Development and Evaluation of a USV Based Mapping System for Remote Sensing of Eelgrass Extent in Southern California

by

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Dedication

This paper is dedicated to my parents, Brian and Karen, whose constant encouragement is never forgotten.

Table of Contents

List of Figures

List of Tables

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List of Abbreviations

ASV	Autonomous Surface Vehicle
AUV	Autonomous Underwater Vehicle
dGPS	Differential Global Positioning System
ESH	Environmentally Sensitive Habitat
GCS	Ground Control Station
GIS	Geographic Information System
GISci	Geographic Information Science
GPS	Global Positioning System
GNSS	Global Navigation Satellite System
MPA	Marine Protected Area
NOAA	National Oceanographic and Atmospheric Agency
SSI	Spatial Sciences Institute
SSS	Sidescan Sonar
USC	University of Southern California
UAV	Unmanned Aerial Vehicle
UMS	Unmanned Marine System
USV	Unmanned Surface Vehicle
UUV	Unmanned Underwater Vehicle
WMSC	Wrigley Marine Science Center

Abstract

Sidescan sonar coupled with a Global Navigation Satellite System (GNSS) provides a near photographic image of features underwater for use in mapping applications. Sidescan sonar acoustic pings are drawn as raw images, spatially referenced using GNSS coordinates and then mosaiced in specialized software to produce coverage areas. The resulting two dimensional images can then be analyzed in Geographic Information Systems (GIS) for manmade or natural underwater features. This technology has a special application for mapping eelgrass extent in Southern California, which has become a focus of research for the National Oceanic and Atmospheric Agency (NOAA) and several National Marine Estuary programs. Eelgrass is a submerged aquatic flowering plant that provides critical structural environments for resident bay and estuarine species, including abundant fish and invertebrates and is often a primary diet for several grazing snails. This project demonstrates the viability of creating a low-cost Unmanned Surface Vehicle (USV) with an attached sidescan sonar sensor for scientist and researchers to use in mapping eelgrass. The remote sensing imagery collected by the USV is classified in ArcGIS to calculate the full spatial extent of the visible eelgrass beds. The results of this project show acoustic imagery collected by a USV can be used to create classified bottom composition maps through manual classification. Unsupervised classification did not produce the desired results and is still a work in progress. By demonstrating these mapping tools, researchers can conduct studies at a much lower cost and on their own time instead of relying on expensive, contracted surveys.

Chapter 1 Introduction

Eelgrass is known as a habitat forming submerged aquatic species because it creates unique biological, physical and chemical values that support a variety of marine species and stabilize the surrounding sediment. Because of its importance as an Environmentally Sensitive Habitat (ESH), the U.S. Government through the National Oceanographic and Atmospheric Agency (NOAA) has established a monitoring program requiring areas with more than 20 acres of subtidal eelgrass habitat to be surveyed every 5 years on the mainland and every 10 years on Channel Islands in the Southern California Bight to determine extent, bathymetry, and percent of bottom coverage within normally defined beds. The bottom coverage percentage relates to the eelgrass extent surveyed for that year and comparing it to the historical extent.

Although there are a few methods for collecting data, sidescan sonar coupled with single beam sonar has been suggested to be the most adequate in determining the extent of eelgrass beds and bathymetry. Surveys over time have been used to calculate bottom coverage percentages (Berstein et al. 2011). Typically, these surveys are costly and require manned vessels with expensive equipment.

Unmanned Surface Vehicles (USVs) are a new remote sensing technology that allows surveyors to gather data and imagery from remote locations either on shore or on vessels for either real-time or post-processing of data. They offer a cheaper alternative to unmanned underwater vehicles (UUVs), which operate entirely submerged, and manned vessels when the subject is in calm, shallow water (1-10m) such as a bay or lagoon. Although the terms *unmanned* surface vehicle (USV) and *autonomous* surface vehicle (ASV) are synonymous, and have been used interchangeably by other organizations, the term *unmanned* will be used throughout this project because surface vehicles retain an element of human control for navigation hazards.

The goal of this research project was to demonstrate that imagery collected by an inexpensive unmanned surface vehicle could be just as effective in mapping the extent of submerged eelgrass as professionally conducted surveys. This was accomplished by (1) determining if a low cost USV could be built to remotely sense submerged eelgrass; (2) collecting sidescan sonar imagery from two different study areas with known eelgrass; (3) processing the collected data in sidescan software and ArcGIS; and (4) comparing the results to professionally conducted eelgrass surveys.

1.1 Motivation

Within Southern California, four species of seagrass are known to occur: (1) narrow-bladed eelgrass (*Zostera marina)*; (2) wide-bladed eelgrass (*Z. pacifica*); (3) surfgrass (*Phylospadix torreyi* and *P. scouleri*); and (4) widgeon grass (*Ruppia maritima*). Narrow-bladed eelgrass is the most prevalent and most commonly referred to. Eelgrass is a community plant that is capable of forming large beds of growth or can be restricted to small areas based on environmental factors. Eelgrass provides critical structural environments for resident bay and estuarine species, including abundant fish and invertebrates and is often a primary diet for several grazing organisms. Eelgrass also traps and removes suspended particulates, improves water clarity, and reduces erosion by stabilizing the sediment (Berstein et al. 2011). Therefore, protecting eelgrass has become a concern of not only scientists, but community planners who do not wish to erode the environment and subsequently, their own construction projects.

Beginning in the 1990s, advances in technology allowed scientists to reliably measure eelgrass extent, conditions and characteristics. These methods include diver surveys, singlebeam sonar surveys, towed video and ROV surveys, aerial photographic surveys, and sidescan sonar surveys. Sidescan sonar combined with multispectral or true color aerial imagery has been suggested to achieve the most consistent, repeatable results due to its ability to spatially acquire the greatest coverage (see Figure 1.1Figure 1.1 Different eelgrass mapping techniques and effectiveness (Source: *Berstein et al. 2011*).).

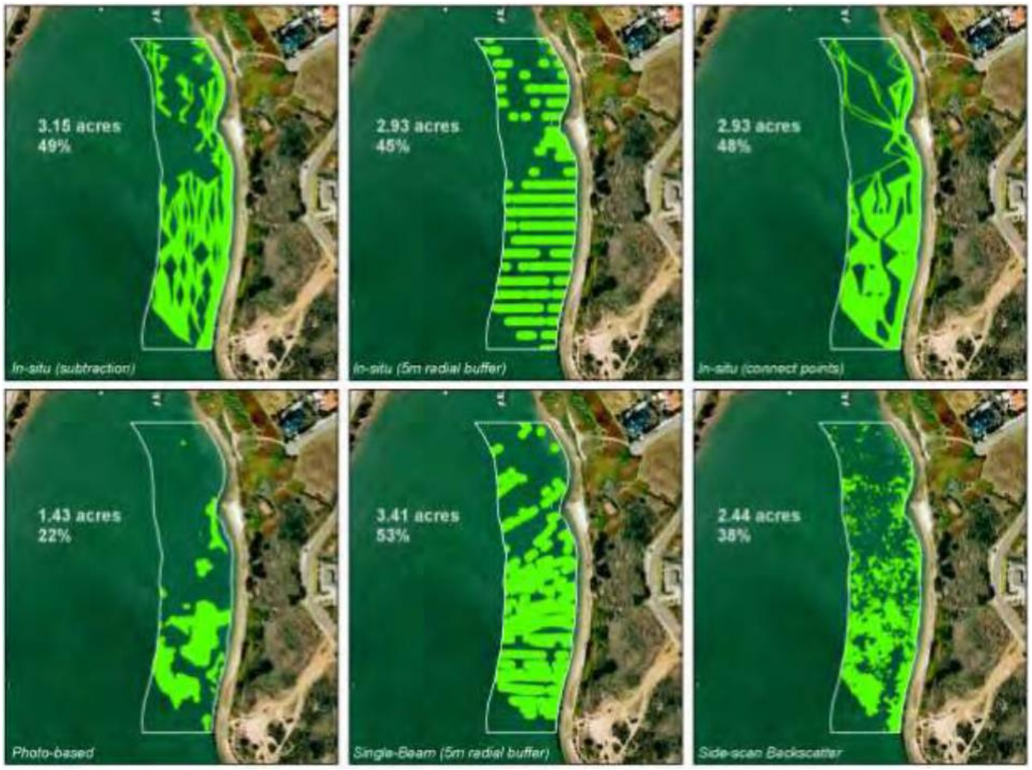


Figure 1.1 Different eelgrass mapping techniques and effectiveness (Source: *Berstein et al. 2011*).

