

The Office of Naval Research has an interest in the welfare and safety of sailors manning the front lines. It is commissioned with advancing the technologies available for deployment into any theater of operation. Today's escalation of terrorist activities poses great challenges to the men tasked with protecting American values. The capabilities of these foes and the countries which harbor them bring a significant military threat to the Unites States. This enemy has a history of unprovoked violence towards others and is currently challenging all of the free countries of the world. As a result, the United States has been constructing equipment to decrease the risk to the warfighters. The United States military forces have been deployed into foreign countries in an effort to reduce the threat these countries impose to the free world. Gaining access to these countries is the first step. Very few countries are landlocked. However, many defiant countries have allies or neutral neighboring countries. Neighboring countries in some cases play a neutral role fear of retaliation and concern for safety of their citizens. Their neutral role typically precludes the use of their land as a passageway by international forces. If a defiant country is surrounded by friendly or neutral countries but has seashore access, two options exist for gaining entry: amphibious and or airborne assault.

2.1 Amphibious Assault's History

The root mission of sea warfare for naval forces is defined with a primary mission of transporting ground offensive forces into a position where they can project military power ashore and engage the enemy. In previous eras amphibious assaults stood as the preferred method to deploy troops onto foreign land. In modern times, this still remains true even though airborne assaults have gained popularity with the expansion of air power. In the past and present, the bulk of forces are landed from the sea. They allow for a large amount of warfare equipment to be brought ashore in a short period. Enemies familiar with amphibious warfare fortify beaches with defensive weapons: mines, barricades, impingements, and beach artillery emplacements are set to block any advances by foreign countries through their shores.

Historically, the first known amphibious assault was recorded in 490 BC during the Battle of Marathon, when the Persians attempted to conquer the Greeks. The vessels in the assault force numbered approximately 600 while the number of soldiers involved were 40,000 [3]. The losses sustained by these forces were high due to poor planning of the amphibious assault. Due to sea conditions encountered during the invasion, more then half of the troops never made it ashore. Rough seas forced the ships onto rocky shores destroying the ships and forcing the men into the hostile waters. When the remaining armada returned to sovereign soil, they had less then 200 ships surviving and only 30% of the men.

Amphibious assaults have been a part of American history. George Washington's crossing of the Delaware in 1776 won a decisive victory over the British at Trenton. This victory has been singled out as having reinvigorated the American Revolution spirit. History refers to this as the turning point in the revolution. In the Battle of Normandy, an estimated three million troops crossed the English Channel into occupied France. In fierce fighting, the allies broke through the German lines and began to win the war. The Battle of Normandy was the turning point in World War II. Naval power was also used extensively in other US conflicts such as Korea, Cuba, and Vietnam.

2.2 Manned Clearance History

Manned underwater obstacle clearance has occurred throughout history. During the Battle of Normandy, United States Navy swimmers were called on to conduct pre-assault hydrographic reconnaissance of the objective beach areas. Swimmers were launched from submarines and ships, under the cover of night. They swam ashore to locate and map obstacles; in addition, they mapped the beach gradient from twenty feet deep to the shore. Once the data were composed, follow-on clearance missions were sent before and during the assault, sometimes in broad daylight, to remove the mapped obstacles from the landing area. The swimmers cleared a number of enemy beach emplacements prior the arrival of assault forces and continued to clear obstacles throughout the battle thus increasing the landing beach area. Their only protection from enemy fire was naval gunfire support which was not accurate enough for defeating targets within rifle range. The result was personal losses of over 70% on some beaches but the number lives the surveying forces saved was substantial. The overall job of these men has remained the same over the years; they had been called Naval Combat Demolition Units (WWII), Scouts and Raiders (Korea), and Underwater Demolition Teams (Vietnam). Today they are called Navy Sea Air and Land Commandos (SEALs), a small tight group of men ready to take war to the enemy, to be employed when diplomatic relations fail. In addition to these forces, Navy Explosive Ordnance Demolition (EOD) has also been used to ensure beaches are clear of enemy threats.

Countries know being invaded from the sea is a high probability. In an attempt to discourage amphibious assaults, they fortify their defenses by placing obstacles in the littoral waters. Wide varieties of fortification obstacles have been used, and have been made of metal, concrete, wood, and composites. Some are very elaborate setups of steel structures with buttress and inverted arches to impale approaching landing craft. More simple designs such as a wooden pole angled toward the beach approach are effective as in Figure 2.1.

Figure 2.1: A simple beach obstacle- landmine on a tree stump

Some are made exclusively to house explosives (mines); they have a variety of different detonation methods. Three major types of mines can be deployed: bottom, water column, and free-floating. Bottom and water column mines are typically placed in close proximity to the beach, while free-floating mines are unrestrained and thus can be encountered in seemingly countless places. The capability to remove these obstacles with minimum risk to troops is of great interest.

2.3 Beach Survey

An up to date and accurate map is required to effectively prosecute any beach clearance mission. Beach defenses are typically a mixture of different types of obstacles; not all have explosives and not all are made of steel. Properly deployed defenses will defend a given beach independent of the current and tides.

Beach defenses are deployed usually in some arranged fashion. However, the exact location of an obstacle in the surf zone varies as the forces of the tides move them throughout the surf and shallow water. Sometimes the obstacle locations vary every time a tide occurs. As shown Figure 2.2, large surf dislocated these concrete-weighted steel structures onto a rock jetty.

Figure 2.2: Dislodged beach emplacements

The result is that a beach survey has a limited life to remain accurate; water conditions, such as extreme tides, currents, or storms, continue to modify the seafloor, particularly in the littoral waters. Obtaining an accurate map of a littorial area is often difficult to do; some areas have a twenty-foot vertical difference between low and high tide, which can cause the waters to recede a normal beach gradient by more then two miles, as shown in Figure 2.3.

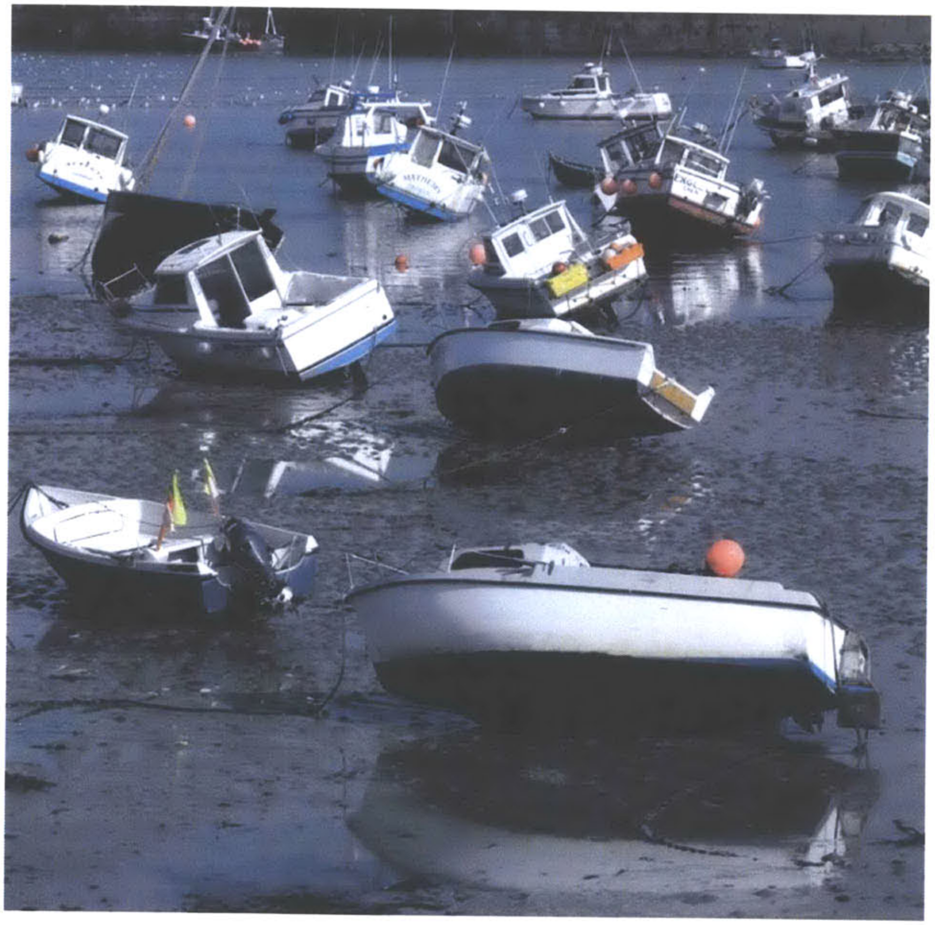

Figure 2.3: Large tidal zone

Performing a manned survey on this beach would be difficult to do, due to the shear size of the beach area. A prior survey of tides and current to ensure the validity of the proposed beach is necessary for a beach landing.

2.4 Manned Beach Clearance Techniques

This sub-section contains a detailed description of manned clearance operations; it is intended to give the reader a background of current capabilities and can be passed over at reader prerogative. The current techniques of all military manned clearance detachments are similar to one another and are described below. Significant detail is expounded here because it is important to understand what an autonomous vehicle (and every autonomous vehicle designed for Navy for use in littoral waters) is supposed to replace.

Swimmer Loadout

A swimmer loads out for a beach clearance mission with minimal gear. The reason is that loose gear slows forward progress. He has the water distance and surf to protect him from the enemy and conceal his movement. A swimmer will use a wetsuit to combat water temperatures and increase his duration; it is also good for protection against coral, rocks, barnacles and other sharp objects underwater. Other standard items include mask, knife, gloves, fins, and explosives to leave behind.

Over the Horizon Launch

The first step is getting to the beach. Before insertion of swimmers, a large Navy vessel will dispatch smaller vessels from over the horizon at an infiltration point. Small vessels including surface rubber boats and mini-submarines are used. Submarines such as the SEAL Delivery Vehicle (SDV) are launched from a variety of naval platforms. An SDV's can enable swimmers to travel long distances in shallow water while remaining undetected. Other times a small boat is launched underwater. A stowed rubber boat is worked free by swimmers on the deck of the submarine. The boat may have engines and other equipment lashed inside it ready for use once it reaches the surface and is inflated. A variety of insertion methods are shown in Figure 2.4. All swimmers are wearing the standard gear (note mask, knife, and fins). Some swimmers are also using an open circuit compressed air system; these are not used near the shore and will be left on the ship. Pulmonary air embolisms have occurred in divers when the large sea surf cycles over them while searching the bottom.

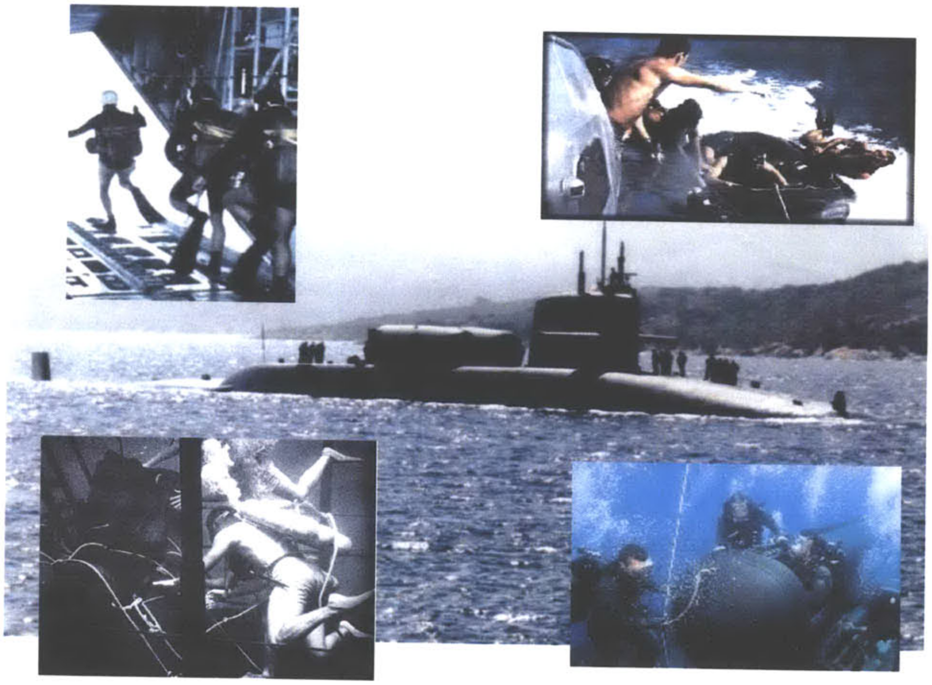

Figure 2.4: Variety of insertion methods

Transports

Some missions call for fast raids into small shallow harbors. Combat Rubber Raiding Craft (CRRC) are used as a high-speed motorized transport for OTH insertion of swimmers into a hostile beach area. These have maximum payload of six men at up to 20 knots, as shown in Figure 2.5.

Figure 2.5: Loaded Combat Rubber Raiding Craft

Special rubber kayak's have been used in the past and can be employed as a speedy human power shallow-draft transport. The two-man kayak can be carried and paddled easily for long distances in shallow water, as shown in Figure 2.6.

Figure 2.6: Navy SEAL's using a rubber kayak for insertion

Another manner in which to enter the water in a short period is a high-speed boat drop off, as shown in Figure 2.7. This allows multiple swimmers to arrive at a beach expeditiously.

Figure 2.7: Navy SEALS performing a high-speed boat cast

This allows a boat to decrease its chance of enemy contact by staying at speed. Men climb from the drop-off boat into the rubber raft towed alongside, ready to drop overboard on a given signal. They are dropped off about every fifty feet along a straight line a few hundred yards from shore. They will return to this line later to be picked up by the same boat. As fast as the two men in the rubber raft drop off, their places will be taken by the next pair to be "delivered." The first man is given a signal to drop and the rest follow as fast as possible.

Figure 2.8: Navy SEALS performing a high-speed boat cast

Figure 2.8 shows the actual dropping of swimmers to perform an initial inspection of a beach. The swimmer entering the water on the right is dressed for warm-water work.

Getting To Shore

Insertion methods vary and are dependent on the capabilities of the enemy. Under the cover of night, insertion methods include: small surface craft, high-speed drops from RHIBs, Zodiacs with small outboard motors, small inflatable boat under paddle power, kayaks, airdrops, and others. At two miles out from the shore, swimmers deploy to swim the remainder of the way. The speeds at which they can swim are directly dependent on the surface conditions. Sea State III and above greatly hamper forward progress. In all cases, the overall time personnel can be in the water is limited by the onset of hypothermia.

Beach Search

The area that can be surveyed in one night is greatly dependent of environmental factors. How much and how fast a beach can be surveyed is proportional to the number of swimmers, the range of visibility, the extent of illumination and sea conditions. A typical method of searching for underwater obstacles is called the "parallel beach survey" technique. Swimmers form a line parallel to the shore at an interval determined by sea conditions. The swimmers on each end of the line ensure the swimmer line is parallel to the shore. These two swimmers position themselves by using GPS and take bearings to known positions to triangulate a fix. Their task is to maintain a steady position for the rest of the swimmers to use as a reference. The remaining swimmers, using only visual clues space out evenly between the two ends. When the lead end swimmer is satisfied with the form and separation of the swimmer line, he signals for them to dive. The swimmers then submerge and visually search a predetermined area and note the depth. When a swimmer surfaces he records his findings along with the depth on waterproof paper. Then the swimmer line moves perpendicular to the shore and the swimmers dive again. This process is repeated until the desired beach has been searched.

Extraction

Once the swimmers' mission is completed they proceed for recovery. For a high-speed pick-up, the swimmers swim to the predetermined recovery area. They form a straight line horizontal to the beach, with some separation. A small rubber boat is towed along side of a high-speed boat. In the small rubber boat, an individual holds a large rubber loop over the side. This loop is used to snare and snatch the swimmer from the water. As a boat approaches, the swimmer extends his arm to be hooked and is snagged by the loop, as shown in Figure 2.9. The velocity of the boat pulls the swimmer from the water and literally flips him into the boat. As he quickly moves out of the way, another swimmer is snagged until all swimmers are recovered. Speed of the pick-up is important as it helps flip the swimmer into the boat.

Figure 2.9: Navy SEAL performing a high-speed pick-up

The most important aspect of the pick-up falls directly on the shoulders of the high-speed boat's coxswain. A pick-up is successful only if all swimmers are snared on the first pass. If the pick-up craft is detected, it is often moving fast enough that most enemies fail to realize that a swimmer pick-up is taking place. If a swimmer is missed, the boat has to make a second run and that increases the chance of detection and as well as being engaged by weapons. Therefore, it is the responsibility of the boat coxswain to maneuver the boat down the pick-up line, close enough to the swimmers so they can be snared, and at a speed that will allow each swimmer to be pulled into the small boat before the boat reaches the next swimmer. Timing, speed, and boat location are critical to the success of this operation. This method greatly reduces overall recovery time and any danger to the boat from enemy fire. However, many swimmers returned from these recoveries with black and blue bruises covering the entire inside of the arm, caused by the impact of the pick-up sling.

2.5 Beach Clearance

When a beach has been designated for use in an amphibious assault, missions are performed to remove any objects that were found during the beach survey. On this mission, a swimmer line is formed again, with each swimmer carrying a bag of explosives. The end of the line swimmers attempt to align themselves in the same position as the previous survey, and an underwater search is performed again. Once a target of interest has been located such as this steel hedgehog in the shallow surf zone, the swimmer attaches the package of explosives to it.

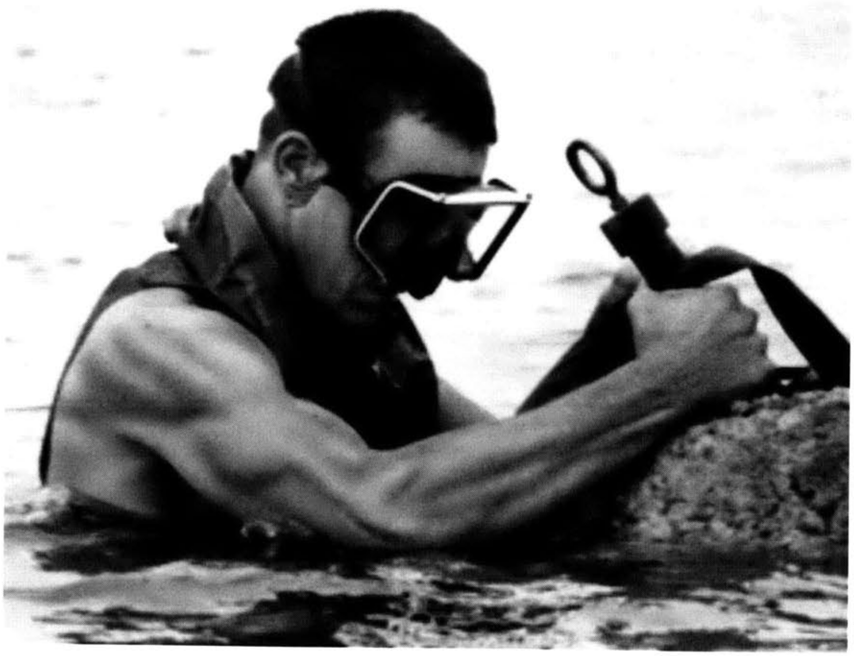

Figure 2.10: Navy SEAL loading a shallow water obstacle

Figure 2.11: Navy SEAL loading a hedgehog with explosives

When the two swimmers at each end of the swimmer line are certain all targets of interest have been loaded with explosives, the line proceeds to the extraction point. This is very tedious and time consuming because of the detail procedures in loading targets correctly, as shown in Figure 2.12. It is a very delicate procedure that warrants absolute attention for the team's safety.