Professional grade survey technology is expensive and therefore unobtainable for most local monitoring agencies. For example, in a 2013 survey of Mission Bay in San Diego by Merkel & Associates, the following equipment was utilized: (1) a SEA SWATH plus-H interferometric sidescan sonar operating at a frequency of 468 kHz; (2) a 210 kHz single-beam fathometer: (3) a differential global positioning system (dGPS) navigation system; (4) a Hemisphere VS111 for horizontal positioning; (5) a Valeport mini SVP sound velocity sensor; (6) and an SMC IMU-108 motion sensor (Merkel and Associates, Inc. 2013). Although not mentioned in the report, the total cost of this equipment is well over $200,000. A key to the future of eelgrass surveys is making them more affordable and convenient for operators and decision-makers who need more timely data to make better judgements.

In the 1990s, the technology of USVs was in its infancy and finding application uses in areas of marine technology. The first USV was created at MIT Sea Grant and named ARTEMIS. It was used to collect bathymetry data (Manley 2008). USVs branched out into other applications and there are now numerous manufacturers. Although using USVs for GIS work has been attempted, affordable systems, costing less than $25,000 and utilizing sidescan sonar have been unavailable (Dreger 2010). The introduction of affordable autopilots, commonly used in unmanned air vehicles (UAVs) (ArduPilot Development Team 2016), and sidescan sonars into the recreational market (Lowrance 2016) has allowed for a significant cost decrease in required components. A vehicle can now be designed to fulfill marine survey needs at low cost.

Processing imagery from the USV is also critical in achieving results for remotely sensed imagery. Although there are a few programs that handle recreational side scan sonar data, “Reefmaster” from an Australian company has been chosen based on its ability to create and export sidescan mosaics (Reefmaster 2016). Mosaiced imagery can then be used in the commercial remote sensing software, ArcGIS, for classification of eelgrass in a raster format. This process needs to be studied to determine its accuracy compared to professional surveys in order to show if this is a viable method for lowering the costs of shallow water marine surveys.

1.2 Sidescan Sonar for Biomass Mapping

Sidescan sonar is a piece of marine technology that is able to capture images of the seafloor using high frequency acoustic beams of energy. Sidescan transducers may be either hull mounted to a ship or carried in a towfish behind the ship, the latter of which allows for imagery at greater depths to be collected. The sonar works by transmitting two beam of acoustic energy, one on either side of the transducer perpendicular to the axis of motion. These beams are narrow along the axis of motion to get a high resolution, but wide outwards so as to cover as much as they can. Most of the acoustic energy is reflected outwards away from the transducer, some energy is absorbed into the seabed or targets and whatever energy is reflected back and recorded is known as backscatter (Blondel 2009). See Figure Figure 1.2 for a diagram of sidescan sonar scattering. The intensity of the reflected backscatter is dependent on what medium the sonar ping strikes. Fine sediment and mud yields little return while rocky substrate and metal offer better returns. Air, however, has the greatest reflectance and offers the best return.

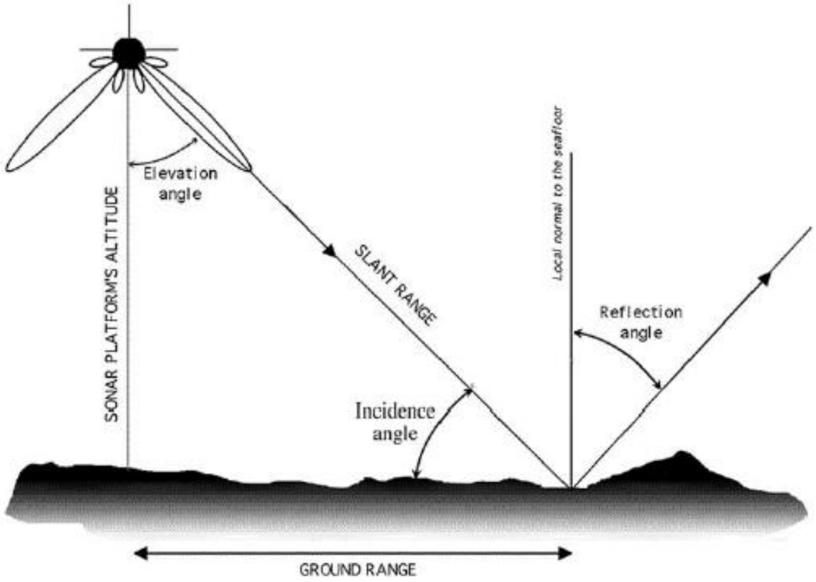


Figure 1.2 Diagram of acoustic scattering from a sidescan sonar (Source: *Blondel 2009*).

The backscatter from one sonar ping is recorded in what is known as a “waterfall” display where successive pings build up the image. See

Figure 1.3. for an example of successive pings. GPS coordinates are able to spatially reference the pings for later mosaicking. Thus, the slower a sidescan transducer is pulled along an axis of travel, the higher the image resolution.

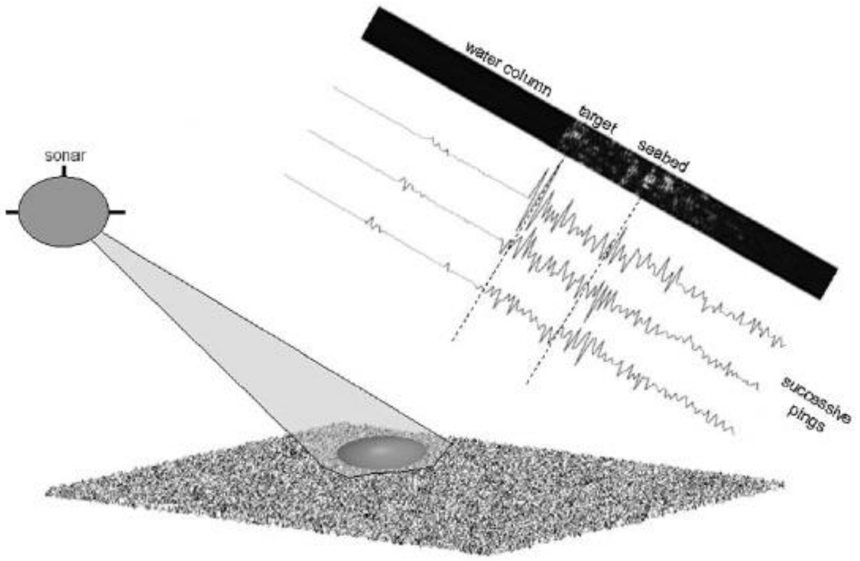


Figure 1.3 Example of successive pings from a sidescan sonar to build up an image of the seabed (Source: *Blondel, 2009*).

Imaging seagrasses and algae is often complicated due to their small size and variable gas contents. However, if a sidescan has a high enough resolution (typically above 300kHz), individual blades of seagrass can be identified due to their higher reflectance of the trapped gasses in their membranes that support them off the seabed (Blondel 2009).

1.3 Study Area

Although this research project could be accomplished on any inland waterway with eelgrass, some waterways are better than others for a prototype survey such as this. In selecting requirements for proposed sites, it was determined that the area: (1) had to be accessible by 1-2 personnel from shore; (2) deep enough water to minimize propeller fouling until propeller guards could be manufactured; (3) had minimal recreational vessel traffic; and (4) a large enough area to survey with variable eelgrass features. An area meeting these requirements were found to be the middle lagoon of Agua Hedionda Lagoon in Carlsbad, California.