Figure 2.12: Navy EOD loading a column mine with Explosives

Figure 2.13 shows a segment of a network of explosive line that is routed throughout the beach area. A surf surge makes staying clear of hazards quite difficult.

Figure 2.13: Jap-Scully loaded with Explosives

The risk of human life does not exist only underwater. The threat from shore defenses can be extremely high. After the charges have been set, all the swimmers return to the pickup boat for extraction. Explosive charges are fired by timers or remotely, giving the men time to clear the area prior to the blast. Any swimmers not clearing the area can be incapacitated or killed by resulting underwater shock waves.

2.6 Ship Hull Inspection

Although the duties of the swimmers are primarily offensive against enemy obstructions along beaches, other tasks can be assigned. These can include making close-in shore inspections for enemy pillboxes and fortifications, charting underwater obstructions and mines and destroying them, marking or blasting channels, making maps of invasion landing routes, and other similar missions. Additional missions performed for friendly forces can include inspecting friendly ships for battle damage and propeller obstructions, and other underwater work such as rescue and recovery. Figure 2.14 shows a swimmer under a ship, perhaps accomplishing a propeller inspection. Some swimmers can hold their breath up to three minutes without special breathing apparatus. This swimmer, with no oxygen - just mask and fins - may be able to conduct quite an extensive inspection without going up for air. This research is ongoing for future AUV development beyond the research of this thesis.

Figure 2.14: Swimmer performing a ship hull inspection

2.7 History of AUV navigation and localization methods

Navigation

There are several navigation systems used by AUV researchers. One system is a non-acoustic approach; this system can be totally passive and requires no initial setup. The major method used in this approach is to install a GPS receiver and an inertial navigation system (INS). Throughout the mission, the AUV performs a number of surfacing maneuvers to relocate itself and reset inertial navigation system (INS) drift. There are some downsides to this approach: if a hard requirement exists, such as no surfacing being allowed, the accuracy of the navigation system relies solely on the INS, which can become inaccurate after long periods, as navigational errors accumulate. An INS is also costly and difficult to implement. If this is the case, the high cost of an accurate INS can sway research to a different approach. Another approach is an acoustic method, where the range of a vehicle is determined from transponders using acoustics.

Acoustics

Acoustic systems require some additional setup and utilization of hardware components external to the vehicle in order to assist in navigation. Currently, the different approaches can be broken into four subsets: long baseline (LBL), moving long baseline (MLBL), short baseline (SBL), and ultra short baseline (USBL) [3].

In LBL navigation, fixed transponder buoys are pre-positioned to encompass an operating area. The working vehicle sends a transmission and waits for replies. By recording the two-way time of flight of the acoustic signal, the range can be determined, if a constant sound speed is known. This process is initiated by the AUV and returned by the transponder. Using multiple transponders, the location of the vehicle can be triangulated. Navigation using two transponders can be achieved, but the possibility of baseline ambiguity exists. Using three or more transponders eliminates this problem. The height or depth of the transponders must also be determined to minimize error. This method has been investigated by many researchers [4-7], [15], [16], [17].

Processes have also been developed to actively determine the location of the transponders to help minimize the error [4]. An LBL system is the primary navigation system of the Woods Hole Oceanographic Institute (WHOI) REMUS system [16], [17].

MLBL is similar to LBL by using a transponder and two-way time of flight measurements, but differs in that the transponders are on mobile surface platforms allowing minimal setup and positioning of transponder buoys. In addition, the AUV area of operation is not confined by pre-located transducers. Tests performed by Curcio *et al.* in 2005 were able to track surface craft by using multiple platforms each carrying a single transducer to triangulate the location [7], [12].

SBL works by attaching multiple transducers to a single platform to track an AUV. The platform determines the location of the AUV by a modified two-way time of flights. A single transducer initiates a signal to the AUV. When the AUV responds, the one-way time of flight measurement is recorded by all receivers. Each of these measurements varies and needs to be normalized to a one-way time of flight by removing the initiation time of flight. The AUV location can be determined from as little as two transducers but as in the LBL case, ambiguity exists. The ambiguity can be eliminated by adding an additional transducer off the baseline of the first two transducers. The ambiguity can also be determined by angle changes of the baseline for sequential measurements or movement of the transducers. SBL has been employed on several different ROV and AUV platforms [14].

USBL systems use a surface ship following at a close range. A one-way signal from the AUV is received by a number of receivers in close proximity on the surface ship. The receiver system measures the difference in phase each receiver reports. This system does not allow for two-way communications. Bidirectional communication (sometimes through a tether) allows the AUV to receive updates of its position. In a reversed format, this system has also been used for terminal guidance into an underwater vehicle-capturing device [14], [15].

These navigation systems, LBL, and SBL, have been combined in the past in an effort to track sperm whales [15]. This method used SBL to estimate a relative direction to a sperm whale emitting clicks. On a submerged AUV tethered to a surface GPS buoy a four hydrophone SBL setup was utilized to determine the relative direction by calculating the difference in arrival times to the hydrophones. The single SBL system was employed on two vehicles. Two vehicles independently calculated bearing angle and elevation angles to the target whale using the SBL systems. Using LBL techniques between the two vehicles allowed for an intersection and the probable location of the whale to be determined. The tests determine that a precise inclination measurement of the array was important to minimize error. It was difficult to quantify an absolute error because no ground-truth navigation system is available for whales. All error estimations were made by observations of whale surface positions.

Localization

Acoustic range-only Self Localization and Mapping (SLAM) has been preformed by researchers using a variety of methods: Monte Carlo, Kalman filters, Markov Doppler/Compass/LBL assisted navigation filters have been tested, [4], [59], [60]. The Kalman filter assumes a multivariate Gaussian distribution [17], [20], which is fully described by a mean and a covariance matrix. Extended Kalman filters approximate linear solutions to nonlinear problems [21]. This allows for an efficient implementation, but divergence is also a potential problem with an extended Kalmen filter. The divergence is exacerbated when angle errors are high, and the Gaussian is a poor approximation.

Monte Carlo localization provides yet another method of representing multimodal distributions for position estimation. Also known as particle filtering, Monte Carlo localization approximates a distribution using a finite number of weighted samples. The estimated distribution is updated using importance sampling: new samples are drawn from the old distribution at random, propagated in accordance with robot odometry, and then weighted according to available sensor information. One advantage of Monte Carlo localization is that the computational requirements can be scaled as needed by adjusting the number of samples of the distribution [19], [59]. Computational complexity can be an issue with this approach.

For range-only navigation, research has shown Kalman filter tends to perform better then other approaches [59]. Tests were performed by Newman *et al.* [4] to determine beacon location and vehicle trajectory. Localization of the vehicle using multiple range measurements along with vehicle depth created a two-dimensional problem to determine the vehicle location. A non-linear optimization algorithm was used to simultaneously determine beacon locations. Better results are achieved when multiple methods are used such as Kalman filtering with Doppler velocity log. Newman [4] performed test in 2002 to verify the capabilities of Kalman filters to locate accurately and AUV using range only measurements, Doppler and compass data. The results of this work showed that AUV tracking was possible.

In 2002, experiments were performed to enhance range-only location from two-way time of flight. An AUV was deployed using stationary acoustic transponder beacon as navigation aids. The locations of these beacons were known. A robust outlier rejection method was used to remove non-Gaussian noise [55].

Environmental Geo physical properties have also been used to determine underwater location. In 2003, Nygren and Jansson tested a technique using a bathymetric multibeam sonar to map the seabed topography. The data obtained from bathymetric image for a given area were compared to previously existing map. From this, the vehicle calculated its location within the previous map. The AUV was able to achieve accuracy from one to seven meters within a one square kilometer grid.

Geospatial navigation is not a promising method for clearing a beach. Historically, assault beaches have been chosen for a smooth gradient and sandy bottom. The ability to determine your location from bathymetric means requires a significant height change in the bottom images; sandy bottom beaches are typically smooth and gently sloped toward the shore. Sandy beach bottoms typically shift with the tide; forever changing small sand ridges on the seafloor lay down in different patterns with the prevailing current. The texture of these ridges is similar to an enlarged fingerprint with ridges in some cases reaching a maximum height of two inches. Navigation using these techniques is problematic because the a priori map will soon be obsolete due to changes in target locations and an altered bathymetry from tide and storms.

2.8 Sonar

There are two types of sonar used for creating the prior map for the final reacquisition of targets. The first used by the REMUS vehicle is a side looking sonar (SLS) [16]. It works by taking a thin picture of a small swath of the floor, and example is shown in Figure 2.15. The thin picture is perpendicular to the direction of travel. At the end of a run the thin pictures are stitched together to form a coherent image. This image will show details of the ocean floor. It relies heavily on the shadows created by an object for recognition and classification. This is a labor-intensive process. Algorithms are currently being developed to minimize the human interface required.

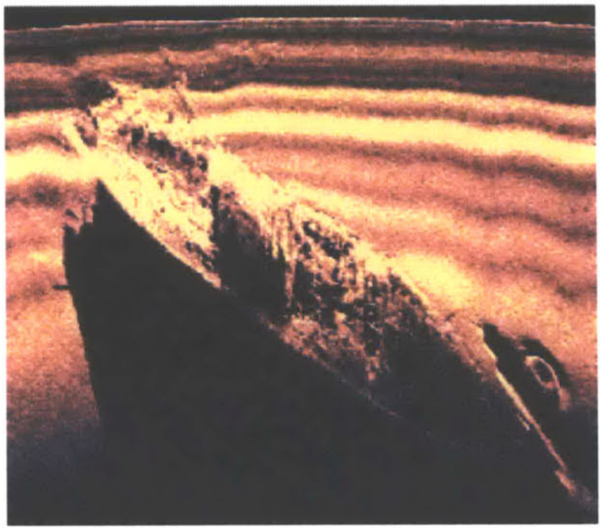

Figure 2.15: SLS Image- USS Monitor of of

The capabilities of SLS mapping are extensive. They have been fitted to small AUV and performed well in a variety of roles. Most recently, a SAHRV (the military version of REMUS) was used to map Al-Basrah, an Iraqi oil port [16]. During this mission other assets were also employed. The SAHRV worked more effectively and cleared more area than any other platform. It was able to locate objects of interest for Navy divers to check. It was the first major step for operations of AUV by the U.S. Navy [16].

The clarity of an SLS image is directly correlated to the stability of the vehicle carrying it. A smaller less stable vehicle is susceptible to uncontrolled motion, which skews the images. As the title suggests, SLS looks to the side of the vehicle. It has a fast update rate requiring minimum CPU speed to process the images because only a small swath is added after each return. It is not capable of seeing or recording features that are approaching the vehicle. This limitation eliminates it from being used as the sole device for location and terminal guidance of objects of interest in littoral waters.

A Forward Look Sonar (FLS) enables the AUV to see what it is approaching. The image return from a FLS is different than a SLS. The FLS image is similar to an overhead shot that depicts ranges and bearings. Each ping returns a new full image; a single ping return is shown in Figure 2.16. It does not perform as well in identifying objects, as shadows and the clarity are not as refined as the SLS.

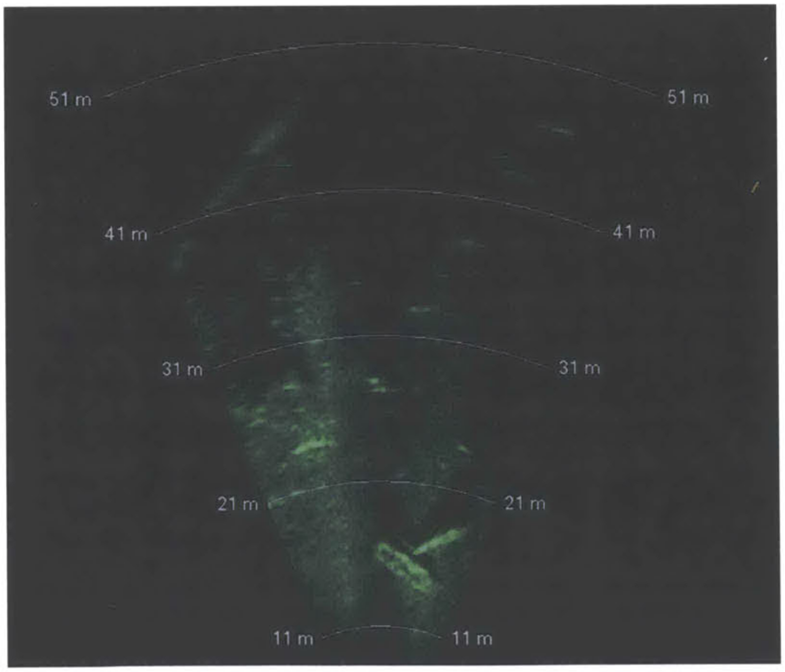

Figure 2.16: FLS image- sunk sailboat in Charles river

The refresh rate is highly dependent on CPU speed because most systems require the image to be processed before the next ping is sent. The single image contains more information then a single swath of images from the SLS. Typically SLS refresh rates are greater than those from a FLS. If processing of images can be controlled, minimizing CPU overhead, the refresh rate can increase substantially. Technology is also processing the majority of the image prior to reaching the main CPU. Taking this overhead off the main CPU will greatly increase the refresh rate.

Vehicles that contain both FLS and SLS have been developed and used with exceptional results. They allow the user to see an object of interest from both perspectives, furthering their ability to classify the object.

This chapter has shown the current capabilities of manned assets and techniques used for insertion and infiltration of a littoral beach. It has also described the current capabilities of the two types of sonar's available and provides an explanation of common navigation techniques in use today.

3. Advances in Design

This chapter presents the design of the RUSSO ASC, a robotic surface craft designed for autonomous deployment and operation of AUVs. The design has been developed as an extension of the Scout ASC, created by Curcio *et al.* at MIT [7], [12], [56]. We use the Nekton ranger as the target host AUV [6]. This chapter reviews the goals of the design and provides details of key subsystems, including vehicle modifications, hardware designs, and autonomous launch constraints.

3.1 Current design

The first version is the Scout ASC which provided an easy-adaptable test platform for developing algorithms and initial testing of new equipment for use on other platforms. Over the past few years, the Scout ASC has proven to be a sturdy and reliable platform that is used extensively for software and hardware validation. It has been used in support of multiple ONR field experiments, in a variety of environments, including ponds, lakes, and protected and unprotected ocean environments in both fresh and salt water. The Scout ASC has proven its ability to be rapidly configured by strapping on new sensors for evaluation and testing of software algorithms.

3.2 Wet bay construction

In order to build the next version of an ASC, a clear understanding of its purpose needed to be defined. This new ASC is to be capable of all of its past missions and be able to have an increase in durability of both hardware and software. The major design change for the new vehicle is the ability to house and launch an AUV from an internal wetbay, shown in Figure 3.1. The design is not limited to launching one particular vehicle. The wetbay is expanded to accommodate the largest possible payload allowable by the ASC hull, allowing for expansion of future roles and missions of the ASC.

Inner dimensions of the wetbay are fifty inches long, by ten inches wide and nine inches tall. The top is open to the middle section of the ASC, which allows for easy connection of hardware mounts and electrical connections. The bottom is also open to allow for the release of the payload at anytime and for payload sensors to be mounted below the hull. The open top, open bottom design adds flexibility in that the payload is not confined to fit into the vertical area.

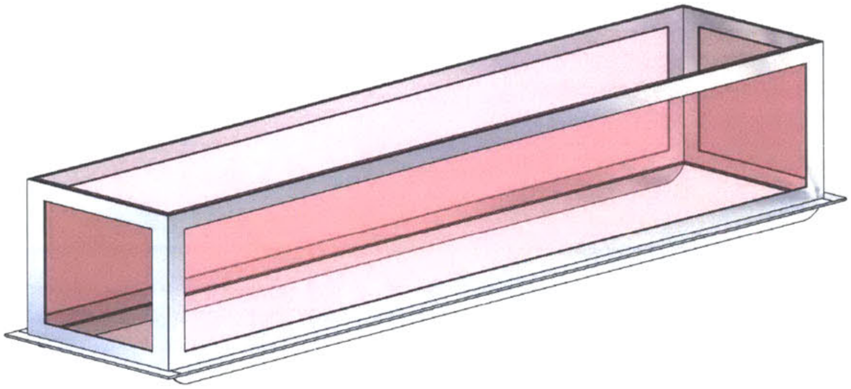

Figure 3.1: Wetbay frame and panels

Construction of the internal wetbay walls used quarter-inch thick High-Density Polyethylene (HDPE) welded at the seams. These seams serve as the first barrier in waterproofing the center section of the ASC. A second waterproof barrier is a coating covering all seams in the center section. The urethane epoxy sealant remains flexible once cured, thus allowing the wetbay to sustain some abuse while preserving its watertight integrity. The walls were supported by aluminum extrusions to disperse the torsional load on the walls. Aluminum "L" angle extrusion is used for the four vertical attachment, reducing the capability of the walls bulging between connection points due to water pressure and loads. A large (1½") flange surrounds the base of the wetbay for two reasons. The first is to allow a gasket to be compressed between the flange and the ASC hull to form a watertight seal. The second is to add strength to the middle of the ASC.

We were concerned with the longitudinal and torsional strength of the ASC hull once the wetbay was installed because of the large amount of hull material removed from the center that was the original load dispersing webbing. In addition to the loss of strength, fifty-eight percent of the ASC keel was lost from the open area consumed by the wetbay; the result would be a less-stable craft. To add dynamic stability, aluminum "T" angle extrusion was used on the left and right sides of the hull at the wetbay interaction, as shown in Figure 3.2, two bilge keels extend into the slipstream and allow for the attachment of additional keel components if necessary.

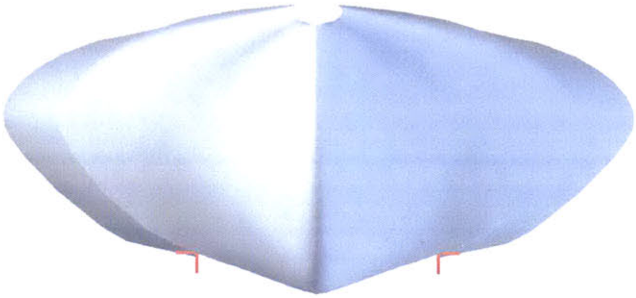

Figure 3.2: ASC front view with bilge keels

One by 1/8 inch bar was used to tie together the top four corners of the housing together, allowing for several attachment points to distribute the load evenly between the bay insert and the ASC frame rails.

Inside of the ASC, 8020 extruded aluminum frame rails were used to secure the wetbay, as shown in Figure 3.3. The ASC internal frame is further strengthened by the wetbay housing. The 8020 rails were bolted to the front and rear 3/4 inch thick HDPE bulkheads, forming a rigid box frame and adding strength to the hull.