1.3.1. Agua Hedionda Lagoon

Agua Hedionda Lagoon is a shallow waterway in Carlsbad, California. The lagoon has three basins, commonly referred to as the outer lagoon, middle lagoon, and inner lagoon, separated by a railroad bridge and the Interstate 5 Freeway. Before the middle of the 20th century, the lagoon was a shallow flooded river valley and wetland. In 1954, the lagoon was dredged in order to be a cooling water basin for the Encina Power Station, and was permanently opened to the ocean through two short jetties (Merkel & Associates 2013).

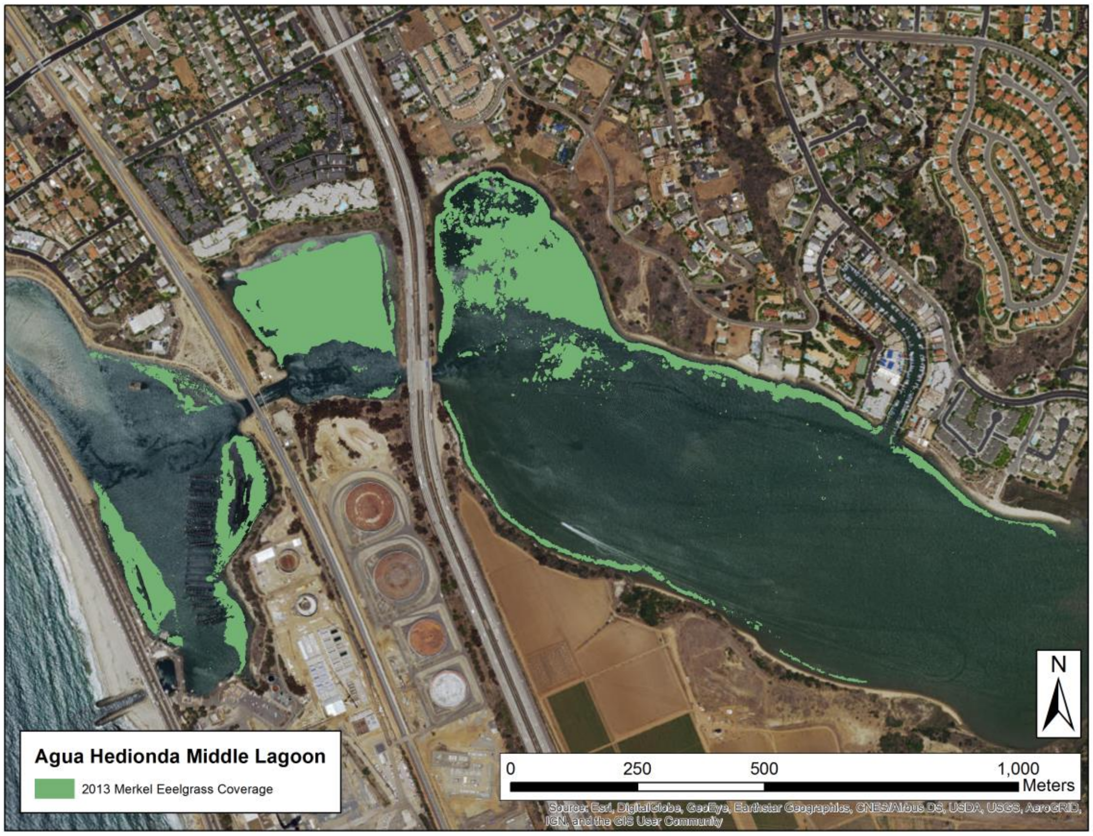


Figure 1.4 Eelgrass extent in Agua Hedionda Lagoon (Source: *Merkel 2013*).

The 2013 Merkel & Associates report of eelgrass extent in Agua Hedionda Lagoon notes that the shallow depths of the lagoon and permanent opening to the ocean create an environment that is an ideal location for eelgrass. Due to the proximity of the ocean, there is high turbidity in the outer and middle lagoons and this is where eelgrass is most prevalent. The inner lagoon has never had an abundant amount of eelgrass in its eastern extent (Merkel & Associates 2013).

In further selection of a suitable survey site, the outer basin was not pursued due to its proximity to the Encina Power Station and Carlsbad Aquafarm that commercially grows mussels and oysters. The inner lagoon was also dismissed due to the high recreational boat traffic in the recreation area. The middle lagoon, however, provided an optimal location for testing and surveying with a publically accessible trail and launch point at the northwestern corner of the lagoon, abundant eelgrass and limited recreational traffic.

1.4 Organizational Framework

This study continues with four additional chapters. Chapter 2 briefly examines eelgrass on a biological level, notes bed classification descriptions and NOAA survey policy, before exploring results of contemporary research studies. Also examined is a sampling of unmanned marine vehicles for mapping projects. Chapter 3 presents the methods for conducting a survey with a USV and subsequently processing the data. Chapter 4 discusses the results of the mapping products produced in Chapter 3. Chapter 5 reviews the implications for the study, sources of error, and areas of future improvements.

Chapter 2 Related Work

This chapter provides further information on eelgrass, its definition in regarding defining beds, most recent professional surveys, and an introduction of current unmanned marine systems (UMS) that have been used to survey eelgrass. Although unmanned marine systems have been in use for several years, they have not been used extensively to map ecological features, nor have they been affordable to research groups.

2.1 Eelgrass Ecology and Policy

Eelgrass (*Zostera marina*) is the most common of all seagrasses and is mostly found in northern temperate oceans with lesser extents in the Southern Hemisphere. Eelgrass beds are located in littoral regions and can be found as deep as 11m. The maximum depth is dependent on the minimum light required for photosynthesis, which has been determined to be 10-20% of surface light. This percentage of light is higher than other marine plants most likely due to the demand to live in areas with lower than normal dissolved oxygen, such as inland estuary systems

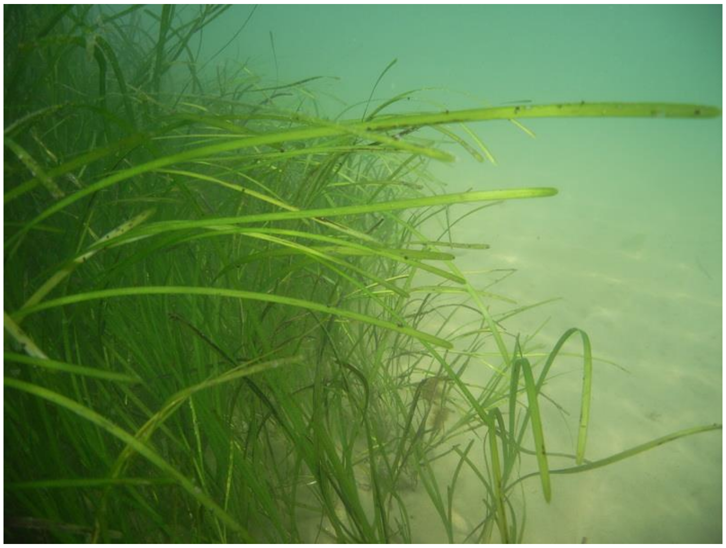


Figure 2.1 Example of eelgrass bed in sandy sediment (Source: *NOAA 2016*).

(Short et al. 2011). Blade size has been found to be linked to increases in latitude and average from 0.2m to 3m in length (Short 2001).

In identifying eelgrass through taxonomy, it is described as a moderately sized species with blades up to 3m long and between 3-12mm wide and a rounded blade apex. The shoot is up to 4m long and repeatedly branched with multiple blades (Kuo and den Hartog 2001). See Figure 2.1 for a photograph of several eelgrass shoots and blades in sediment.

2.1.1. Eelgrass Bed Definition

Spatially measuring individual eelgrass shoots is impractical, therefore areas where eelgrass is observed are called “beds.” In providing recommendations for an integrated Southern California Bightwide eelgrass monitoring program, one of the most important topics the group of professional surveyors and ecologists defined was the eelgrass bed itself. They state that a bed is defined as the area encompassed that has individual plants greater than 20m from neighboring plants. When a separation occurs, either a separate bed is defined or a gap in the bed is defined by extending a line around the separation. When depth, substrate, or existing structures limit bed continuity, the boundary of the bed is defined by the limits of habitat suitability to support eelgrass (Berstein 2011). This is due in part to the nature of eelgrass and its ability to advance or receed in yearly cycles based on environmental conditions. These beds and subsequent gaps are clearly noted when the eelgrass beds are mapped and visually displayed.

Although NOAA does not have a formal deinition for eelgrass beds, the Washington State Department of Natural Resources further defines the bed edge as, “Begin[ing] at a point within the interior of the bed; move along any radial transect. Find the last shoot that is within 1 m of an adjacent shoot along that transect. Continue 0.5 m beyond this shoot: This is the bed edge. Both exterior and interior edges of bed can exist (Donoghue 2011).” See Figure 2.2 for a visual representation of this definition. These definitions are important because there is concurrence within the scientific community that an eelgrass bed does not simply end at the last observable eelgrass shoot. It encompasses an area where eelgrass may exist, but is currently not present.

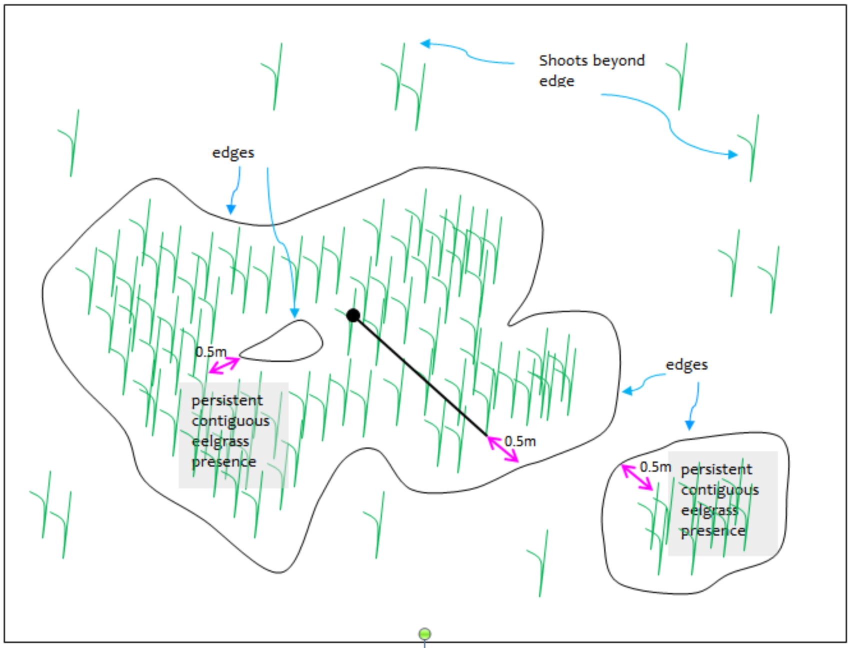


Figure 2.2 Visual definition of eelgrass beds (Source: *Donoghue 2011*).

2.1.2. NOAA Survey Policy

With the definition of eelgrass beds established and recognized by the scientific community, mapping efforts can clearly define the spatial extent of these beds. NOAA has set forth in their eelgrass mapping policy for habitat studies that, eelgrass should be surveyed using visual or acoustic methods and mapping technologies and scales appropriate to the action, scale, and area of work. Surveys should document both observed vegetated eelgrass cover as well as unvegetated areas within areas suitable for eelgrass survival. It is also noted that the quality of these surveys is highly important for documentation (NOAA Fisheries 2014). The remainder of NOAA’s policy on the subject is not very precise, leaving further refined requirements to the regional level. Thus, for a study in Southern California, a policy with hard requirements has not been fully developed, but there is a system of recommendations by surveyors and ecologists that provides a baseline from which to work.

2.2 Professional Eelgrass Surveys

Eelgrass studies along the Southern California coast have been conducted either by contracted surveyors or small groups of researchers since the 1980s, with the last yearly survey conducted in 2013 in all the major locations where eelgrass is known to exist. The principal means of collecting data on eelgrass extent is aerial surveys, combined with acoustic data for deeper water areas. In all the surveys, the total acreage is an approximation as one of the primary issues with acoustically imaging eelgrass is their small size, variable gas contents (which reflect acoustic transmissions) and movements with currents and tides (Blondel 2009).

2.2.1. Morro Bay

The 2013 survey of Morro Bay featured a combined approach using aerial surveys from a Cessna small aircraft and sidescan imagery from a manned vessel. For the aerial approach, imagery was acquired at a spatial resolution of 0.48 meters using a Microsoft UltraCam-X digital camera acquiring in the red, green, blue and near-infrared bands (Morro Bay National Estuary Program 2013). In conjunction with the aerial imaging, Merkel & Associates collected sidescan sonar data of eelgrass in regions of the bay including open areas, shallow channels, developed areas supporting piers, and docks. Sidescan sonar data was collected at a frequency of 468 kilohertz (kHz) over a 70 meter wide swath that was centered on the survey vessel. Sidescan sonar survey swaths were run parallel to each other to ensure overlapping imagery (Morro Bay National Estuary Program 2013). After the conclusion of the sidescan survey tracks, the scans were joined together and mosaiced. A drop camera was used to verify eelgrass located in the sidescan sonar surveys. Once verified, eelgrass on the planted transects was digitized by creating

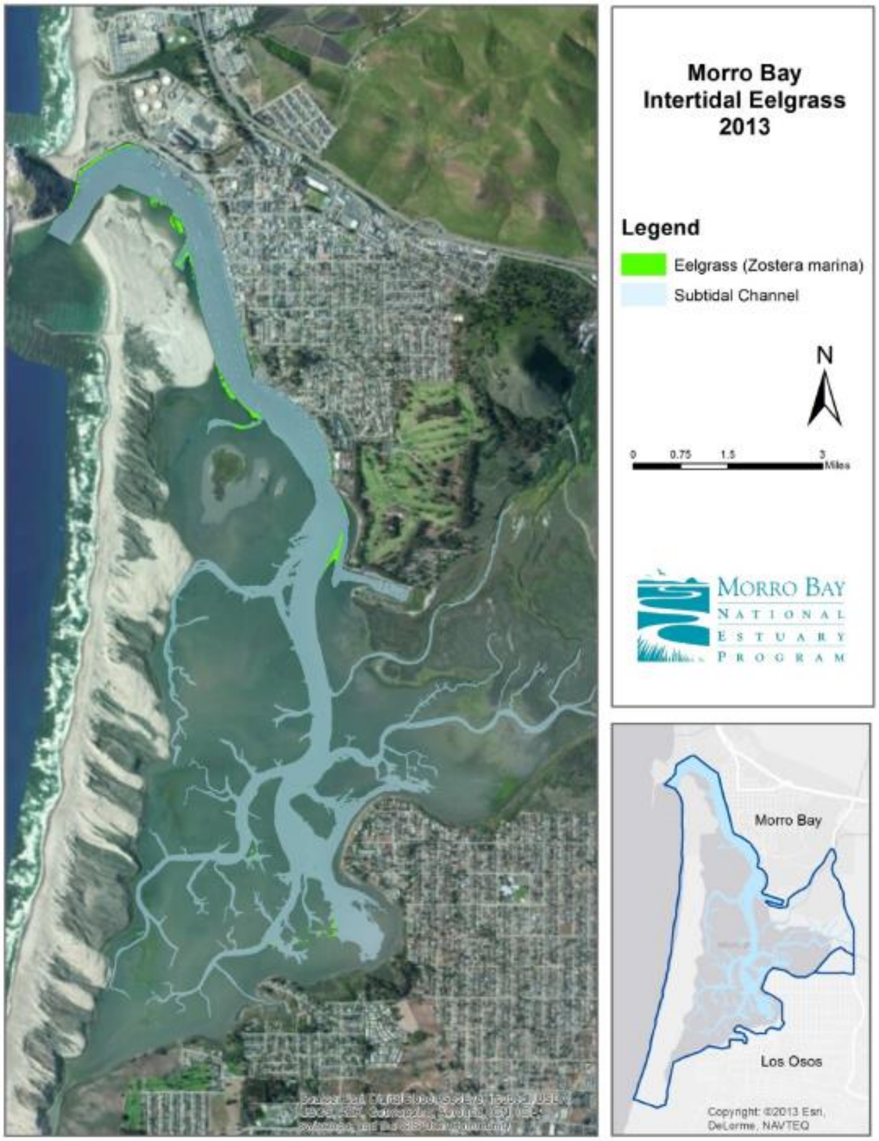


Figure 2.3 Spatial results of the 2013 eelgrass mapping in Morro Bay, CA (Source: *Morro Bay National Estuary Program 2013*).

bounding polygons using ESRI ArcGIS software on the spatially rectified aerial photograph that was generated from the aerial flights. (Morro Bay National Estuary Program 2013). See Figure 2.3 for the spatial results of the 2013 mapping project.