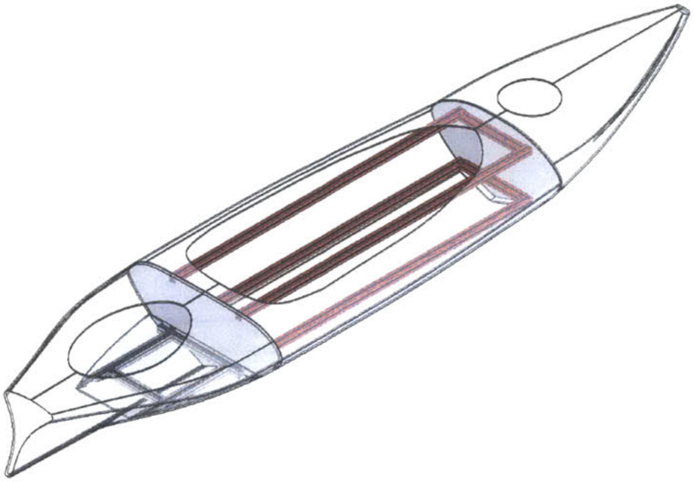

Figure 3.3: Kayak with 8020 frame rails

The bulkheads were made slightly oversized for force fit in the front and rear then sealed into place. Over sizing the bulkheads does not allow for any movement of the frame rails in the ASC, as shown in Figure 3.4. Silicon glue sealed the three compartments to form three independent watertight chambers. This added safety in the design ensures that any one compartment can flood but the vehicle will remain buoyant.

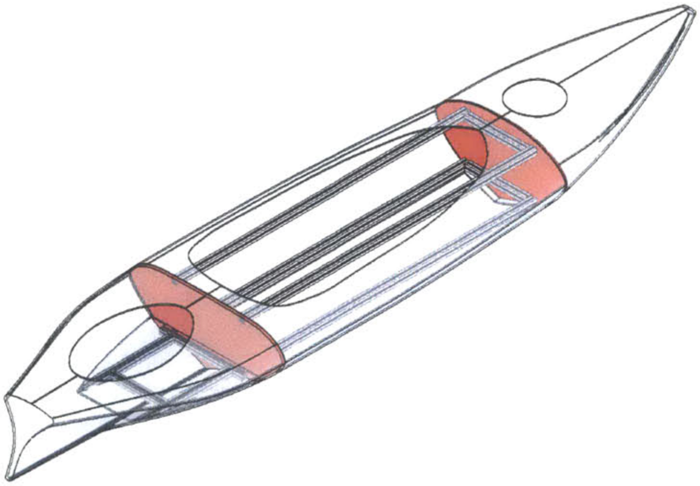

Figure 3.4: Kayak with bulkheads

The wetbay slips into the ASC framework from the bottom and is designed to be semi-permanent, as shown in Figure 3.5. However, the ability exists to replace the bay with only a minimum of labor.

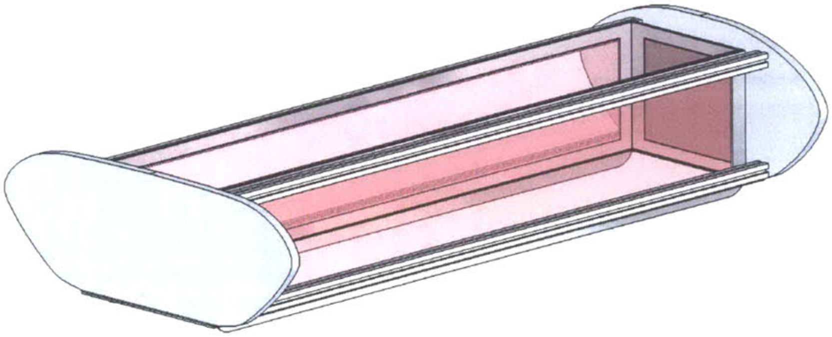

Figure 3.5: Wetbay mounted in ASC frame

Once the AUV mounts are installed, the AUV can be mounted from either underneath or the top. Shown in Figure 3.6, a Nekton Ranger AUV is installed at a fifteen-degree downward angle, allowing the sonar head to be fully submerged for use during the transit. At this angle, the maximum range of the sonar in a typical water depth of 18 meters is 67 meters. The effects of this are discussed in detail in Chapter 4.

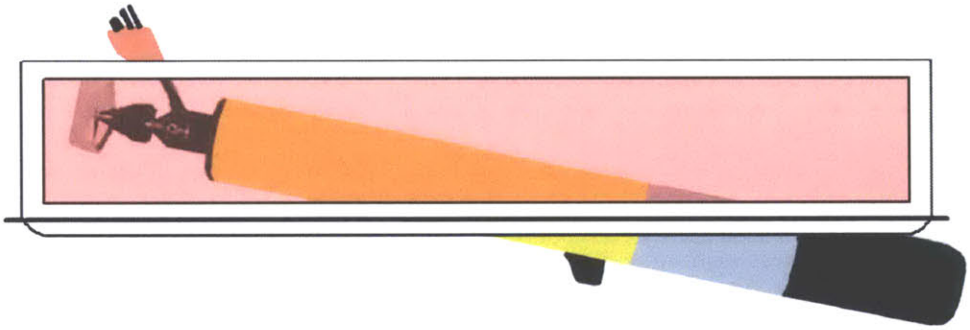

Figure 3.6: Ranger AUV mounted in wetbay

3.3 Cooperative Navigation Hardware

The surface navigation of an ASC is a simple process of GPS waypoint following, provided a high-level control has been implemented. A waypoint and thrust are defined and the ASC navigates a straight line to the waypoint then waits for the next instruction. During this process, it continuously updates its position using GPS and compass inputs. It can also use data from the FLS on the AUV to assist in the Self Localization and Mapping (SLAM). The ASC performing a search pattern using the SLAM code localizes underwater targets with respect to a global (above water) reference frame. The ASC is able to update the command and control database via the RF link. It can also pull the new information from the other ASC's that might be operating in the area and thus update the AUV a priori map before launch. At this point command and control can, if needed, change the independent target to which the AUV is assigned. This final global update will increase the chance of the AUV finding its intended target.

The Ranger AUV is designed to be a simple system and thus lacks an expensive Acoustic Doppler Current Profiler (ADCP). The addition of an ADCP would increase its underwater navigation capabilities, but would increase the cost by tens of thousands of dollars. Currently the AUV is limited to operations within thirty degrees of level flight before the inertial measurement unit is unable to accurately measure changes. Regretfully, this limitation is often exceeded during normal operations, especially in degrees of roll. When this occurs, the error in the navigation system increases dramatically. The global location of the AUV must be corrected. Currently this correction is performed by surfacing to obtain a GPS fix. To surface and dive uses a significant amount of finite battery resources. If when an error correction is needed surfacing could be avoided, the AUV's underwater range would increase. In addition, anytime the vehicle is diving or surfacing, there is an increase in false detections in the target and tracking code caused by the sonar's strong reverberations from the surface and bottom. To use the data obtained during surfacing and diving, additional filters are needed to reduce the unnecessary noise induced by the surface and bottom. Limiting the code to operate only in level flight would eliminate this problem but it would also significantly reduce the search area coverage.

Configuration

To assist the AUV in correcting its navigation error, we approached the location error correction differently then current low-cost MLBL and LBL research. We used an SBL acoustic array setup on the delivery ASC allowing the AUV to be tracked and located underwater. The two-modem array consists of two WHOI Micro Modems at each end of an adjustable length array. Two different configurations were tested, fixed and mobile. The fixed array was used for pier-side testing and was rigidly mounted. Figure 3.7 below shows this two meters long array, the distance between the acoustic modems, and mounting pole allowing a deployment of down to two meters below the water's surface. In addition, the deck computer box, router (used for time sync) and GPS unit are shown.

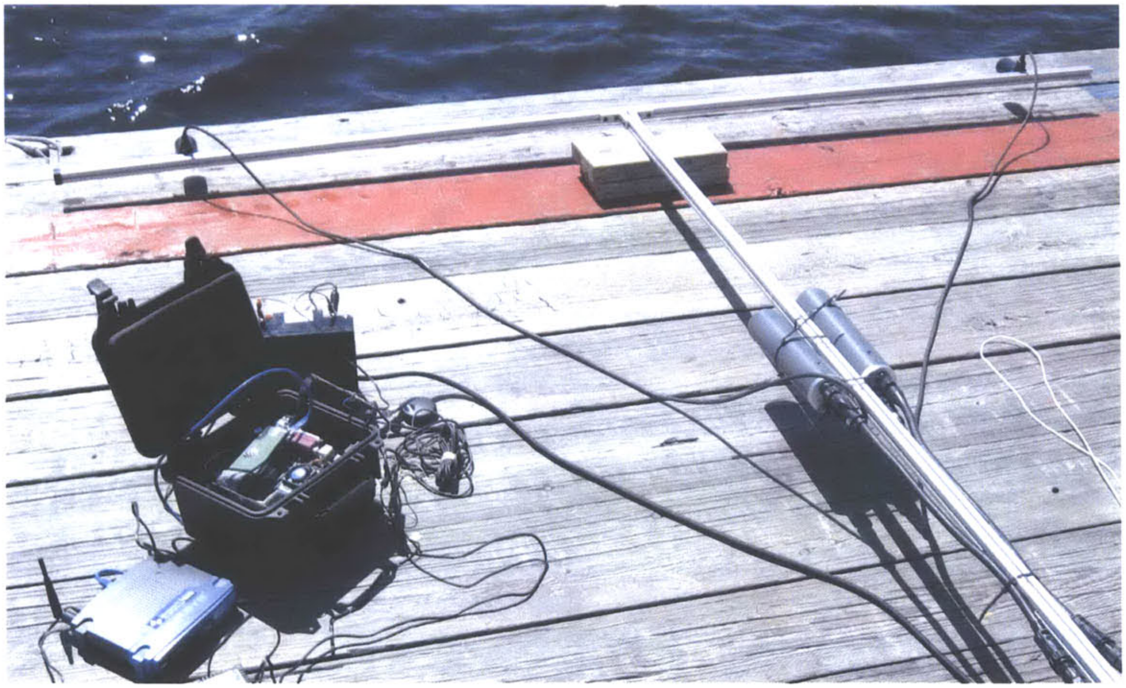

Figure 3.7: Fixed array with deck CPU and two WHOI Micro Modems

A more advanced mobile array was deployed and towed beneath the ASC SCOUT vehicle. Its design uses a combination of two towfish as discussed in Chapter 3.5. In this configuration, a two-axis compass is attached to the array to determine the magnetic angle of the array during free flight under the ASC, as shown in Figure 3.8. Operationally the array did tend to sway slowly under the kayak due to line drag, making the array heading different from the kayak heading.

Figure 3.8: Scout ASC with mobile array

Transmission

The underwater acoustic transmission package used is the smallest available for the WHOI Micro Modems. The AUV sends this transmission every three seconds when it receives a signal from the GPS pulse per second (PPS). The two WHOI Micro Modems on the ASC start their internal clocks when each PPS signal is received and each stops independently when the acoustic signal is received. From this, a one-way time of flight is recorded and then a range is calculated. Using the two range circles about each WHOI Micro Modem transducer location, two possible locations of the underwater vehicle are determined. One location is correct. However, because of baseline ambiguity, software code is implemented to determine actively on which side the AUV is operating. This determination is made significantly easier by using the mobile array on the ASC. This is discussed in greater detail in Chapter Five.

3.4 Towfish Design

Testing revealed that the WHOI Micro Modem transceivers had a large increase in range performance when they were not attached to a vehicle. During testing in summer of 2005, an ASC was maneuvered away from a WHOI Gateway buoy to determine the maximum effective range of the modems installed on the ASC. By extinguishing non-vital systems to minimize both self-noise and the EMI/EFI effects of the ASC. The maximum effective range was 470 meters. However, the only systems were the CPU and modem. The maximum range of a fully operational configuration was less than 300 meters. This reduced range was attributed to the transducer's close proximity to the water's surface and its intimate contact with the hull causing reflection, refraction, and multi-paths. To increase the effective reception range of the modem's transducer a towfish was designed to permit the transducer to be towed at an adjustable depth under the vehicle.

Towfish Body

The passive towfish was designed to house a WHOI Micro Modem transducer, mounted so the omni-directional signal travels parallel to the water's surface. To remain omni-directional, the towfish have minimal rotations around any axes, enabling it to fly relatively flat and streamlined throughout the velocity spectrum of the ASC. A constraint when the ASC is at zero velocity is, that the towfish must hang in the same manner it does during forward velocity. This streamlined towfish position helps optimize the range of the WHOI Micro Modem.

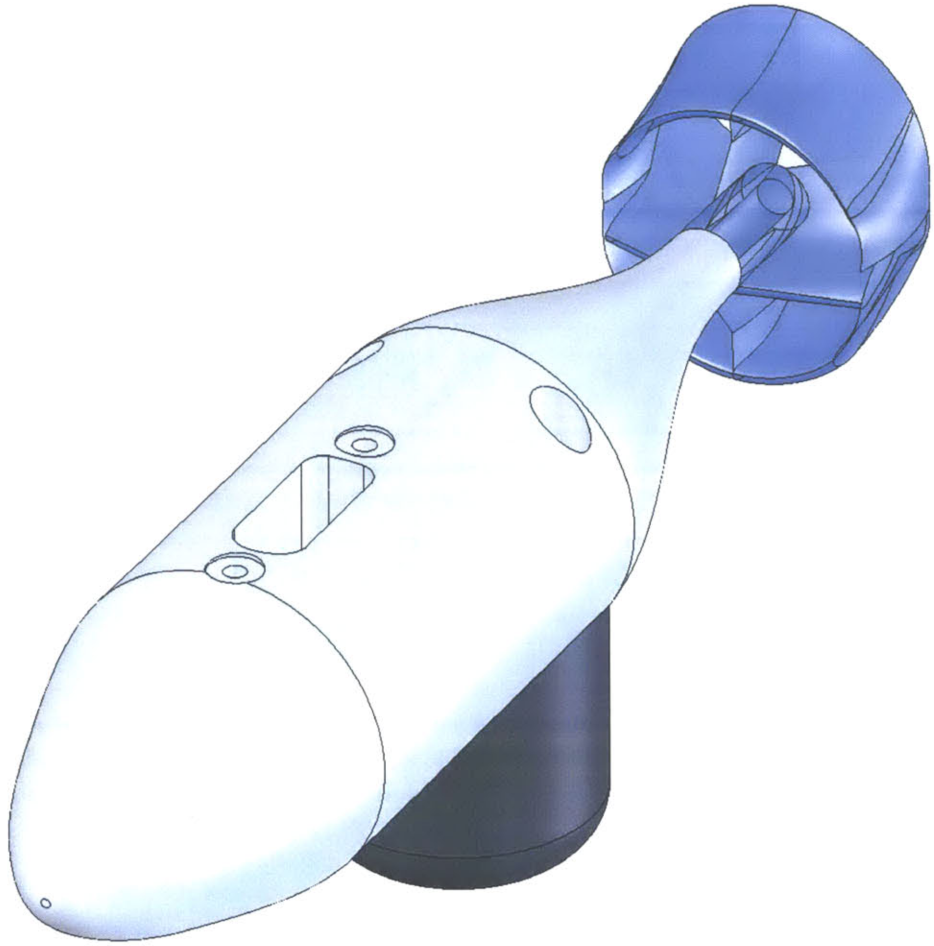

Figure 3.9: Towfish with WHOI Micro Modem

To meet this criteria, the 2-1/4" inch diameter towfish was constructed of aluminum, and both ends were tapered to minimize both turbulence and vortex-induced vibrations. The overall length, of nine inches, was calculated to keep the center of gravity and the center of lift in the same longitudinal location to keep the towfish flat at zero velocity. Two longitudinal mounting points hold a cable strain relief. They are also used for fine-tuning the balance of each towfish at zero velocity.

Towfish Tailfin

To keep the towfish at a parallel attitude throughout the velocity spectrum a tailfin was added. The effects of hydrodynamic drag on the WHOI Micro Modem transducer were calculated using equation 3.1.

$$F_D = \frac{1}{2} C_D \rho v^2 A + Added\ Mass \qquad (3.1)$$

A tailfin was designed to counteract both this drag and the resulting pitching moment created when the towfish travels through the water. In an effort to reduce the possibility of the tailfin contacting the ASC during launch and recovery, the maximum diameter of the tailfin was to be no larger then that of the main body. This allows the towfish to be rolled around on a ship deck prior to deployment or during recovery without breaking the tailfin.

A single-element-airfoil (modified MH-115) tailfin with an eight-degree angle of attack was tested [56]. During MIT water tow tank testing at a velocity of two meters per second, a typical ASC surface speed, the tailfin did not create enough down-force to counter the pitching moment created by the transducer. This was attributed to the effect of being towed from a top mounting position. A pitched towfish did not create an optimum omni-directional range situation and needed to be adjusted. Second and third airfoil (modified MH-112) elements were then added to the tailfin to increase the force of the tailfin, while still maintaining a two-inch diameter, smaller than the main body [57]. By adjusting the angle of attack of all three airfoils, a down-force equaling the effect of the pitching moment and towing force was achieved during testing at the MIT water tow tank. The progression of the tailfin design is shown in Figure 3.10.

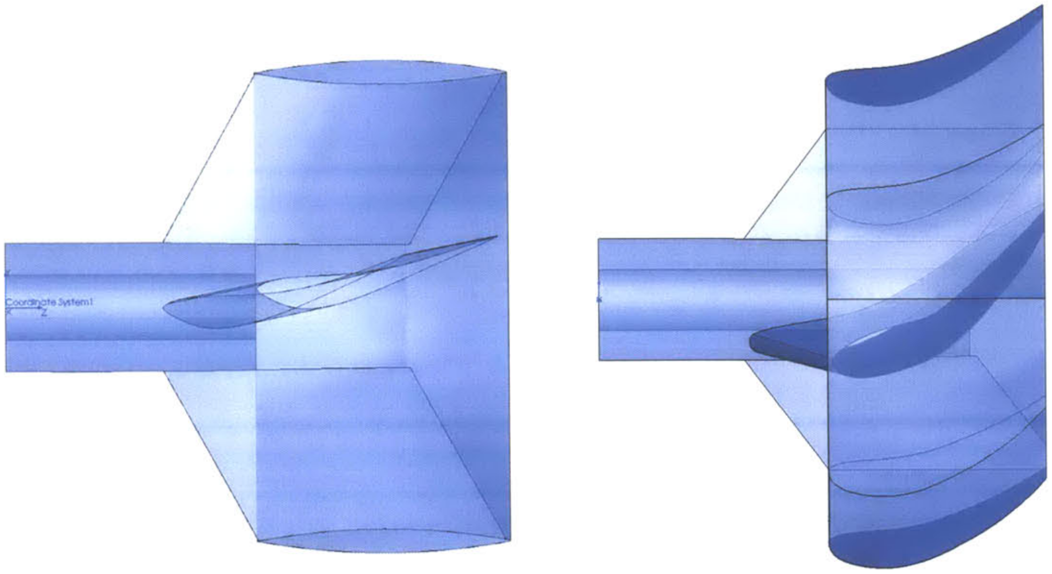

Figure 3.10: Original and final tailfin design

Testing of the final assembly in the MIT water tow tank, indicated that the towfish was now stable and did not oscillate. It was further determined that the towfish pitched down a maximum of five degrees at two meters per second, well within the main vertical lobe envelope of the WHOI Micro Modem. Further open water testing on an ASC under operational conditions showed the towfish to be stable throughout the range of ASC velocities and maneuvers.

Towfish with mounted transducers increased reception ranges considerably and were employed during testing in 2006, at a tow depth of three meters. Figure 3.11 shows three final-version towfish on the aft hatch of an ASC. Sea conditions were two-meter waves with wind-driven white caps, Sea State Two, as shown in Figure 3.12. The effective range increased to 2,700 meters before a significant drop in reception occurred, resulting

Figure 3.11: Three towfish during surface checkout

in a 570% increase in operational range from the previous year's testing. In addition, these results were obtained with all of the ASC systems operating (with self-noise and EMI/EFI present).

3

Figure 3.12: ASC operating off Monterey Coast

4. Fusion of Sensors and Components

This chapter focuses on the sensor interaction component of the design, including power, and communication. It also describes the advantages of sharing resources between vehicles to maximize effectiveness.

4.1 Power and Communication

Currently, the Scout ASC and Ranger AUV have no conduit to share information. This lack of communication limits the overall ability of both vehicles. Powering the AUV through the ASC power source was the first step in initiating a communication link while the AUV is docked. This was done for a number of reasons. First is the ability of the RUSSO ASC to utilize SLAM by processing images from the AUV's FLS [4, 6, 9, 11, 13, 17, 18 ,19, 21]. The ability to use the sonar returns for underwater navigation during over the horizon transits is limited by power consumption and the ability to transmit the information to the host platform for use. Second, the ability to use the GPS, and compass that are available on both vehicles to assist in navigation is advantageous to reduce error. Thirdly, being able to launch the AUV at a predefined point not a predefined time allows an increase in control. Limiting the launch of the vehicle to a predefined time would become apparent if the ASC encountered a current and was unable to arrive as planned.

Nekton Ranger AUV has a maximum battery life of two hours. This exceeds the mission requirement it was originally designed to operate in, defined by ONR. However, we intend on sharing the sensors the ASC and the AUV to increase the overall capabilities of the pair of vehicles during their over-the-horizon transit. First off, this requires the AUV to be powered during the transit as previously discussed. If the ASC did not power the AUV through the RUSSO power system, the overall operational duration would be limited to under two hours.

Currently, the RUSSO ASC has 120 amperes-hours of lead-acid batteries. This allows for a theoretical five-hour operating window. Using the current lead-acid batteries, the powering of both AUV and ASC will decrease that to a four-hour window. A hard-line connection between vehicles contains the power connection and an Ethernet connection. The connection itself is a six-pin hard-line, light-force-fit connector that will detach during the launch process. The Ranger AUV requires 18 volts direct current for power; while the RUSSO ASC operates on 12 volts direct current. The ASC system is modified to feed an 18-volt direct current line to Ranger for powering and keeping its batteries charged during the transit. It is intended that the AUV will be mounted with a fully charged battery. However, if the vehicle is mounted with less than a full charge it is more efficient to charge both vehicles at once. Provided the batteries are charged, the AUV's electrical demands from the ASC will be approximately 60 watts to keep the primary systems operating.

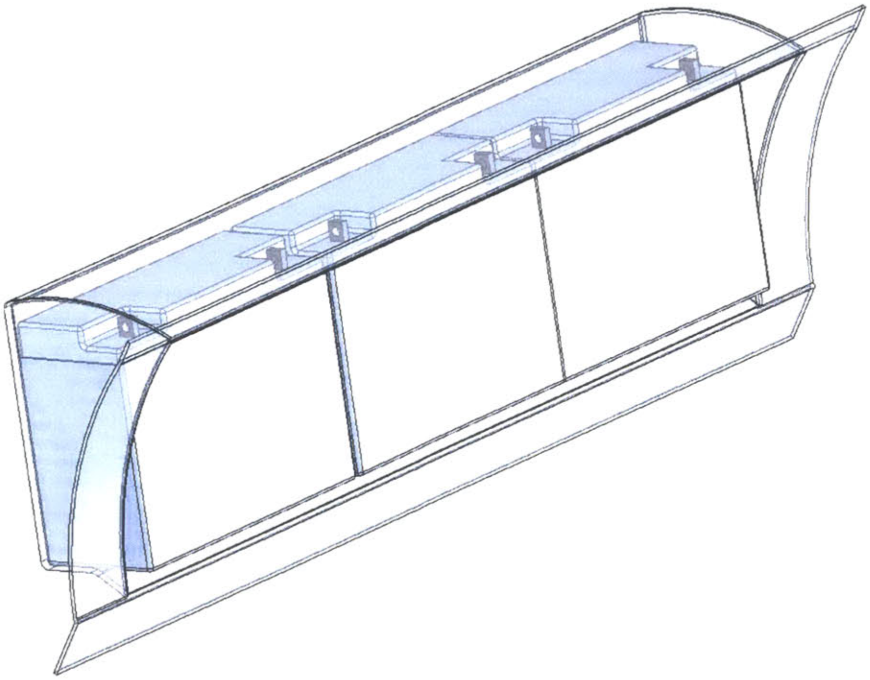

Figure 4.1: Port side battery tray

Shown in Figure 4.1 is half of the RUSSO ASC battery pack. This three-battery tray and another are located on each side of the wet bay, for a total of six batteries. For a standard overnight duration mission discussed earlier, this would be inadequate power. To increase the available power provisions have been made to upgrade from lead-acid to

Lithium-ion Polymer batteries. Changing the batteries to Lithium-Ion will increase the duration of operations to 32 and 26 hours when powering the AUV. Another advantage is that the weight and volume of the upgraded batteries is comparable to the current lead-acid design.

4.2 Sonar

Two Forward-Looking Sonars, both made by Blue View Technologies have been used during testing [61]. The older model, P450E, has an operating frequency of 450 kHz ± 150 kHz, and is shown in Figure 4.2. It has a 45-degree horizontal field of view and a maximum usable range of 70 meters. Its range resolution is two inches. The newer model is the P900E which has an operating frequency of 900 kHz ± 300 kHz. It also has a 45-degree horizontial field of view and a maximum usable range of 40 meters. Its range resolution is one inch. Determining which sonar to use is a trade-off between range and resolution. The P900E is half of the size of the P450E but the major limitation is range.

Figure 4.2: Blue View Blazed Array (450kHz)

Each Blazed Array Forward-Looking Sonar (FLS) is coupled to a CPU that has a primary function of image processing. Image processing is very CPU-intensive and can severely bog down all of the processes running. For the SLAM algorithm to work effectively with the beamforming, the FLS CPU needs to have substantial uninterrupted computational power, as the CPU dictates the frequency of image pings by speed alone. Each ping return must be converted to an image, using a beamforming algorithm. Once the CPU completes the beamforming, the next ping is transmitted.

Then the SLAM algorithm processes each image, defining objects from the image intensity information. The range and bearing of each object in a single image with respect to the AUV position is determined. If an object can be linked from frame to frame, a track can be determined. As soon as five observations on a single object have been obtained, they can typically be localized to a specific target location. The sequence of sonar images in Figure 4.3 shows two targets that can be tracked visually. One target is at 57 m and the other at 22 m, in the first frame. The return sequence i is actually of the ASC movement through the area over stationary objects, identified as targets. These targets are then converted to a global position in a latitude and longitude format or other coordinate system if needed. The tracking algorithm looks for these recorded target positions on any leg that travels through the area and attempts to associate the previous targets with new objects.

To increase the FLS ping rate, the ability exists to process only a fraction of the images. This is convenient for post-processing but does not help the real-time SLAM problem. We have been able to achieve sonar rates of six hertz when not processing all of the images but this decreases dramatically when we process all of the images. Typically, a two-hertz ping rate is achievable with full image processing on a 1-GHz CPU that is also running core navigation processes. Future developments will include a parallel processor to perform the beamforming. This will reduce 80% of the image-processing load from the main CPU. In addition, a 1.4-GHz CPU upgrade will be installed and used for the remainder of image processing and for running the SLAM code. These upgrades should allow for an image-processing rate close to five hertz.

The image processing rate is important for the targeting and tracking software. The software is dependent on the number of times it has a return on each object. For a target to be tracked a typical minimum of five returns is necessary prior to passing over it, helping the targeting and tracking algorithms to minimize error. To optimize this, another important aspect in the setup of a FLS is the angle at which it is mounted. Results have shown that the optimum angle for a surface kayak operating in five meters of water is around 11 degrees. At this angle, the maximum range of the sonar is obtained in 18 meters of water is 67 meters. However, the operational range limit of the 900KHz FLS is 40 meters, yielding a maximum depth of 10 meters. Therefore, each ping would return an image of the bottom from six to 40 meters in length. The maximum usable width of the sonar path would reach 20 meters wide at 40 meters range, in a fan similar to one image in Figure 4.3. A target acquired at this range would have more then five returns for the targeting and tracking algorithm to localize it prior to passing it.

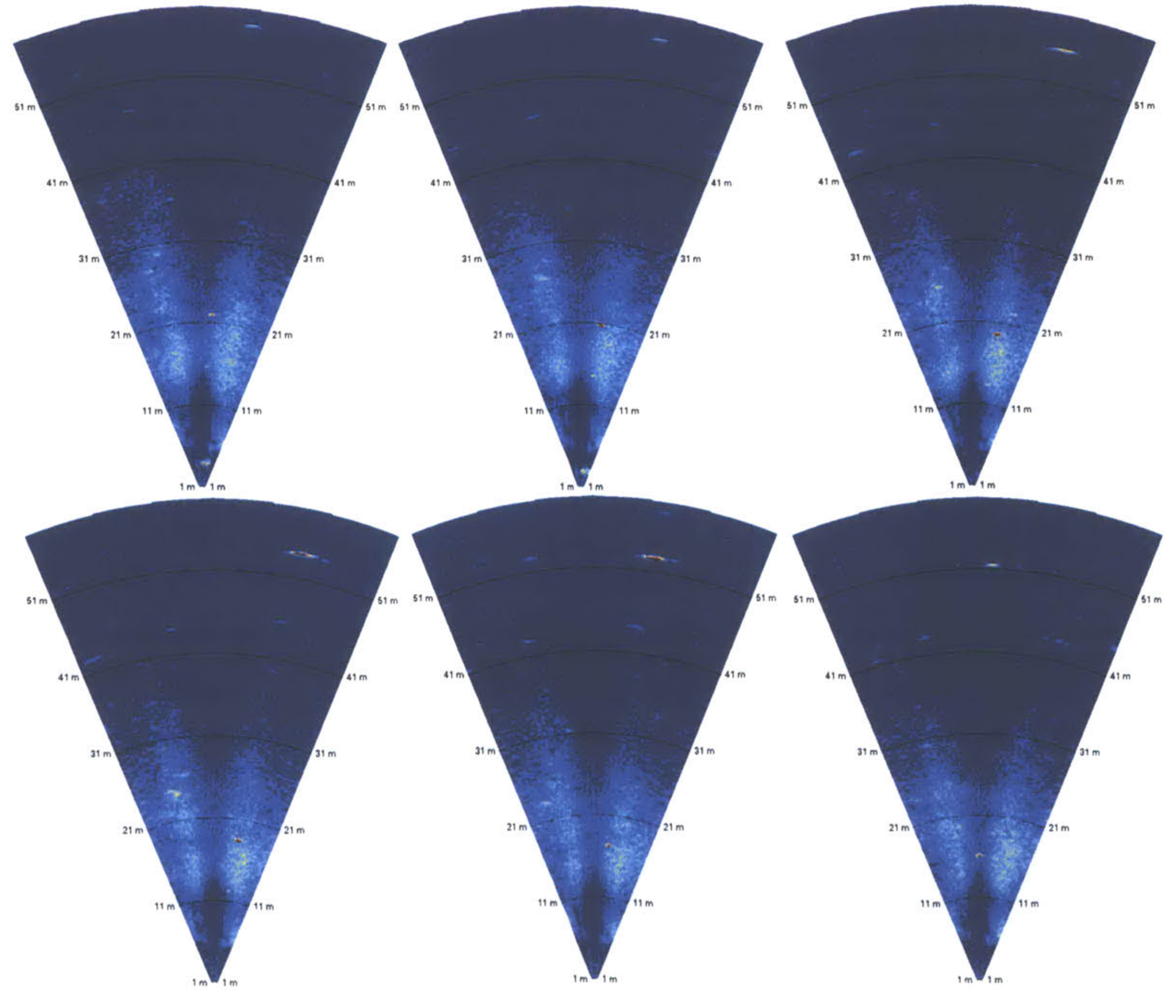

Figure 4.3: Sequence of sonar images with two targets

With the AUV mounted in the ASC, the data transfer takes place via the hard-line Ethernet connection. The data transferred over this line include the processed sonar images that can be for RF transmission to the command and control element or for the ASC SLAM navigation. The vehicles share state data for cooperative navigation mapping. The separation of navigation and beamforming processes onto different CPUs allows the RUSSO ASC resources to execute essential navigation commands and processes. In turn, it allows the AUV to increase its maximum ping rate by having a dedicated CPU to process images.

5. Cooperative ASC/AUV Navigation

This chapter will address the cooperative ASC/AUV navigation problem, presenting a new approach to tracking an AUV from the surface, using standard WHOI Micro Modems in a short baseline configuration.

5.1 Methodology

Short baseline tracking has been used extensively in commercial oil platforms to track underwater ROVs. Most of the work has been done in a tethered configuration using a simple ping to determine two-way time of flight. The same approach is used here but also exploited the added ability to transmit data through the ping transmission. By synchronizing the clocks between the vehicles allows a one-way time of flight to be recorded.

5.2 Array Configuration

As discussed in chapter 3, a two-meter array is tethered two meters below the ASC. On each end of the array is a WHOI Micro Modem. The array also has a compass installed to determine the magnetic angle of the array when transmissions are received, as shown in Figure 5.1.

To simplify the problem, the depth of the array was adjusted to fly at the same depth as the AUV transducer, creating a two dimensional problem. The separation of the transducers on the array (L) was tested at different lengths: 1/2, 1 and, 2 meters. Two meters was determined to have the greatest resolution and was used exclusively after conducting preliminary testing. The length could be reduced depending on the precision of the track required and precision of the WHOI Micro Modem.

Figure 5.1: ASC with mobile array

Evaluations of water conditions were preformed throughout the duration of the test. The sound speed (c) was determined from recording the time of flight (T) of a test transmission from Transducer 1 to Transducer 2, over the known length of the array (L), Equation (5.1). From the results, it was determined that the sound speed changed minimally throughout the day in the test area, but day to day changes were adjusted for as discussed in Section 5.6.

$$c = \frac{L}{T} \tag{5.1}$$

5.3 Transmission package

The standard transmission used is a small 32 byte package. Larger transmission packages are available; however, a small, short package is used for two primary reasons. First, there is a greater chance of transmission success. Second, more packages are sent in the same duration of time, allowing for a denser track of the vehicle. The short package transmission time is under two seconds, which is allotted a three-second window. Therefore, we typically receive a transmission every three seconds.

The CCMPC (Mini-Packet Ping Command, host to modem) is the specific command used exclusively throughout testing. Although this command is used to determine if a particular unit is in range it includes all the required information. An imaginary destination unit is program into the transmission. This causes the receiving modem to log a reception time but it does not reply (it would reply if it was the destination modem). The ping command transmits several National Marine Electronics Association (NMEA) sentences as described below.

$CCMPC,SRC,DEST*CS

SRC	Source (unit designated as ping originator)
DEST	Destination (unit designated as receiver of the ping)
***CS**	Hex coded checksum (8 bit XOR of sentence) optional

The time of flight recorded is generated from the receiving modem only. The modem restarts an internal clock every time it receives a pulse from the GPS. The clock is not related to an absolute time nor does it need to be; however, the GPS pulse is. The recorded time of flight does not have any bearing on when the transmission was sent. The recorded time is the delay between the most current GPS pulse per second (PPS) signal and the reception of the AUV transmission. For example, if the transmitting modem signal has traveled 200 meters, the receiving modem will log a flight time of 0.1333 seconds (assuming a standard sound speed of 1500 meters per second). A problem arises when the reception distance is greater than 1500 meters. If the transmission signal has traveled 1700 meters, the receiving modem will log a flight time of 0.1333 seconds. This is the same time logged when a signal travels 200 meters, not the actual flight time of 1.1333 seconds. The additional one second of transmission flight is not recorded because a new GPS PPS signal arrived during the time of flight. During testing, the range increased at a predictable rate. When the transmission range jumped 1500 meters, it was straightforward to compensate by adding in an extra one second to time of flight.

5.4 Transmission Range and Localization Calculations

In the three-second period between pings, the Ranger AUV travels approximately 2.4 meters. Throughout the duration of the test mission, transmissions were received from the AUV. Each ping received by both transducers on the array had the following calculations preformed to determine the location of the sent transmission with respect to the ASC and the angle of the array. Transducer 1 is the aft modem on the array and is used as the ASC coordinate frame origin for all received transmissions. The second modem is located along the x–axis at a distance of L, as shown in Figure 5.2. First, the radius (r_x) of the range circle around each transducer that receives the signal is determined, using Equation (5.2).

$$r_x = (\text{Sound Speed})(Time) \tag{5.2}$$

From determining the two range circles and using the length of the array, the intersection of the two range circles can be determined and the associated angle from Transducer 1 is found, using Equation (5.3), graphically shown in Figure 5.2.

$$\theta = \pm\cos^{-1}\left(\frac{L^2 + r_1^2 - r_2^2}{2r_1 L}\right) \tag{5.3}$$

The location of the AUV target in reference to the array on the ASC, ${X_t}^A$, is determined from the range from Transducer 1 and the θ angle, an in Equation (5.4).

$$X_t^A = r_1\cos\theta \tag{5.4}$$

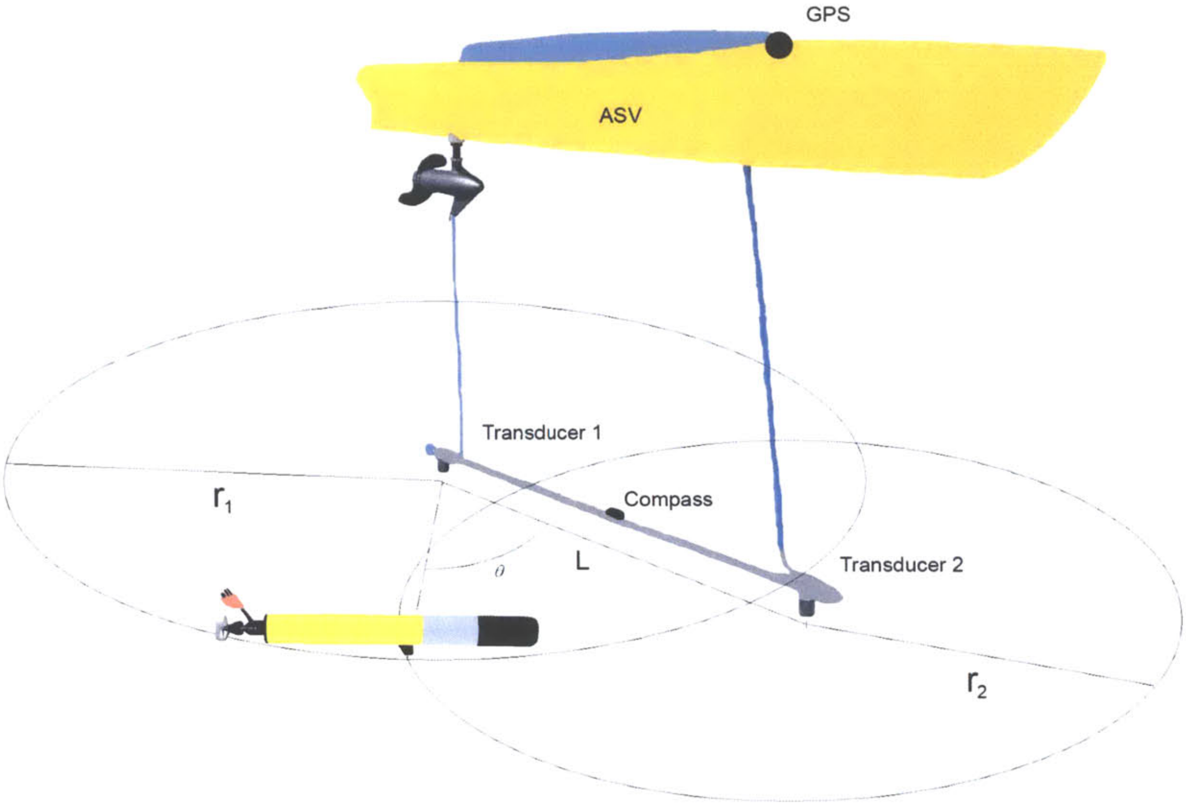

Figure 5.1: Navigation local ASC references

To determine the location of the AUV target in a global frame (X_t^G), a rotation matrix is first calculated using Equation (5.5).