2.2.2. Southern California Bight

The 2013 survey of minor inland areas of Southern California included Alamitos Bay, San Gibriel River, Anaheim Bay/Huntington Harbor, Agua Hedionda Lagoon, Baquitos Lagoon, San Dieguito. As with the work done in Morro Bay, a combined survey with aerial and sidescan imagery was used. Aerial surveys were flown during low tides during the month of April. Photographs were processed digitally and rectified prior to digitizing visible Eelgrass as a shapefile in ArcGIS (Merkel 2014). Acoustic surveys were undertaken in deeper waters using an interferometric sidescan sonar system operating at 468 kHz and integrated a vessel motion sensor to correct for vessel pitch, heave, and roll; a sound velocity sensor that corrects for speed of sound in water; and a dual antenna differential GPS that provided submeter vessel positioning

Figure 2.4 2013 Eelgrass extent map for Batiquitos Lagoon, San Diego County, CA (Source: *Merkel 2014*).

and correction for vessel yaw. Unlike other reports from this year, absolute positional error for eelgrass mapping was approximately ±1-2 meters. Relative positional error is estimated at ±0.5-1 meter as the GPS error was substantially nullified across short distances (Merkel 2014, 5). See Figure 2.4 for the resulting map of eelgrass in Batiquitos Lagoon.

2.2.3. Mission Bay

Unlike the previously mentioned surveys that combined aerial and sidescan, the Mission Bay survey was conducted only with a side scan approach. However, as with the others, a similar small vessel set-up was utilized using interferometric sidescan sonar operating at a frequency of 468 kHz and a 210 kHz single-beam fathometer. A dGPS (differential GPS) navigation system was used to track the position of the survey vessel in the bay. The sidescan sonar surveyed at 70-meter swath widths. Parallel survey lines were navigated and spaced at approximately 25 meters

Figure 2.5 2013 Eelgrass extent map for Mission Bay, CA (Source: *Merkel 2013*).

separation to allow full overlap of the nadir gap at the centerline of the survey swaths (Merkel 2013). Following the completion of the sonographic survey, the stored sidescan data was post-processed into a series of geo-rectified mosaic images covering all surveyed areas of Mission Bay and then imported into ArcGIS to delineate eelgrass beds. (Merkel 2013). The survey identified 979.1 acres of eelgrass within Mission Bay at the time of the summer 2013 surveys (Merkel 2013). See Figure 2.5 for the final eelgrass extent map for Mission Bay.

2.3 Unmanned Marine Systems

USVs and UUVs share a common ancestry, collectively called unmanned marine systems (UMS) in the marine technology field with both having some type of autopilot capable of controlling and navigating the vehicle remotely. The key difference between the two is that a USV is remains on the surface of the water and a UUV is capable of diving within the water column up to its maximum rated depth.

2.3.1. Unmanned Surface Vehicle Development

From the description, it seems as though a UUV is the vehicle to conduct underwater surveys, however this is not necessarily the case. In a 2003 technical report by Florida Atlantic University on their natively built USV, the researchers noted that a major limitation of UUVs is their inability to receive accurate position measurements through GPS while underwater. “This leads to inaccuracies when performing standard missions, such as: (1) mine counter measures (MCM); (2) underwater system inspection; (3) route surveying; (4) and oceanographic sampling (Leonessa 2003).”

In addition to increased positioning information, USVs are able to operate in a safer manner with respect to the vehicle itself than UUVs. In the development of a USV to map complex manmade structures from the surface of the water, Jacques Leedekerken put forth that operations with UUVs are traditionally risky in open water and shallow marine envirnments, however, his platform was able to not only safely navigate, but also map those hazardous regions where a UUV might have been fouled (Leedekerken 2011).

Researchers working on Cambridge's *Autocat* noticed when upgrading their USV that they had to sacrifice speed, from 20 knots to 7 knots. This was acceptable because they noted that all the required scientific missions needed to be at slower speeds, such as sidescan and multibeam sonar sensors. In their end result, no manual intervention was required to begin, end, or resume missions, leading to greater autonomy and ease of use for the operator (Manley et al. 2000). With respect to which type of autonomy a surface vehicle should have (manual control, semi-autonomous, fully autonomous), the Institution of Electrical Engineers mentions that a semi-autonomous mode allows USV operators to interact at a high level of functionality with USV while making a significant functional contribution in terms of situation assessment (Roberts 2006). Thus, a vehicle capable of executing a prescribed mission (i.e. a mission with waypoints), but being supervised by an operator is the recommended autonomy solution for marine surface vehicles.

2.3.2. Unmanned Surface Vehicles for Ecological Mapping

One of the best examples of a scientific-oriented USV is from the University of South Florida, where the research team managed to construct a USV, using off the shelf parts, that was designed to remotely monitor eelgrass for a base price of $25,000. The team added an underwater video camera with a GPS overlay to attempt to visually capture eelgrass beds and mark their position (Dreger 2010). A wireless feed was added to send video to a base station so the operator could navigate the USV around eelgrass beds, thus making the vehicle semi-autonomous (Dreger 2010). See Figure 2.6 for a picture of the finalized USV. Even though the team was unsuccessful in mapping and monitoring eelgrass beds and locating propeller scars because the camera was not a high enough quality, they managed to identify several advantages and disadvantages. The advantages of using this USV were: (1) sensor data could be stored onboard; (2) it was easily launched, eliminating the need for a manned survey boat; (3) GPS allowed operator to return to areas of interest; (4) the vehicle had a small footprint and a limited impact to environment; (5) limited personnel were needed for operation; (6) and it improved safety by removing scientists from cold water and other marine hazards (Dreger 2010, 50-52). The noted disadvantages were: (1) limited battery life; (2) Building and operational costs ($750 per day for USV operations); (3) weather limitations; and (4) a relatively slow speed (Dreger 2010).

Figure 2.6 University of South Florida USV used for imaging eelgrass (Source: *Dreger 2010*)

Another example, also from the University of South Florida notes a USV that was used to monitor seagrass beds in Tampa Bay and in the Florida Keys. An IEEE 1394 firewire high resolution digital camera was coupled to pattern recognition software to acquire digital 1.3

megapixel images at up to 32 frames per second. The video imagery was overlaid with GPS and provided a complete record of transect data (Steimle 2006).

2.3.3. Unmanned Underwater Vehicles for Mapping Eelgrass

Instead of using USVs to visually monitor eelgrass beds, the Pacific Northwest National Laboratory procured a REMUS 100 UUV produced by Hydroid, LLC to prototype mapping of eelgrass beds. The UUV utilized a Marine Sonics 900 kHz sidescan sonar, with mounted transducers on either side of the vehicle (Jones 2007). Once the imagery was collected, processing techniques for image classification were applied to GeoTiff images, which were assigned different histogram stretches during the initial program extraction (Jones 2007). As this was only a preliminary test, the team showed that a UUV with a sidescan sonar can be used successfully to delineate eelgrass beds, and that seasonal monitoring may be implemented for large areas. The scientist working on the project noted this technique has proven to be a viable alternative to approaches requiring divers or sidescan tow-fish methods. (See Figure 2.7).