$$M(\phi) = \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix} \tag{5.5}$$

The global position of the ASC is determined with the GPS unit installed above the array. The position of the GPS on the ASC (X_v^G), in reference to the array origin is known and adjusted by including the distance between the GPS and transceiver 1(d) term in Equation (5.6) and is graphically shown in Figure 5.3.

$$X_t^G = M(\phi) = \left(X_t^A - \delta\,[2\;0]^\top + X_{v-5}^G\right) \tag{5.6}$$

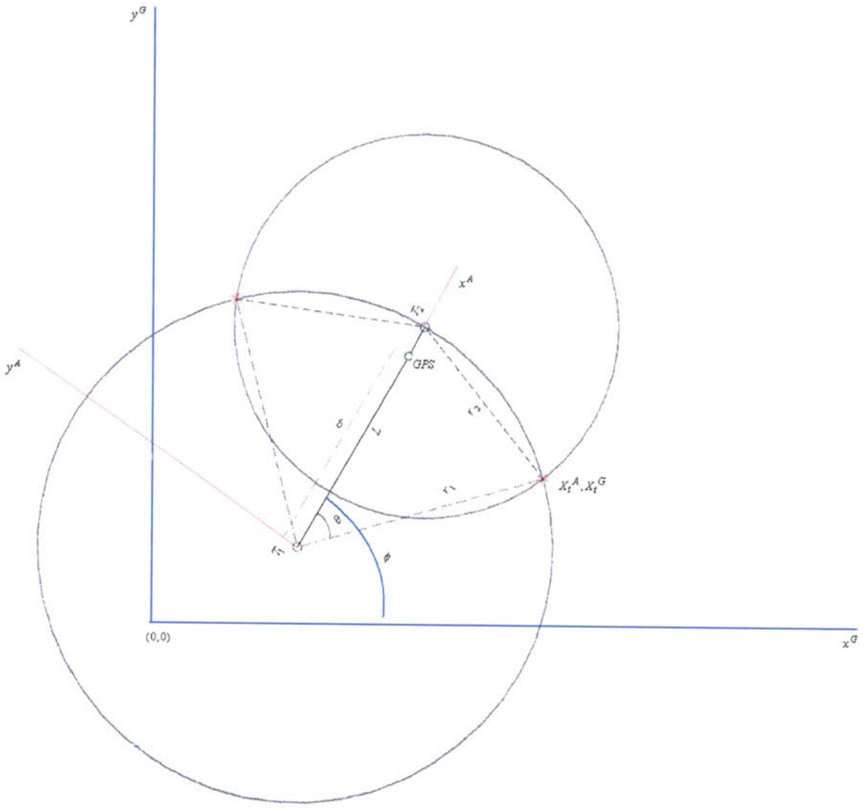

Figure 5.2: Reference frame conversion

For some range results an intersection cannot be determined. This occurs when the results from Equation (5.3) are $|\theta|>1$. This situation occasionally happens when the AUV approaches the baseline, a vertical plane running through the two transducers. The recorded range circles are very close to intersecting but limitations in the precision of the WHOI Micro Modems precludes an actual intersection from occurring.

In some cases, a valid transmission is received by only one of the modems (the other modem does not report any reception). In this case, its range is still calculated. Then by using the previous and the next valid range received in the data, a target vehicle course-made-good bearing can be interpolated. By combining this linear bearing line with the acoustic range measurement, a valid intersection can be obtained. This validity of this method is only applicable over a short timeframe due the freedom of the vehicle to turn. This solution is not causal. It is intended for use in conjunction with SLAM code, using the FLS to accurately map items of interest.

5.5 Baseline Ambiguity

The previous figures referenced all show another possible solution to the location of the vehicle on the mirror side of the baseline. For a single transmission, it is not possible to remove the baseline ambiguity, unless geographic limits such as land exist. However, once additional transmissions are received it is possible to eliminate possibilities, provided the ASC is moving. Removing the erroneous baseline locations and paths when the ASC is moving is preformed by first determining the distance covered between receptions for each side, as shown in Equation (5.7). The distances are typically not equal due to the change in angle of the array. When trying to determine the track of a vehicle on the wrong side of the baseline, the maximum velocity constraints remove the possibility for the UAV to exist on that side due to erratic variation in speed or exceeding the maximum capable speed of the vehicle. Bounding the maximum distance a vehicle can travel over consecutive pings eliminates the possibility for the vehicle to exist on the port side of the baseline, as shown in Figure 5.4. Each side range is verified to see that is does not it exceeds the maximum allowable distance traveled with a known vehicle maximum velocity constraint, $X_{(V\max)}$, as shown in Equation (5.8). If it does exceed the maximum allowable range that side is eliminated.

$$X_p = \frac{(X_{1p} - X_{2p})}{t}$$
$$X_s = \frac{(X_{1s} - X_{2s})}{t} \tag{5.7}$$

$$X_{s.p} < X_{(V\max)} \tag{5.8}$$

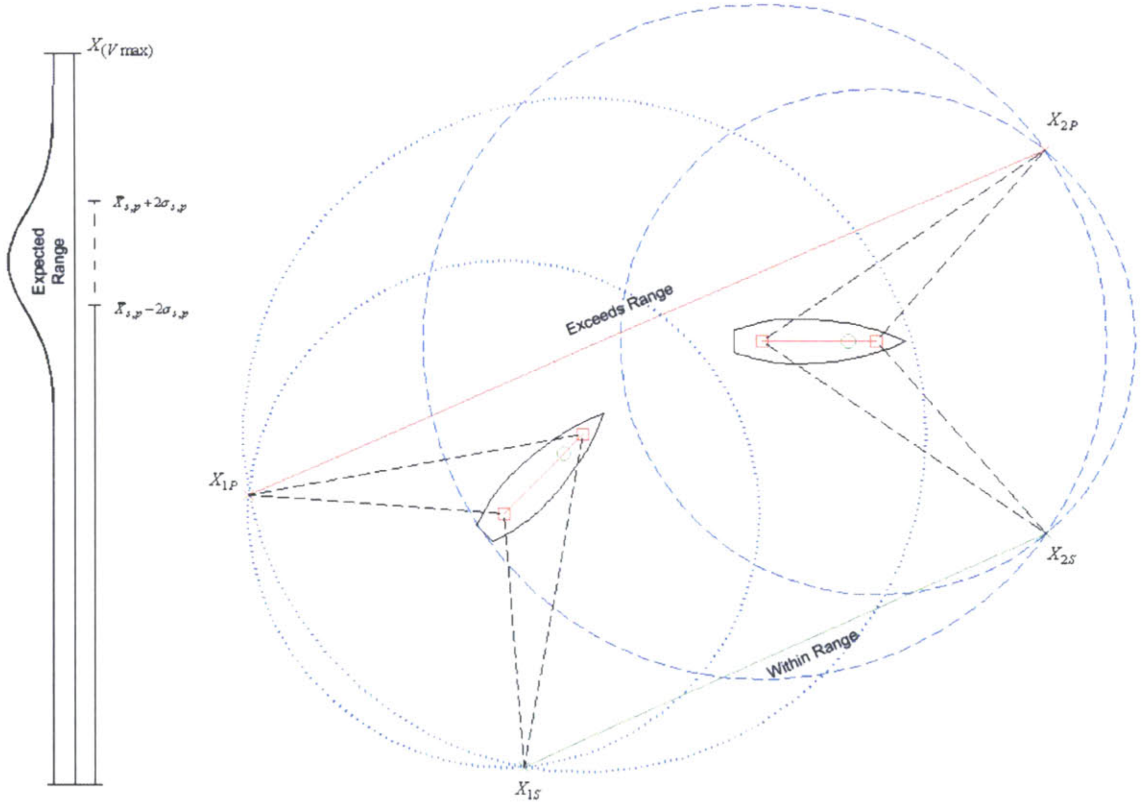

Figure 5.3: Baseline ambiguity

If both sides are still possible, the previous five ranges are used to calculate an averaged distance, as shown in Equation (5.9). The side with the smallest deviation equates to the most constant speed, as shown in Equation (5.10). This side is selected as the best choices.

$$\bar{X}_s = \frac{\frac{(X_{1s}-X_{2s})}{t} + \frac{(X_{2s}-X_{3s})}{t} + \ldots + \frac{(X_{4s}-X_{5s})}{t}}{5} \tag{5.9}$$

$$\sigma_s = \sqrt{\frac{1}{5}\sum_{i=1}^{5}(X_{is} - \bar{X}_s)^2} \tag{5.10}$$

A valid side typically falls within two deviations of the average as shown in equation (5.11):

$$\bar{X}_{s.p} - 2\sigma_{s.p} \leqslant X_{s.p} \leqslant \bar{X}_{s.p} + 2\sigma_{s.p} \tag{5.11}$$

The ambiguity becomes obvious when the ASC is turning. During testing, the mobile-array ASC was driven in an arc path to remove the baseline ambiguities, as shown in the results. The largest challenge in removing the baseline ambiguity is receiving consistent modem transmissions, which enable a range intersection to be determined. Intersection consistency allows the moving average and standard deviation to remain steady. There are other instances when it becomes difficult to resolve baseline ambiguity because both criteria are met. However, as previously stated, these typically happen only when operating near the baseline plane. Once the vehicle had assertively cleared the baseline plane, a solution can be determined. The small amount of time where possible dual solutions exist is when the locations of both solutions are close together. At this point, it is well below the error of the GPS and is ignored for the purpose of this paper. This also eliminates the case when the vehicle travels from (X_{1P}-X_{2S}) or (X_{1S}-X_{2P}).

5.6 Environmental Factors in Testing

Initial testing was preformed on the Charles River in Cambridge, Massachusetts. The MIT sailing pavilion was the host of the shore equipment. The basin of the Charles offers complex bathymetry gradient; dredging and sediment have formatted a unique topography. A shallow gradient with random potholes spans out gradually until a six-meter average is reached then it drops off in the channel as shown in Figure 5.5 and 5.6. The combination of sandbars and potholes proves challenging for defining an optimal FLS angle.

The water is a unique combination of fresh and salt water with a thermocline separating the two layers. There are also unpredictable upwelling between the layers that cause eddies and currents through the test area, as shown in Figure 5.7.

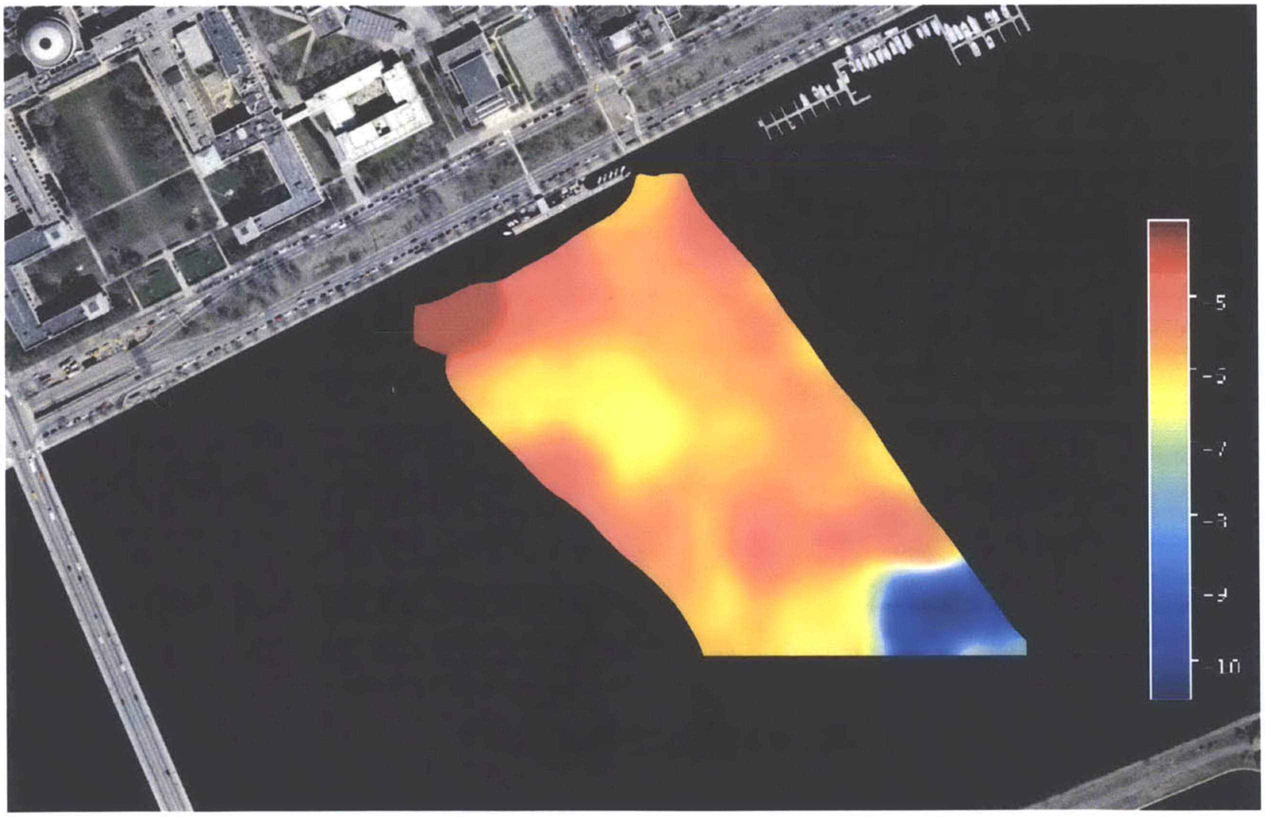

Figure 5.4: Charles River bathymetry top view (Meters, REMUS)

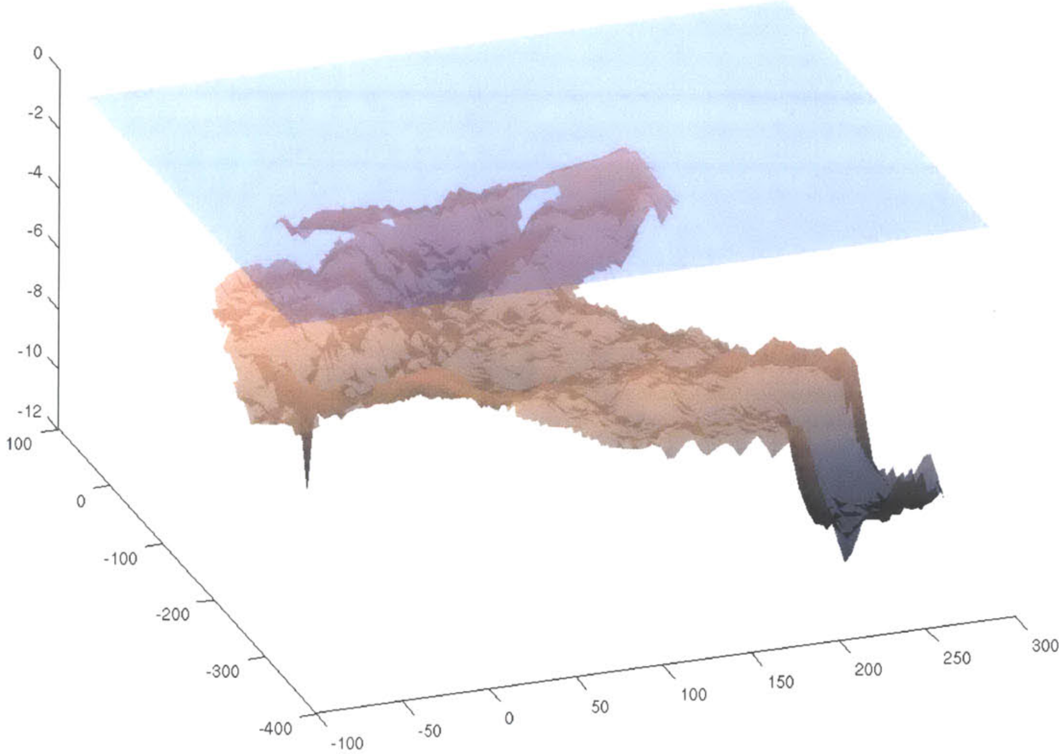

Figure 5.6: Charles River bathymetry three dimensional view (Meters)

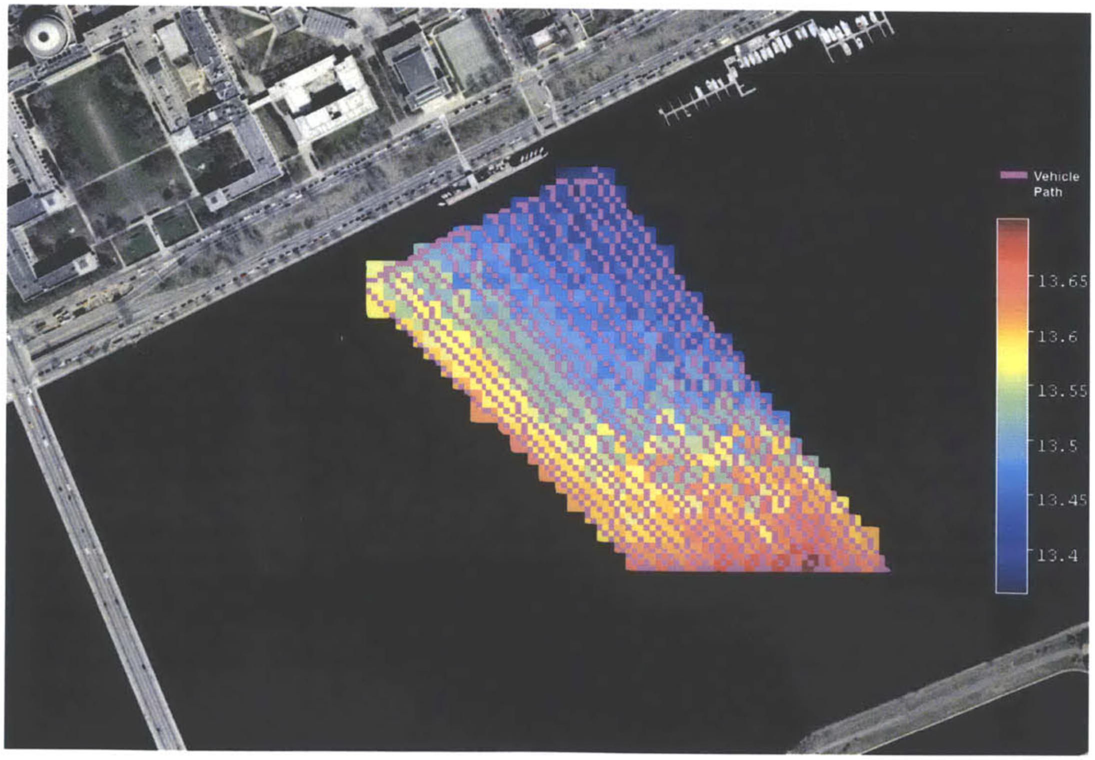

Figure 5.7: Charles River water temperature (Celsius, 2m depth, REMUS)

Other factors included the varying sound speed caused by the salinity change in some areas of the river. Figure 5.8 shows the change in salinity for a small section of the river encompassing the MIT Sailing Pavilion.

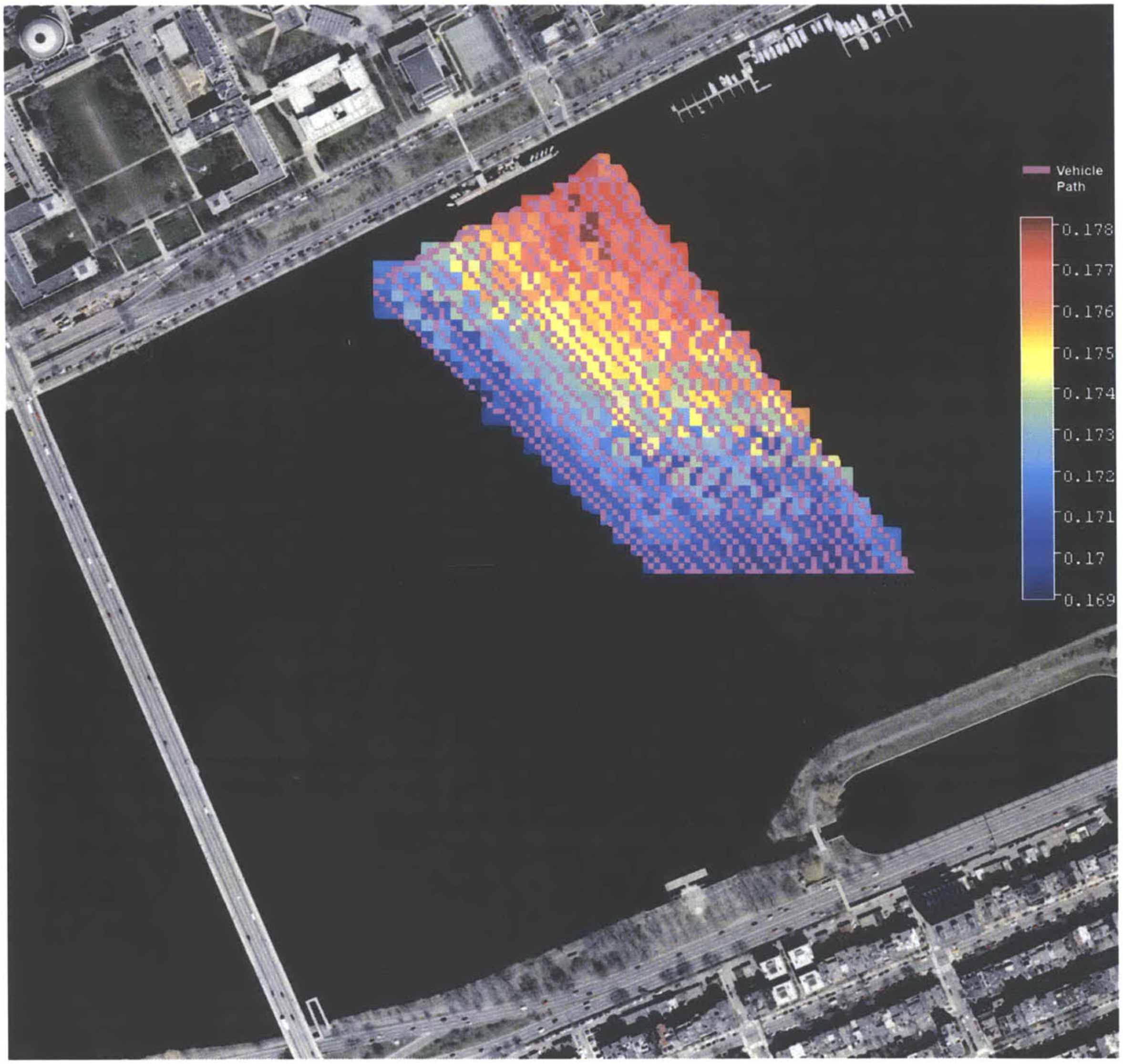

Figure 5.8: Charles River water salinity (Grams/Liter, 2m depth, REMUS)

When compared to Figure 5.7 it can be seen that the salt layer underneath is colder, as would be expected. These results were taken in November, which results in the minimum amount of thermal change and layering compared to other times of the year. The change in the sound speed as a result of the temperature and salinity is shown in Figure 5.9.

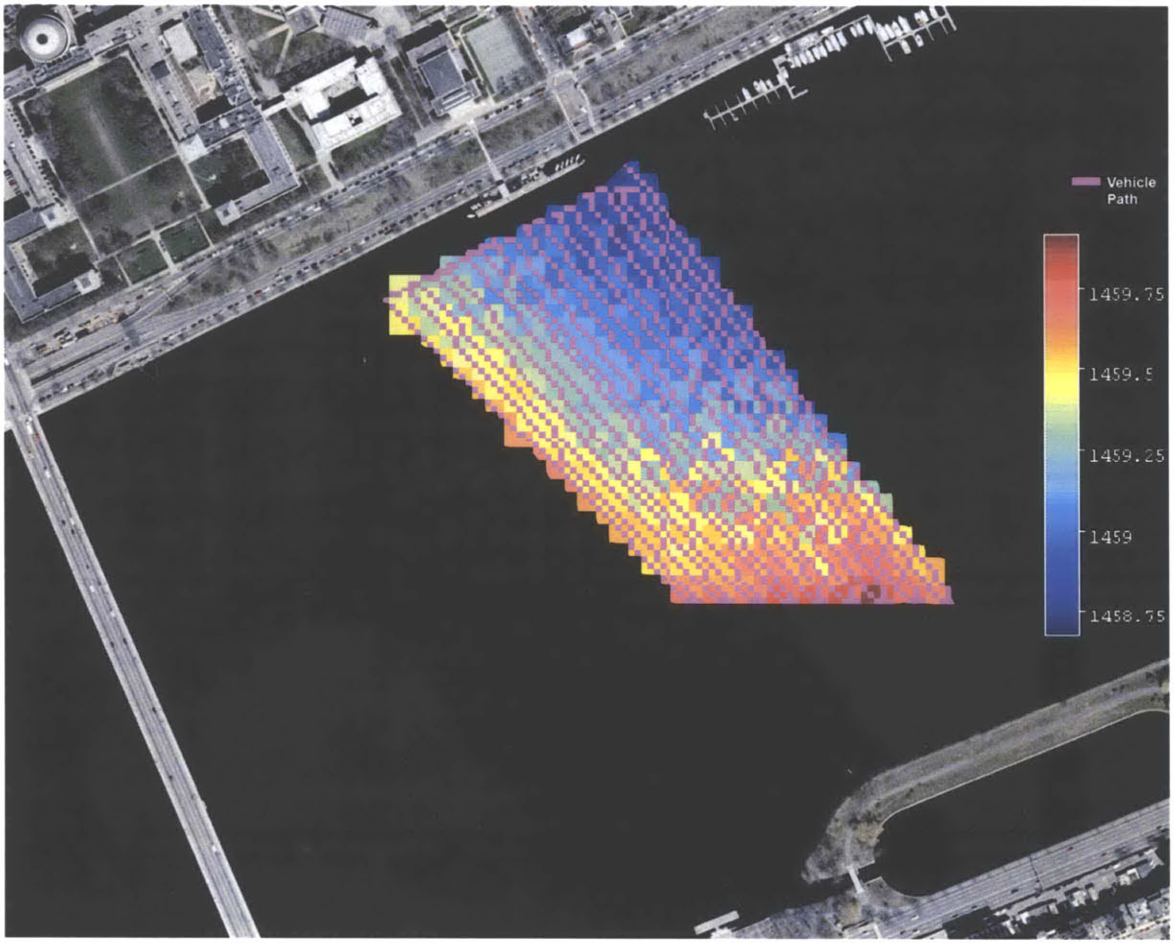

Figure 5.9: Charles River water sound speed (Meters per Second, 2m depth, REMUS)

In addition, the current on the bottom layer is in the opposite direction of the fresh water current on top. The shear current between the top and bottom layers is usually within five centimeters per second, however this changes significantly when the water locks of the Charles River dam are opened to adjust the water level. There is a large amount of material suspended in the water column, decreasing the visibility to less than three feet. This has a small affect on the sonar images by decreasing the resolution, possibly due to small air bubbles attached to the sediment, but acceptable results are achievable using a FLS. WHOI Micro Modem Acoustic transmissions did not seem to be affected by these environmental factors other than the change in sound speed.

5.7 Results

Stationary Array Results

The target test vehicle used was another ASC for the purpose of GPS ground truth and continuous clock synchronization through a WiFi link. A single towfish with transducer, as shown in Figure 5.10, was towed below the vehicle at two meters depth. This was the first test with the towfish and it used the original tailfin design. When the ASC was at its normal velocity of 2 m/s, the towfish with this tailfin did not fly in a streamline orientation.

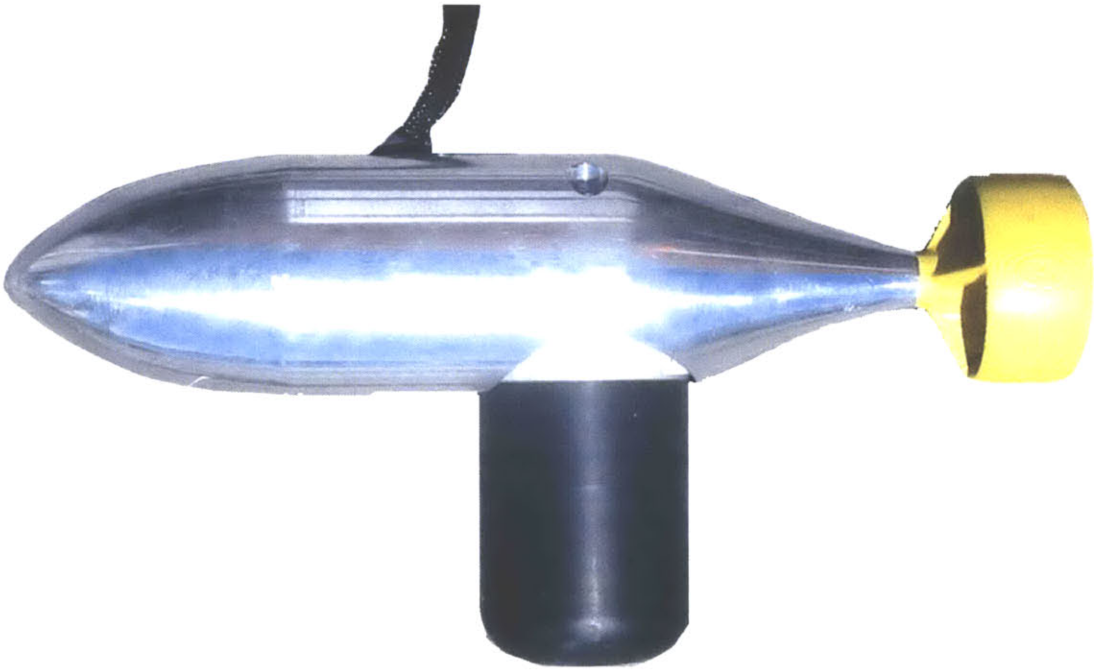

Figure 5.10: Original tailfin towfish with WHOI Micro Modem transducer

Testing was preformed on numerous days throughout 2006. The first test verified the configuration, the resolution of different length arrays, and the consistency of the clock system using the GPS PPS signal. The deck setup is shown in Figure 3.7. The array was fixed to the dock at two meters depth. It was not allowed to rotate, enabling both sides of the baseline to be possible, however the results show that one side of the baseline was not located in the river and was easily rejected, Figure 5.11.

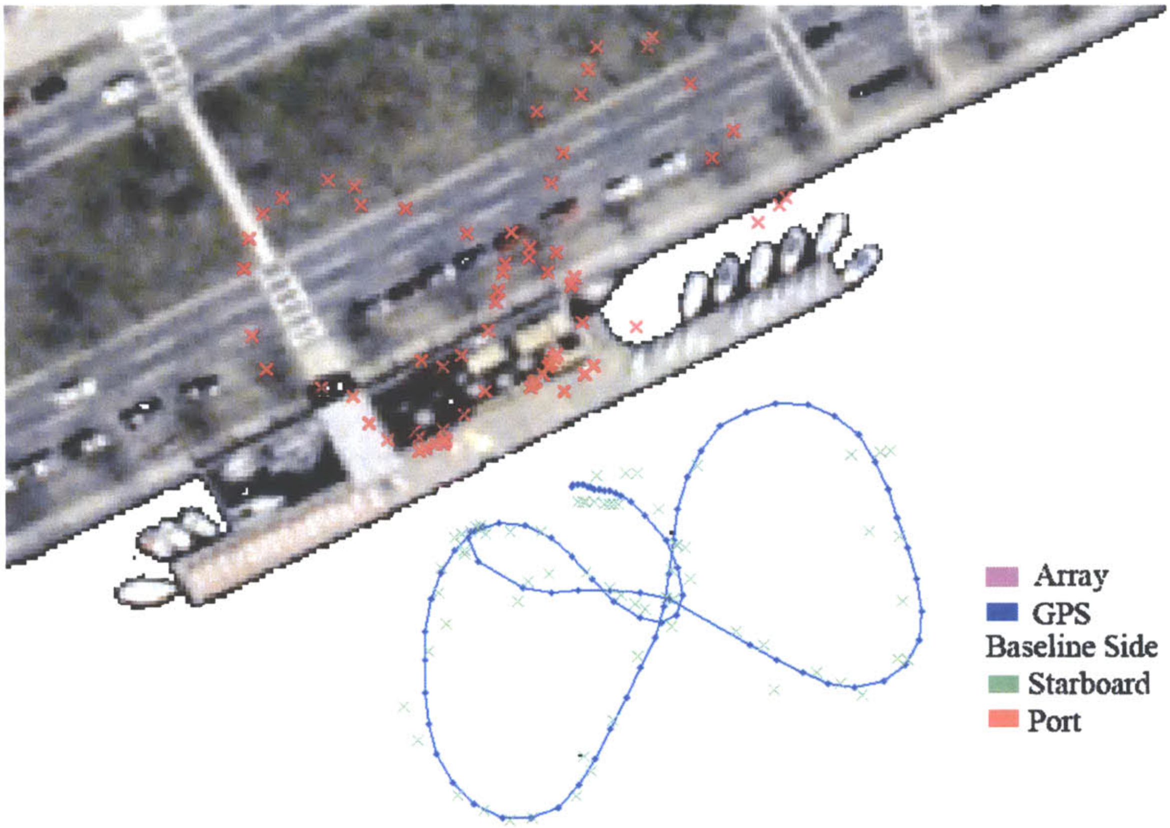

Figure 5.11: Baseline ambiguity solution with stationary array

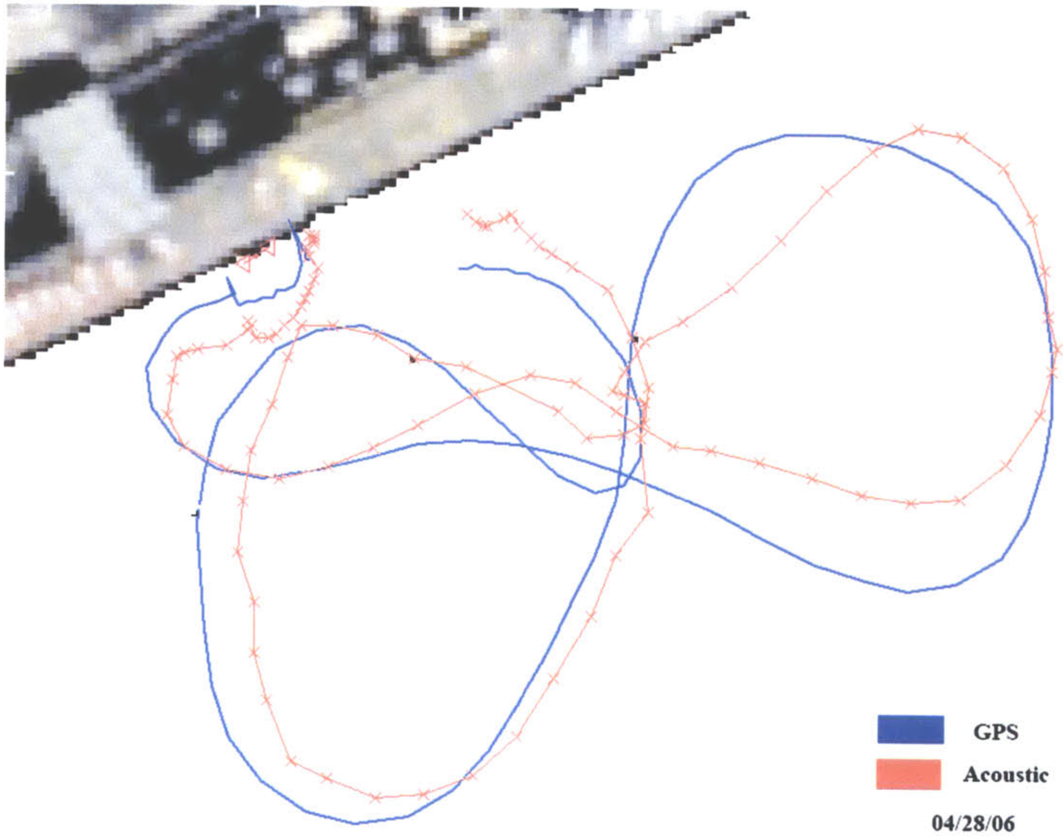

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Figure 5.12: Stationary array initial testing

The results achieved were acceptable and proved that tracking of a vehicle was possible as shown in Figure 5.12. These are the results from initial testing; refinements in software logging were made for future testing. Some test runs showed better results then others when working with the fixed array. The results proved the WHOI Micro Modem clock was accurate enough to record the one-way time of flight values. They also proved that the two-meter array was capable of recording a large enough change in range to track vehicles. Testing of the rigid array showed some anomalies and were noted during post-processing analysis.

Figure 5.13 shows a portion where no intersection was detected, represented by a straight line with no "X" range intersection solutions. This was believed to be caused from transmission reflections off the granite quay wall, which defines the North-West perimeter of the Charles River. Either the WHOI Micro Modem rejected logging the time because of the multiple signals or the overlap caused errors in the transmission.