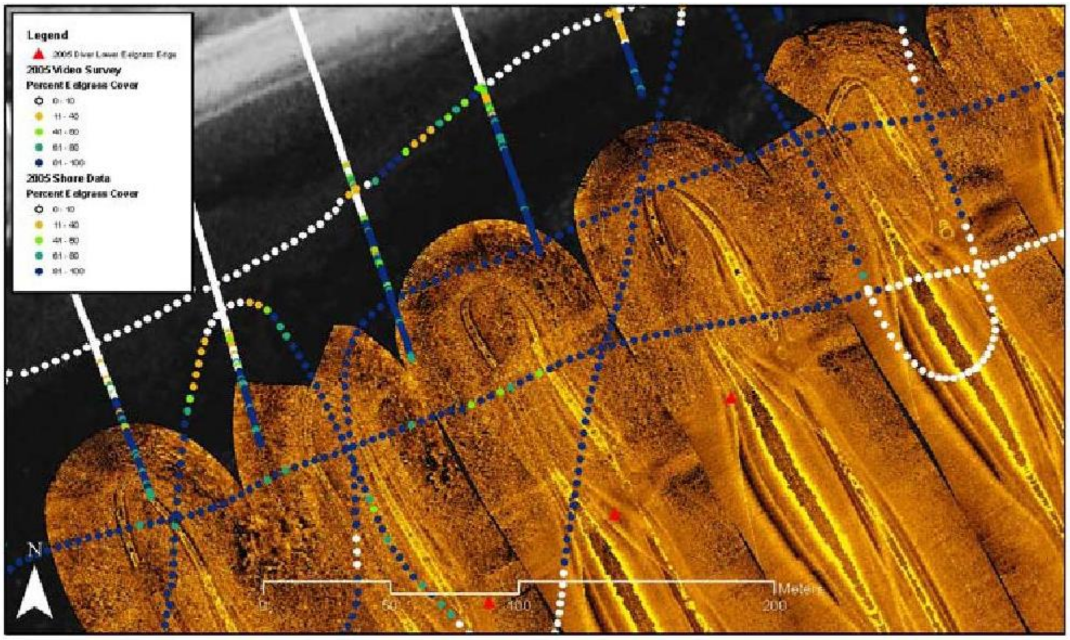


Figure 2.7. Example of eelgrass data collected by the Pacific Northwest National Laboratory UUV compared to other mapping techniques (Source: *Jones 2007*).

However, they stated that initial costs for purchasing an AUV are significant and can range to several hundred thousand dollars, depending on make and instrumentation (Jones 2007). While the team was successful, a UUV with side scan modifications is still noted to be extremely costly and outside the budget for many research firms.

Chapter 3 Data and Methods

This chapter will cover the methodology used in this study for providing a low cost solution to spatially collect and analyze submerged eelgrass data. The study area of Agua Hedionda Lagoon was introduced in Section 1.2. Section 3.1 begins with descriptions of the equipment used throughout the study. The procedures for data acquisition are detailed in Section 3.2, the post-processing techniques are followed in Section 3.3 and the resulting layers are analyzed in Section 3.4. Figure 3.1 outlines the procedures for collecting and processing the sonar data.

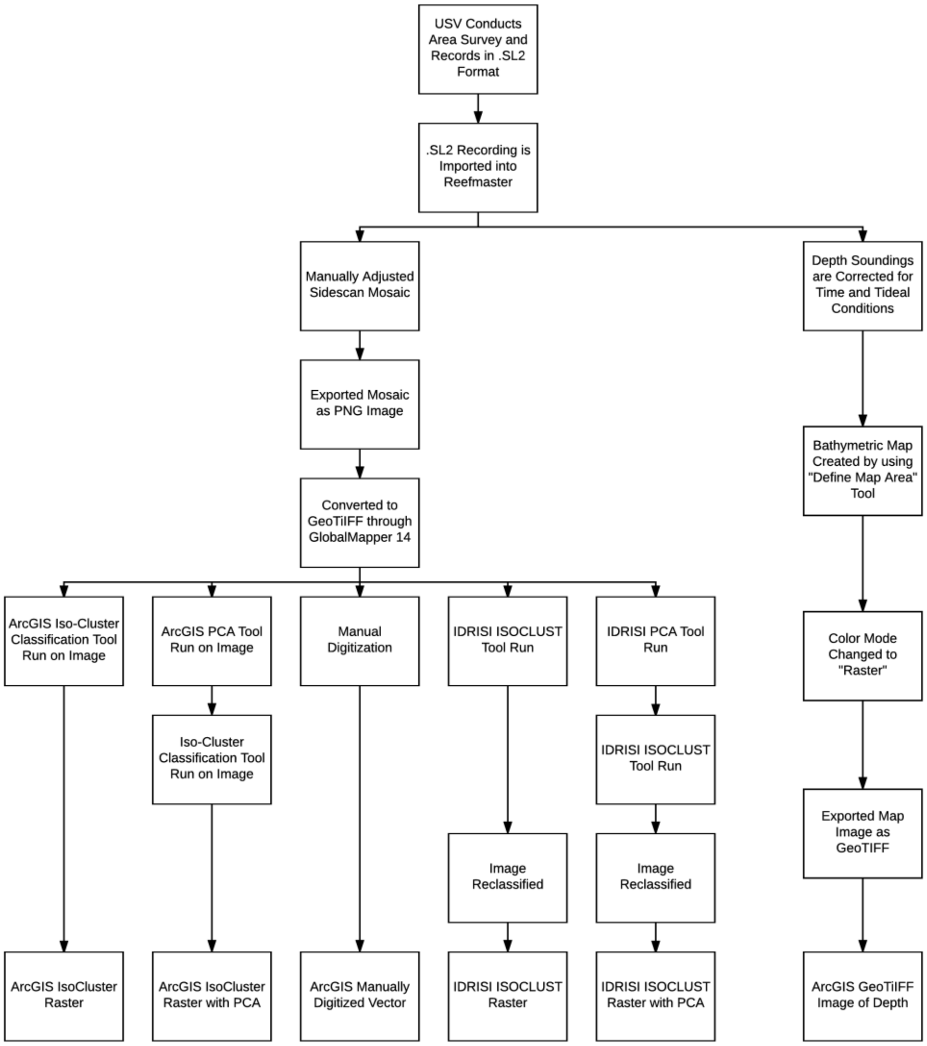


Figure 3.1 Flowchart of USV Image collection and processing.

3.1 Equipment

The equipment used for this project is summarized in the next few sections. It should be noted that the entire vehicle is designated as a “system of systems” where there are many individual parts that alone, are unable to accomplish the task. However, when they are integrated together, the system works as intended. A breakdown of related equipment costs is located in Appendix 1.

3.1.1. USV

The hull of the USV consists of a Sun Dolphin Bali 6 child kayak. A child sized kayak was chosen because it cost $120 with enough room to house a power unit, navigation box and sonar equipment. This hull has been successfully used in other projects in the do-it-yourself (DIY) community, but has not been used in an academic setting.

Propulsion is accomplished through the use of two BlueRobotics T-200 brushless thrusters with Basic 30 Amp ESCs (Electronic Speed Controls). Due to the hazard of eelgrass fouling the propellers, plastic thruster guards were 3D printed and installed on the forward end of the thrusters.

A navigation box was constructed out of a Pelican 1200 case that housed the 3DR GPS module, RFD 900+ telemetry radio, Spektrum AR 8000 DSMX radio control receiver, Pixhawk 1 autopilot, and power distribution board. A second Pelican 1200 case was mounted amidships to house two 14.8VDC 20,000 mAh Lithium Polymer battery packs. One of the packs was wired provide primary power for the navigation box/thrusters and the remaining battery was dedicated to the sonar system. BlueRobotics bulkhead penetrators were used to pass wires through the Pelican cases and potted with clear marine silicone to maintain a water resistant seal.

3.1.2. Sonar System

A Lowrance HDS-7 Gen 3 recreational fishfinder and chartplotter was selected as the sonar hardware platform due to its affordability ($1200), small form factor, and ability to integrate with sonar processing software. A Lowrance TotalScan transducer was selected as the sonar head due to its integration of side scan, down scan, and single beam sonar. Data is recorded onto a micro SD card for playback and extraction.

The sonar system was bolted onto the USV with the chartplotter topside in the bow and the transducer on a plastic mounting plate attached to the underside of the bow. Power was routed to the main bus coming from the dedicated Li-Po battery. Once the chartplotter was initialized for the first time, the TotalScan transducer was selected as the transducer source. (See Figure 3.2 for a picture of the completed vehicle.)