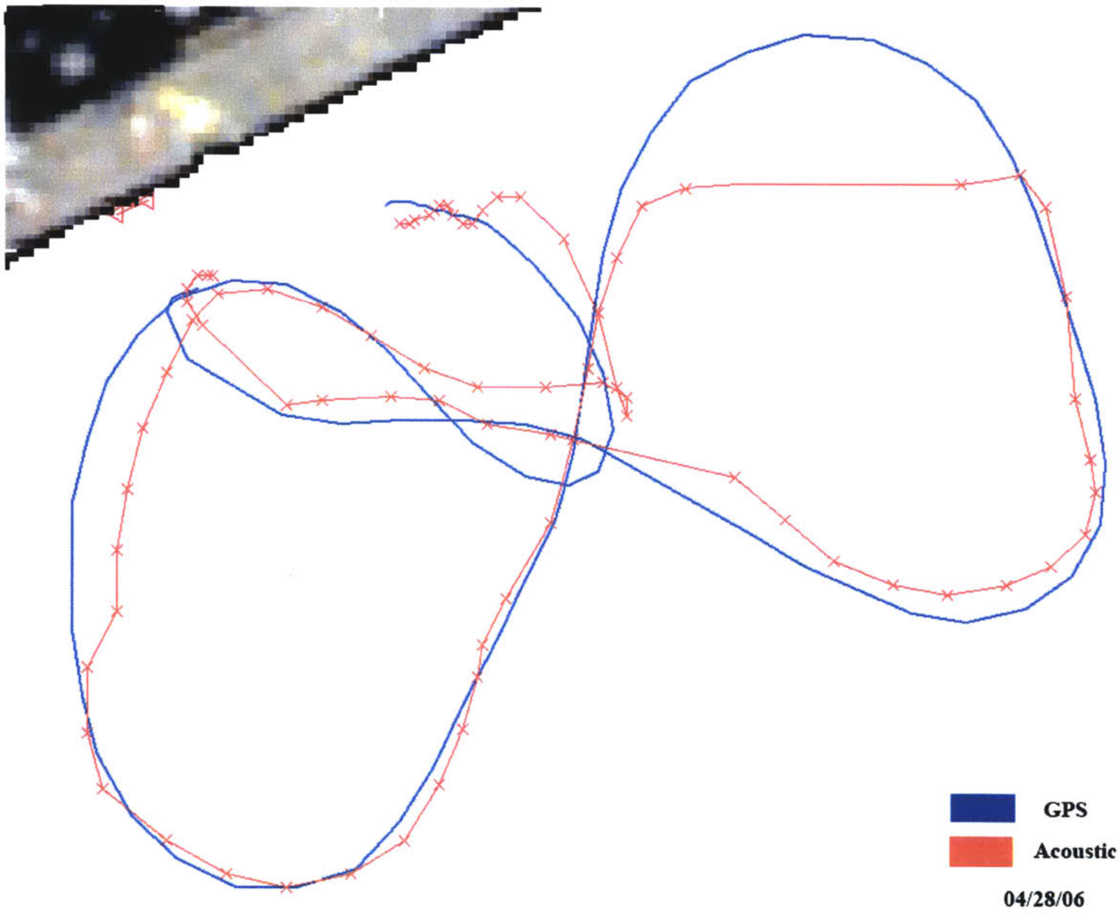

Figure 5.13: Stationary array with missed ranging

Figure 5.14 shows the effects of transmission muli-pathing; again, the quay wall is believed to have caused the interference, shown in the top right portion of the track. Multi-pathing caused the expected distance to be longer than the actual because the signal must bounce off an object, increasing the recorded time-of-flight. These errors occurred only when working with the stationary array that was located within ten meters of the quay wall. All of the fixed array results required using geographical constraints to determine the correct side of the baseline.

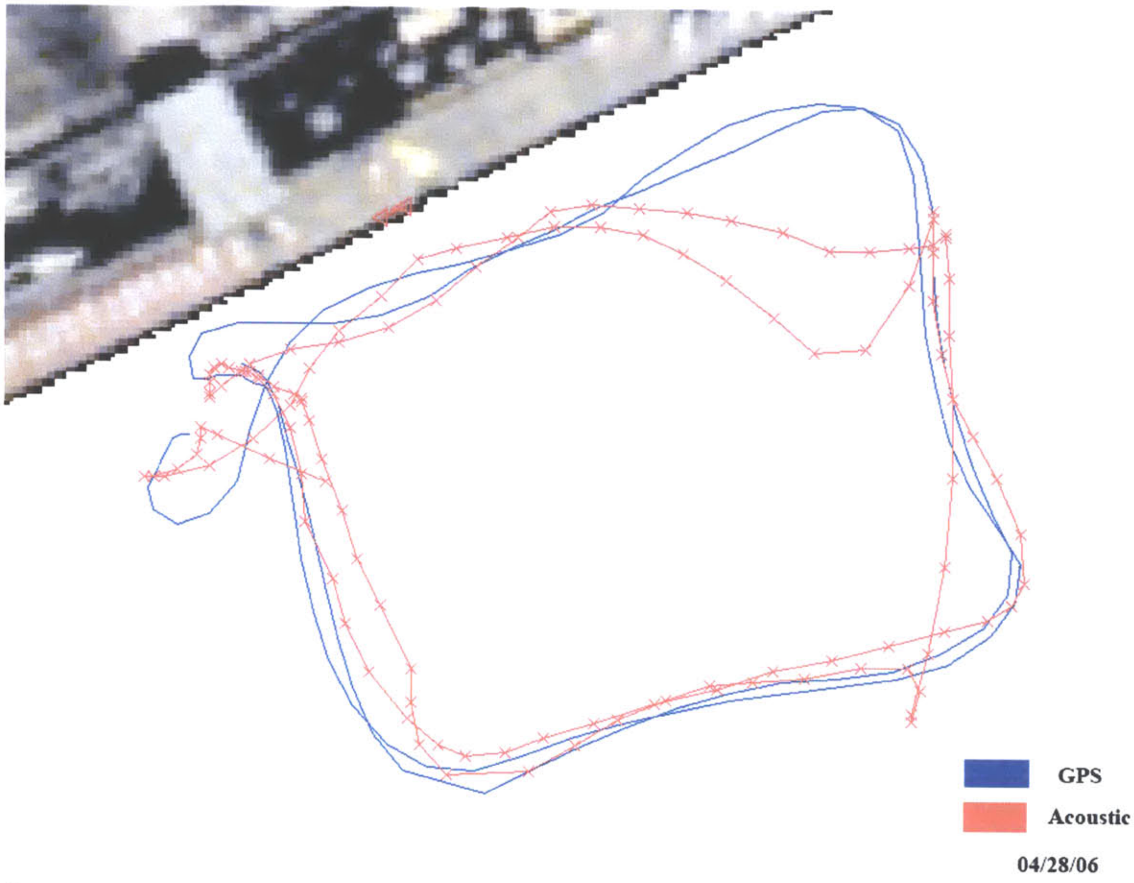

Figure 5.14: Stationary array with multi-path effect

Mobile Array Results

The second tests were completed using two ASC's. The first craft towed the array at two meters depth. The second vehicle setup remained the same as in the stationary testing, except the new tailfin was installed on the towfish. The array vehicle performed a slow arc course outside of the other vehicle, as a shown in Figure 5.15. The intention was to limit the number of times the baseline was crossed or approached.

Figure 5.15: ASC with array course

The second target vehicle had two different courses to run. The first course was a few straight lines paths parallel to the shore. The intention was to simulate the vehicle driving a course to the terminal phase of the Ranger AUV. The second course was three connected circles in a modified figure-eight configuration. This path was designed to simulate the Ranger AUV attempting to require a target by performing multiple passes, as shown in Figure 5.16.

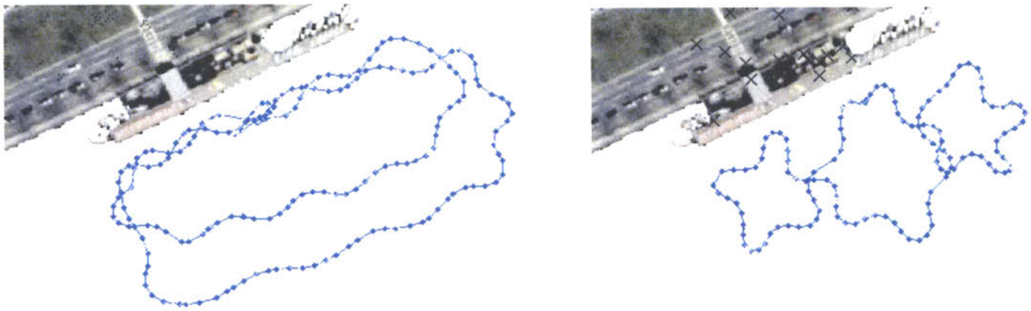

Figure 5.16: Actual course one and two from GPS data

The original paths were intended to be straight lines and the circles and were intended on being at a steady yaw angle. However, during these tests, the ASC had the FLS and code operating to process images, and SLAM code running. The effect of this configuration was not fully known. The CPU at this load caused some helm control messages to be missed, causing an issue with the vehicle control, which can be seen in the course plots. The ASC single 700Mhz CPU is not as powerful as the AUV. Under AUV control, this problem is not expected to occur. Even though the control results were unintended, this set of data made the vehicle much more difficult to track because the vehicle was in a continuous state of turning left or right.

The CPU receiving all messages becomes important when performing the weighted average calculations to determining if the vehicle had crossed the baseline. Calculations became much more dependent on receiving the maximum amount of transmissions, for calculating the minimium deviation. Determining which side of the baseline the vehicle is on with a moving array usually becomes apparent when plotted, as shown in Figure 5.17. During this test, the location of the target ASC was exclusively on “side 1” of the vehicle. When these same results are plotted in Cartesian coordinates, the results become clearer, as in Figure 5.18.

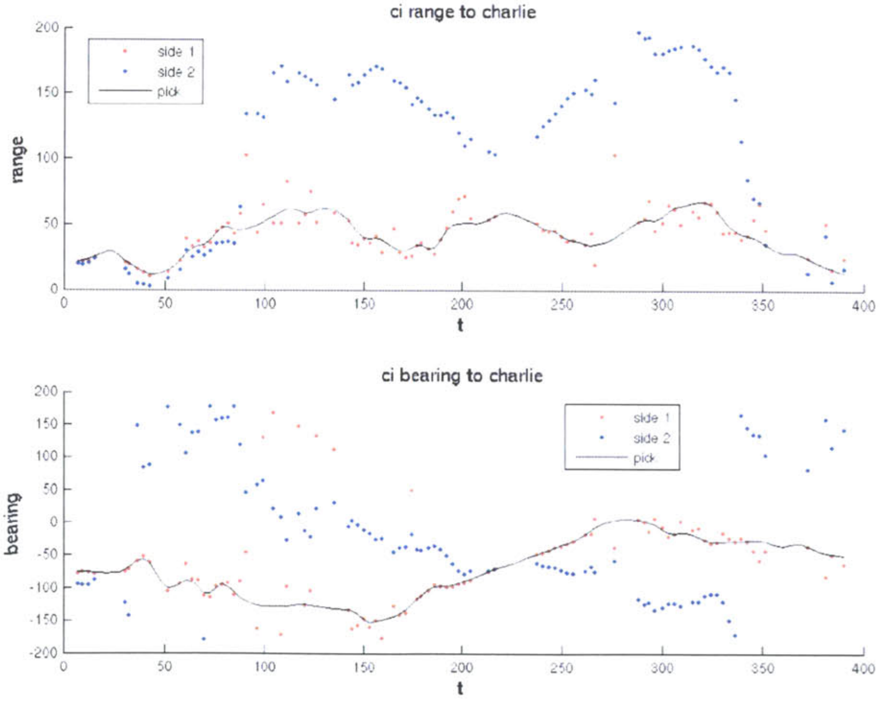

Figure 5.17: Baseline range and bearing results with moving array

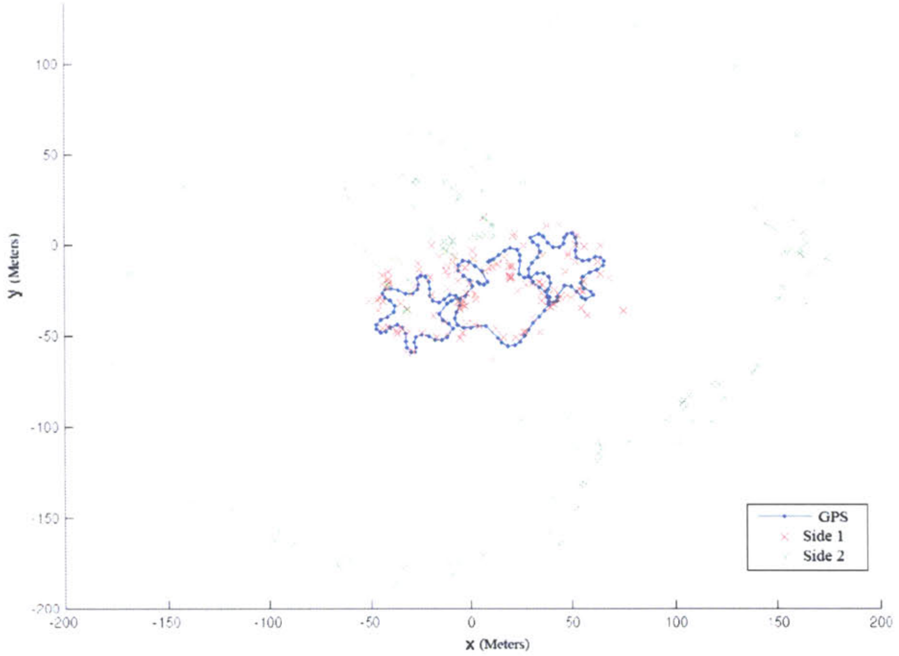

Figure 5.18: Baseline ambiguity results in Cartesian Coordinates

The vehicle track from the data gathered on the above runs was processed, rejecting outliers, isolating the correct baseline, and smoothed, as in Figure 5.19.

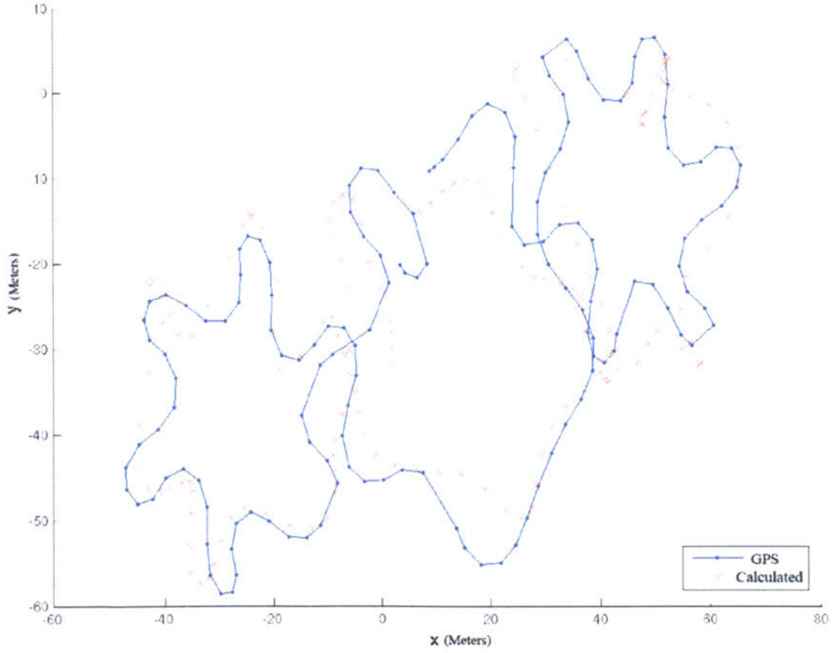

Figure 5.19: Final vehicle track in Cartesian Coordinates

During this test run, the average difference from GPS position to calculated track position was 2.7 meters. The difference between the GPS and the modem range is shown in Figure 5.20. At no time did the range difference exceed the error of one GPS. Throughout the test, the reported GPS error was between four to six meters for each unit. Post-processing of all of the datasets resulted in a mean error of 3.9 meters.

This result is a significant increase in underwater vehicle tracking capability. When compared to a vehicle performing an underwater leg with an unknown current pushing it perpendicular to the intended course, this size error would quickly accumulate. For example, using the Ranger AUV in a small crosscurrent of three cm/s, the vehicle would be pushed off its course with a larger error within 100 meters. In a one-knot current, this error could be accumulated within eight seconds with no correction. Ranger has no correction capability when submerged.

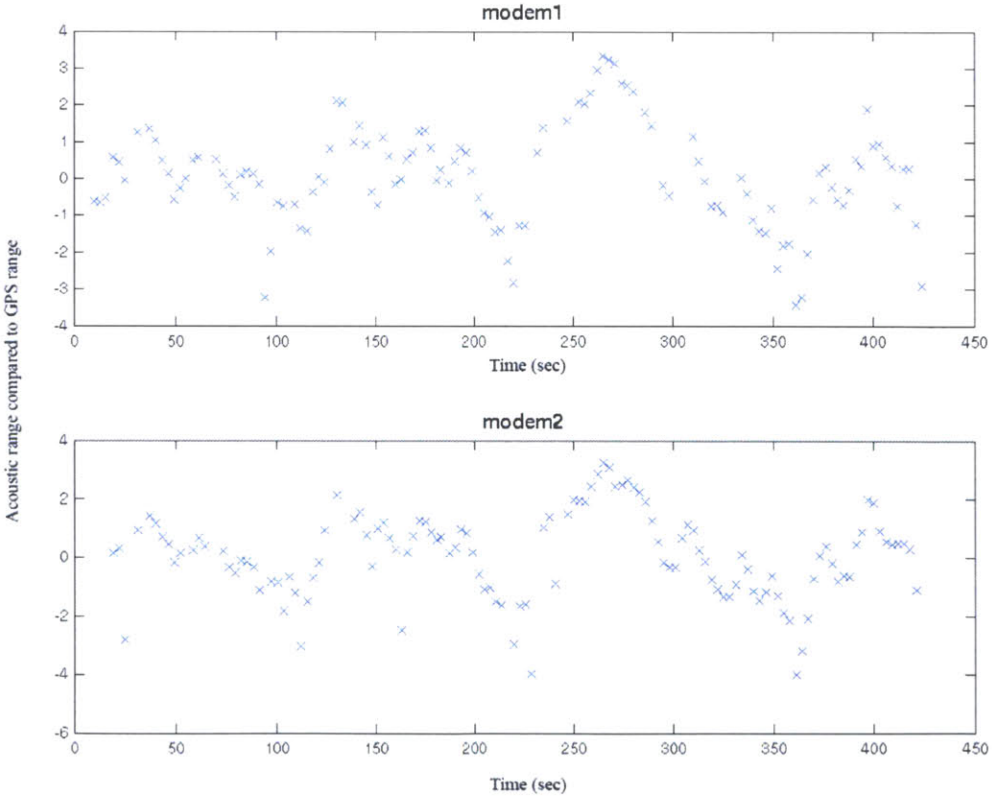

Figure 5.20: Difference in acoustic range versus GPS for course two

Tests were performed that had the target vehicle crossing the baseline, using course two. Below are the results for a run that had a minimal amount of interference caused from the environment. Figure 5.21 shows the results of course two for the raw range error from each transducer, when compared to the GPS recorded position.