Figure 3.2 Completed USV with sonar, battery and navigation box.

3.1.3. Ground Control Station

A Microsoft Surface Pro 4 was selected as the Ground Control Station (GCS) due to its portability, high screen brightness, and ability to run Windows 10. The Surface was mated to a

MobileDemand xCase to increase its ruggedness in the field, fit a 4-point chest harness, and provide attachment points for the required peripheral devices. Attached to the Surface was the complementary RFD 900+ telemetry radio and GlobalSat GPS receiver.

Figure 3.3 Image of Ground Control Station equipment: Chest Harness, Radio Control, Surface Pro 4, RFD 900+ and GPS receiver.

The software “QGroundControl” was selected as the ground control suite due to its cross platform ability. Missions were created on the Surface Pro 4 and then transferred to the vehicle through the radio telemetry link. Missions can consist of any number of waypoints with actions or the ability to create a survey area. Usually this software is used for aerial drones, however the team at QGroundControl and ArduPilot have adapted it for use in rovers and surface vehicles.

The second major piece to the GCS was a Spektrum DX8 2.4 GHz radio for manual control when the vehicle needed precise control for launching and return. (See Figure 3.3 for an image of all the GCS equipment.)

3.1.4. Processing Software

The software program "Reefmaster" was selected to process the sonar data once collected. Reefmaster is specifically designed to mosaic sidescan sonar files from Humminbird and Lowrance chartplotter units. Data can be manipulated, trimmed, and exported into a variety of file formats. ArcGIS 10.3 was selected as the classification and analysis GIS software with its ability to import and manipulate various forms of spatial data.

3.1.5. Safety Vessel

A small inflatable dingy with an electric outboard was selected to be the safety vessel should the USV become incapacitated. All safety procedures were upheld, there were lifejackets for the operators, and the USCG's Navigation Rules (COLREGS 72) were followed at all times.

3.2 Data Acquisition

Table 3.1 summarizes the products that were used in this project and how they were obtained. The professional survey data for Agua Hedionda Lagoon was not readily available and had to be requested through networked contacts.

Table 3.1 Data Sources.

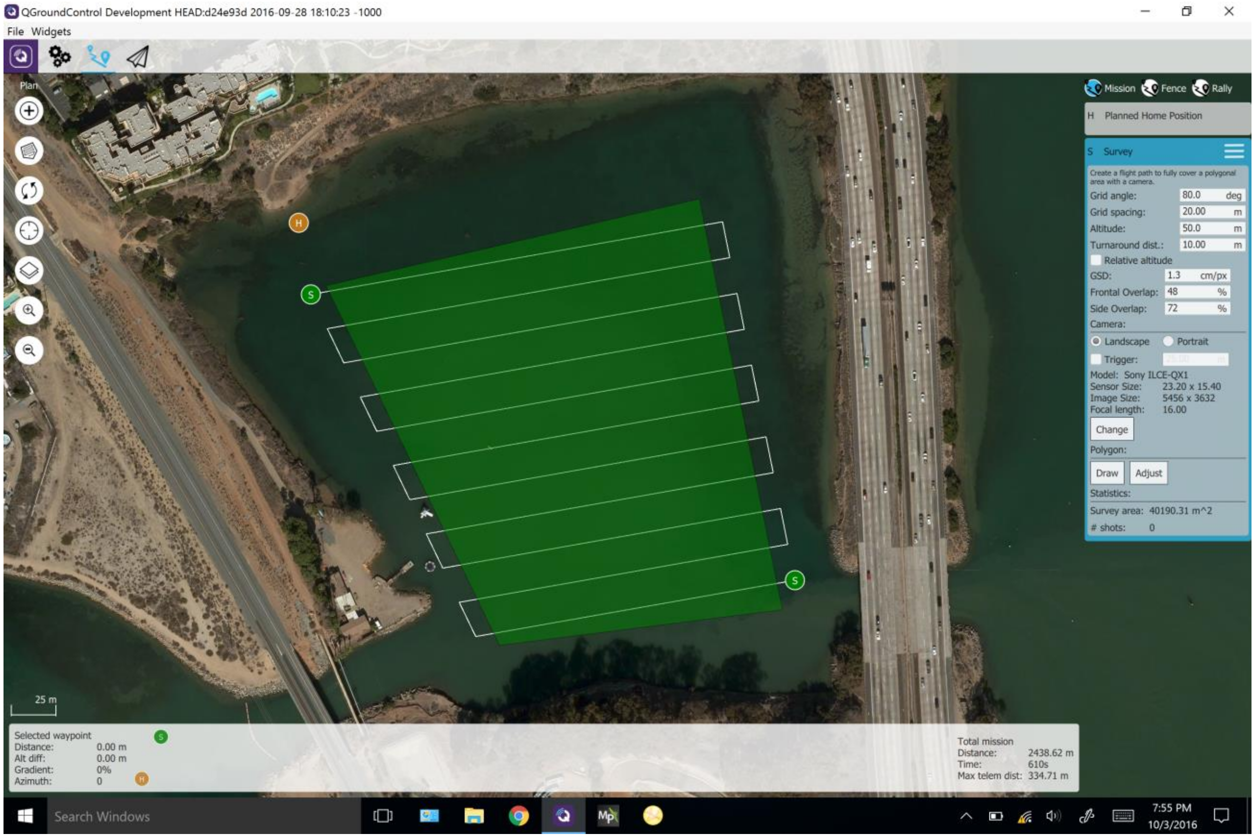
Dataset	Content	Format	Attributes	Quality	Availability	Development
Merkel & Associates 2013 Southern California Eelgrass Extent	Contains eelgrass polygons from 2013 in all major bays and lagoons	Esri Shapefile	Extent only	Professional survey grade	Available through direct contact with NOAA representative	None required, ready for use in ArcGIS
Agua Hedionda Lagoon Hydrodynamic Study	Contains color depth images of the lagoon	PDF images	Depth contours in ft and respective colors	Professional survey grade	Available in PDF format	Absent GIS shapefiles, these images can be georeferenced in ArcGIS for basic depth information
USV collected side scan sonar data	Contains side scan imagery of bottom composition	PNG Image	Mosaic Raster Image	Collected from "recreational" grade equipment	Required to be personally collected.	Analysis conducted to determine extent in comparison to professional data.
USV collected single beam sonar data	Contains single beam sonar data of depth of body of water	Esri Shapefile	Depth contours	Collected from "recreational" grade equipment	Required to be personally collected	Exported to Esri Shapefile

3.2.1. Agua Hedionda Lagoon

USV data collection of Agua Hedionda Lagoon middle lagoon occurred in October 2016. The survey grid for the USV was plotted in QGroundControl Ground Station software at and then uploaded to the vehicle. A "lawnmower" pattern at 20m intervals was used to ensure there was adequate overlap of the scans when the nadir region was edited out. A turnaround distance of 10m was used to turn the vehicle around outside of the survey grid and align it for the next row. Table Table 3.2 Parameters for survey grid in QGroundControl (QGC).shows the parameters in QGroundControl to adjust the survey grid. Figure 3.4 shows the grid in QGC.

Table 3.2 Parameters for survey grid in QGroundControl (QGC).

Parameter in QGC	Value
Grid Angle	080 Degrees
Grid Spacing	20.00m
Turnaround distance (outside grid)	10.00m



H Planned Home Position

S Survey

Create a flight path to fully cover a polygonal area with a camera.