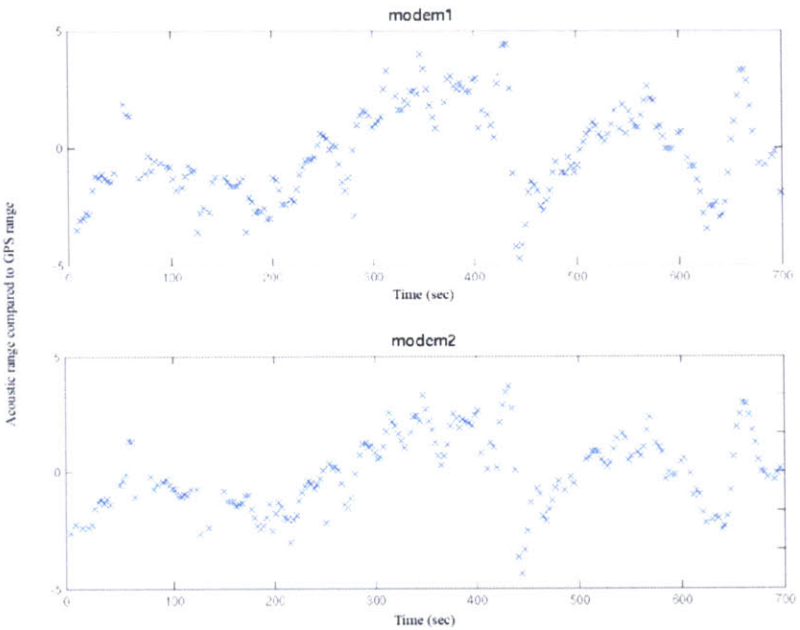

Figure 5.21: Difference in acoustic range versus GPS for course one

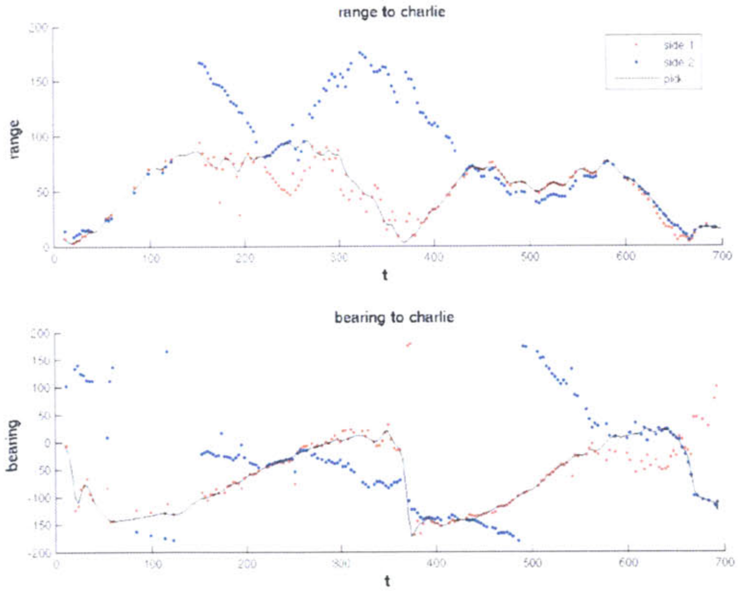

Figure 5.22: Difference in acoustic range vs. GPS for course one

To resolve the baseline ambiguities, a moving average was determined. The results in Figure 5.22 show the corresponding range and bearing measurements for the received range intersections. In addition, it shows which side of the baseline the vehicle was traveling on after filtering.

As in the previous case, the baseline ambiguity is minimized with a moving array. However, it can be seen that crossing the baseline occurred in a number of different locations in this test run. When looking from a Cartesian top view it is easy to see the solution selection for one side of the baseline to the other, as shown in Figure 5.23. The erroneous side tends to become very noticeable once the target vehicle has some angular separation from the baseline plane.

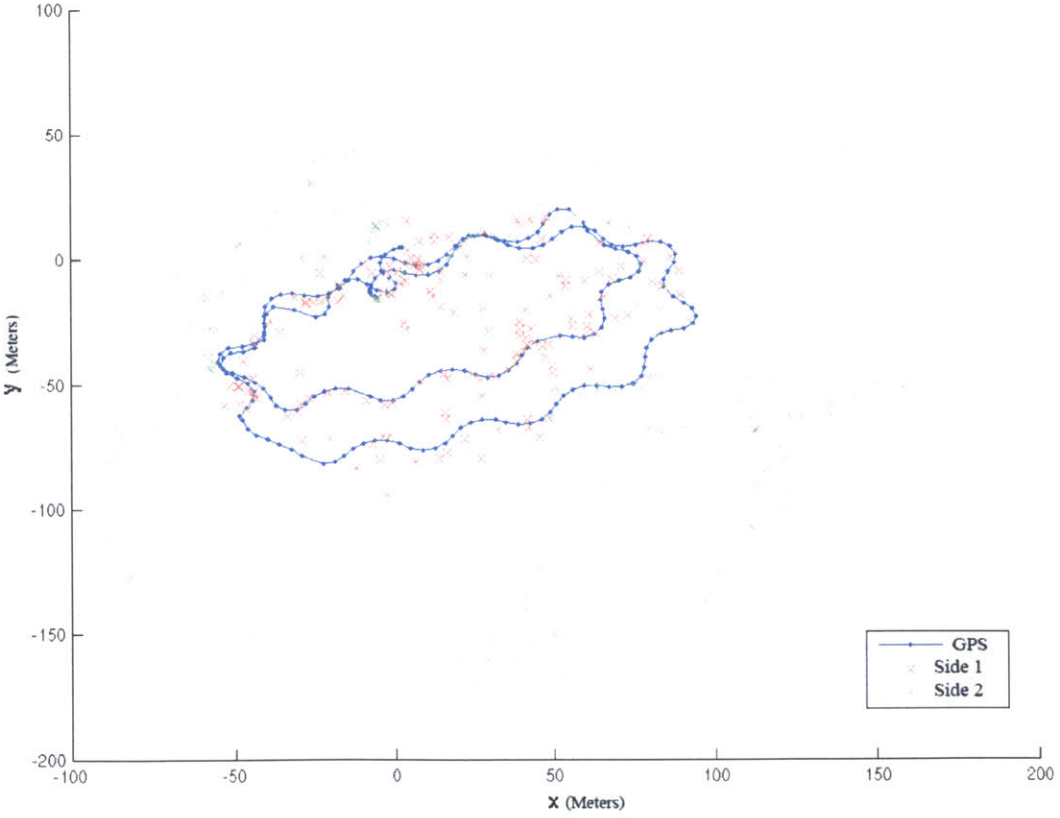

Figure 5.23: Raw data intersections on both sides of the baseline

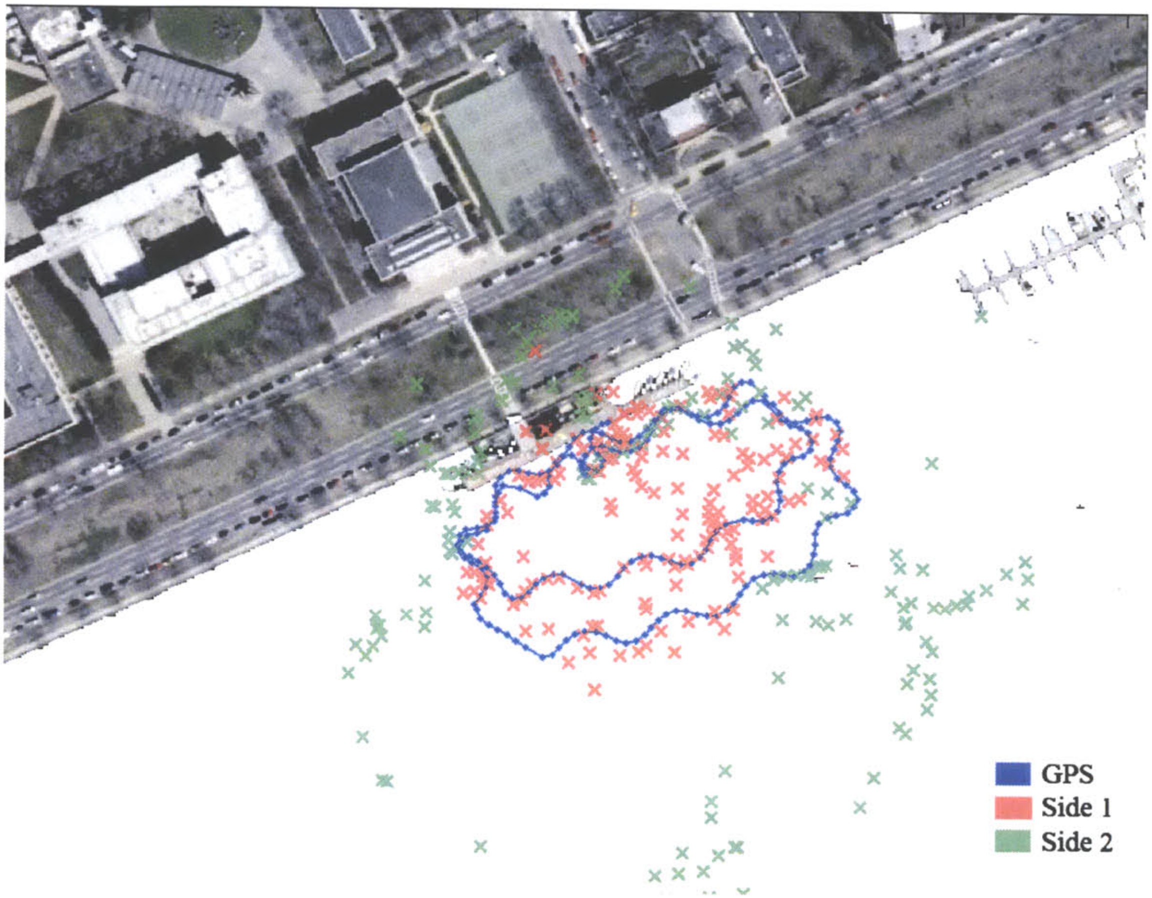

Figure 5.24: Natural baseline ambiguity constraints

No natural constraints were used to determine the correct baseline side. However, when the plot is overlaid on a local map it can be seen that an additional filter is possible, as shown in Figure 5.24.

The final calculated course-made-good (after removing outliers, and baseline ambiguities and interpolating the single range measurements) is shown in Figure 5.25. As seen in the calculated course plots, the determined path is exceptionally close to the GPS recorded path. In this particular run the error was within 4.2 meters.

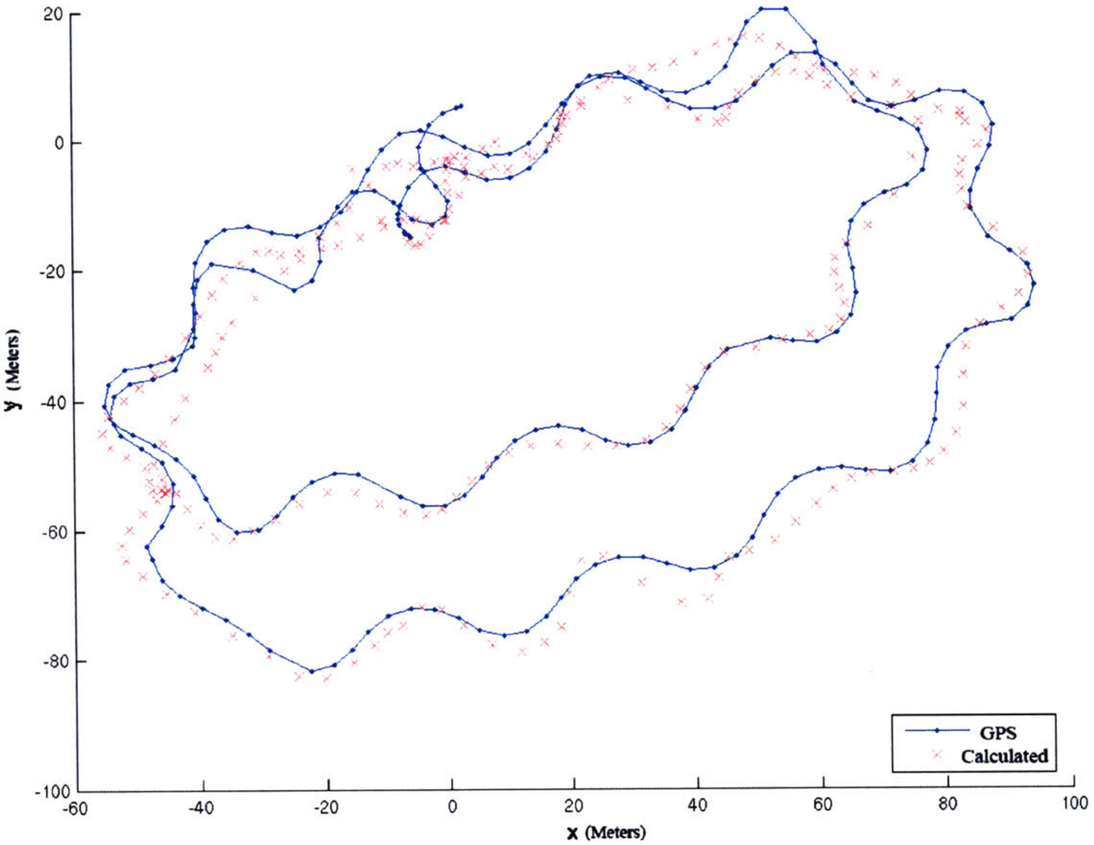

Figure 5.25: Final vehicle track in Cartesian Coordinates for course two

6 Summary and Conclusion

6.1 Summary of Hardware Contribution

In the continuing development of the RUSSO ASC, we expand our current capabilities of the Scout ASC. It will fulfill a number of autonomous vehicle goals outlined by ONR. Fulfilling a number of goals with one platform is an important design criterion, if it is to be implemented by the Navy. The main ONR goal attained is the sensor fusion, combining independent assets from each vehicle to strengthen and increase the mission envelope of all. The integration of an AUV into the wetbay of an ASC capable of transporting the AUV over long distances was the primary goal. By increasing the operational deployment range, it allows for a greater standoff distance for the man asset, which reduces the risk to human life. The integration also allows for the fusion of the power system and the communication systems of the ASC and AUV. The limiting factor of the AUV was its power endurance. The AUV volume required to increase power is not available without adversely affecting the performance characteristics of the vehicle. This is what makes the power conduit imperative. The communication channel allows for the vehicles to synchronize their data and is designed to push or pull data as required by the code.

The RUSSO ASC will be able to perform to the standard set of missions of the Scout ASC and expand into a variety of different roles. The design has added flexibility by being able to support a variety of craft in the wetbay. Systems were installed to include generic ports that are made available in anticipation of supporting other vehicles. These will allow a multitude of future autonomous vehicles and modules to be launched from the bay.

6.2 Future Hardware Research

Future work should include integration of a battery pack with longer life, dramatically increasing the range of silent operations. In addition, the installation of an engine and alternator will increase the operational duration from hours to days. Augmenting the underwater sensor suite with a variety of surface components such as video imaging and meteorological data will also increase the size of operational area logged by the ASC. This would continue to fill additional requirements described by ONR by sending pertinent shore information to the command and control element.

Minimizing the surface signature of the vehicle would be an additional design goal towards a true real-world beach reconnaissance vehicle. This can be accomplished through a number of design innovations. Adjusting the ballast by flooding the chamber of the vehicle would decrease the surface area above water. Creation of a molded cover to place over the entire ASC would assist in camouflaging the vehicle. Any number of water hazards exists and when seen they tend to be avoided not scrutinized for hidden capabilities.

Designing an AUV recovery system would be the next step in the evolution of the RUSSO ASC. This would enable an AUV to be recovered from one target area, moved to another target area, and launched on a new targeting mission.

6.2 Summary of Software Contributions

The results from the acoustic array have shown that one surface craft can be used to accurately track an underwater vehicle. This reduces the number of deployed assets required when trying to perform LBL or MLBL in the same situation. The results have shown that it is possible to achieve underwater vehicle location results similar to receiving GPS on the surface. Continued testing in a variety of environments will enable fine-tuning of the algorithms.

6.4 Future Software Research

Future development such as enhancing the autonomous potential of the ASC would increase the mission capabilities. Specifically, adding the behavioral ability for the ASC to optimize its location and heading with respect to the AUV would allow for the best reception and resolution of the acoustic transmission.

Additional developments would require WHOI supporting a small change in the modem packet. There are a number of unused bytes in the packet that could be filled. In the modified packet, we could send a small amount of vehicle state data. By adding vehicle heading and velocity into the packet, we would eliminate the interpolation process when only one transmission is received.

Testing of multiple ASC's with arrays in the same area could have substantial operational benefits. The fusion of multiple vehicle location logs collected by multiple ASC's would present a novel problem.

Increasing the capabilities of the FLS beamforming software to increase the resolution would enable us to classify objects and simplify SLAM algorithm solutions. If an object comes into view and is determined to be a specific known target, locating your position would only be a matter of solving the rotation matrix.

This area of autonomous underwater vehicle development is still in its infant stage. There are a number of imminent developments on the horizon. These will continue to increase the working envelope of underwater vehicles. The possibilities of different avenues each of these advances will take us are endless. The true test for any development: is it applicable to a real-world operational environment? Is there an operational need for it? We feel the issues described in this thesis have in fact increased our capabilities and will be used in future endeavors.

List of Abbreviations

ACOMMS	Acoustic Communications
ADCP	Acoustic Doppler Current Profiler
ASC	Autonomous Surface Craft
AUV	Autonomous Underwater Vehicle
C/NA	Comunication / Navigation Aid
CRRC	Combat Rubber Raiding Craft
EFI	Electromagnetic Frequency Interference
EMI	Electromagnetic Interference
EOD	Explosive Ordnance Disposal
FLIR	Forward Looking Infrared
FLS	Forward Look Sonar
FNC	Future Naval Capabilities
FSW	Feet Seawater
GPS	Global Positioning System
HDPE	High Density Polyethylene
IMINT	Imagery Intelligence
INS	Inertial Navigation System
ISR	Intelligence, Surveillance and Reconnaissance
LBL	Long Baseline Acoustic Tracking
LPD	Low Probability of Detection
LPI	Low Probability of Intercept
MCM	Mine Counter Measures
MIT	Massachusetts Institute of Technology
MLBL	Moving Baseline Acoustic Tracking
NMEA	National Marine Electronics Association
NSW	Naval Special Warfare
NSWC	Naval Surface Warfare Center
NUWC	Naval Undersea Warfare Center
ONR	Office of Naval Research
OTH	Over the Horizon
REMUS	Semi-Autonomous Hydrographic Reconnaissance Vehicle
RF	Radio Frequency
RHIB	Rigid Hull Inflatable Boat
ROV	Remotely Operated Vehicle
RUSSO	Autonomous Surface Craft
SAHRV/REMUS	Semi-Autonomous Hydrographic Reconnaissance Vehicle
SATCOM	Satalite Communication
SBL	Short Baseline Acoustic Tracking
SCN	Search, Classify, Map
SCOUT	Autonomouse Surface Craft
SDV	SEAL Delivery Vehicle
SEAL	Navy Sea, Air, Land Commandos
SLAM	Self Localization and Mapping
SLS	Side-Looking Sonar

UAV	Unmanned Aerial Vehicle
USBL	Ultra Short Basline Acoustic Tracking
USS	Undersea Search and Survey
USV	Unmanned Surface Vehicle
USW	Under Sea Warfare
UUV	Unmanned Undersea Vehicle
VBS	Variable Ballast System
WHOI	Woods Hole Oceanagraphic Institute

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