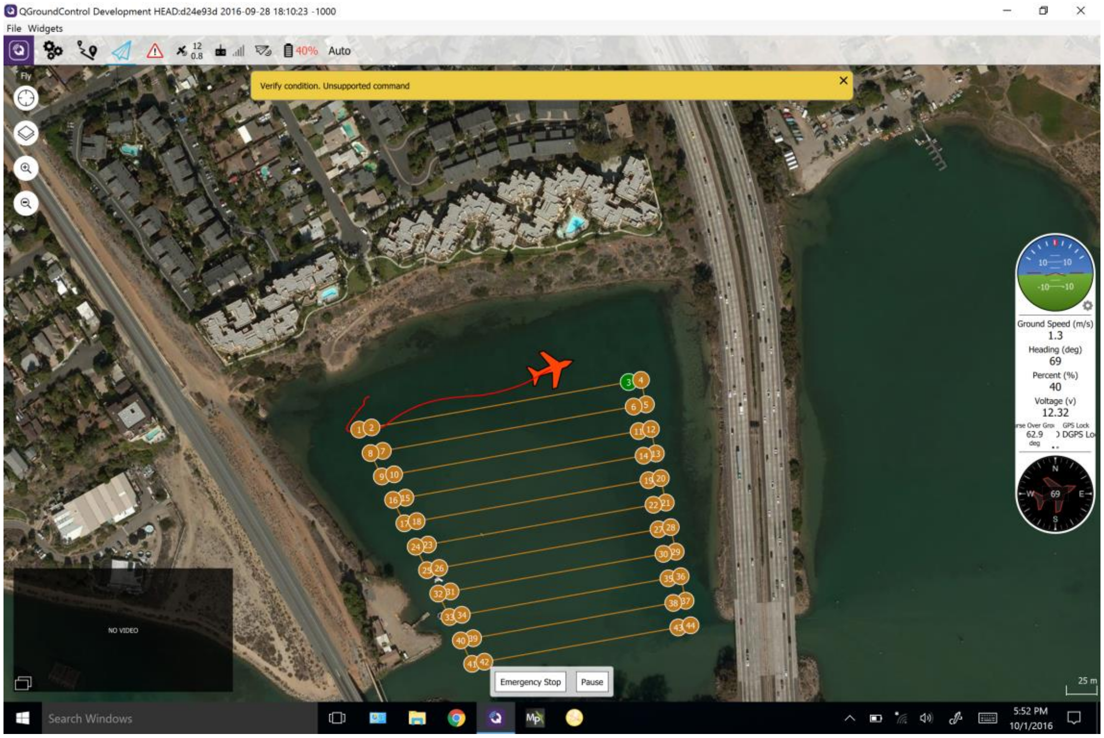
Grid angle: 80.0 deg
Grid spacing: 20.00 m
Altitude: 50.0 m
Turnaround dist.: 10.00 m
☐ Relative altitude
GSD: 1.3 cm/px
Frontal Overlap: 48 %
Side Overlap: 72 %
Camera:
● Landscape ○ Portrait
☐ Trigger:
Model: Sony ILCE-QX1
Sensor Size: 23.20 x 15.40
Image Size: 5456 x 3632
Focal length: 16.00
Polygon:
Statistics:
Survey area: 40190.31 m^2
shots: 0

Selected waypoint
Distance: 0.00 m
Alt diff: 0.00 m
Gradient: 0%
Azimuth: 0

Total mission
Distance: 2438.62 m
Time: 610s
Max telem dist: 334.71 m

Figure 3.4 Visual representation of survey grid in QGC.

Once on site, the USV was placed in the water and main power was turned on, initializing the navigation and chartplotter. The Lowrance chartplotter was started and was set to begin recording sidescan (455 kHz) and singlebeam (200 kHz) sonar data in the proprietary SL2 format. Although the Pixhawk 1 is capable of full autonomous piloting, the survey mode in QGroundControl is not complete and is still a work in progress from the developers, therefore, although full survey mode was trialed, the vehicle encountered navigation issues after the first row. Manual control was regained and the remainder of the survey was completed through manual piloting, closely following the survey guide lines that were plotted out. Areas that had odd shapes or outside the survey grid were manually driven to provide a more complete scan. When the USV returned "home", the autopilot and chartplotter were stopped and power was disconnected. See Figure 3.5 for an image of the vehicle under manual control conducting survey operations.



QGroundControl Development HEAD:d24e93d 2016-09-28 18:10:23 -1000

Verify condition. Unsupported command

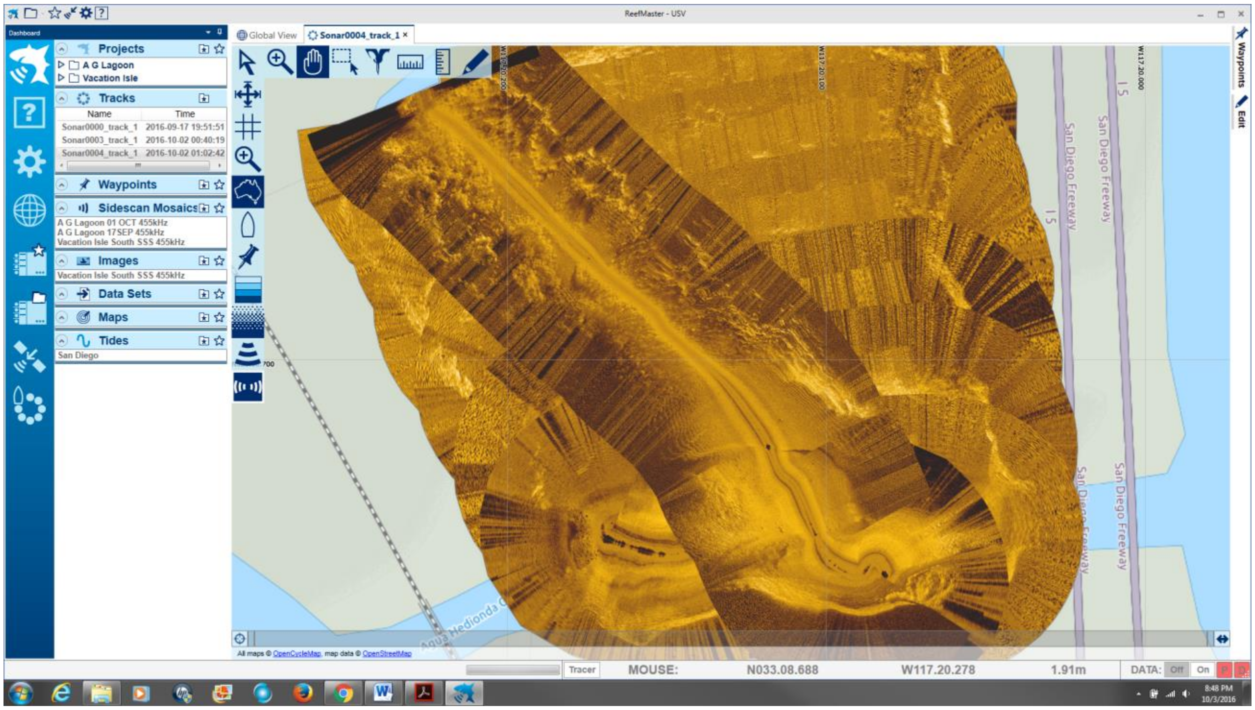
Ground Speed (m/s) 1.3
Heading (deg) 69
Percent (%) 40
Voltage (v) 12.32

Figure 3.5 Image from QGC of vehicle conducting side scan survey under manual control.

3.3 Post-Processing Data

After the conclusion of survey operations, the vehicle was returned to the workshop and the micro SD card was removed and inserted into a laptop with the Reefmaster software. The sonar track files were easily uploaded into Reefmaster as “GPS Assets” and both the sidescan sonar, Figure 3.6, and single beam sonar, Figure 3.7, and were displayed.

Each row was manually reviewed and the swath length and width were adjusted to bring out the clearest sections of the sidescan and remove the nadir region. These individual row sections were added to a new mosaic until the image was built up into the final mosaic. See Figure 3.8 to see the final adjusted mosaic in Reefmaster



Projects
- A G Lagoon
- Vacation Isle

Tracks

Name	Time
Sonar0000_track_1	2016-09-17 19:51:51
Sonar0003_track_1	2016-10-02 00:40:19
Sonar0004_track_1	2016-10-02 01:02:42

Sidescan Mosaics
- A G Lagoon 01 OCT 455kHz
- A G Lagoon 17SEP 455kHz
- Vacation Isle South SSS 455kHz

Images
- Vacation Isle South SSS 455kHz

Tides
- San Diego

MOUSE: N033.08.688 W117.20.278 1.91m

Figure 3.6 USV collected sidescan sonar data at 455kHz. The entire swath is displayed.

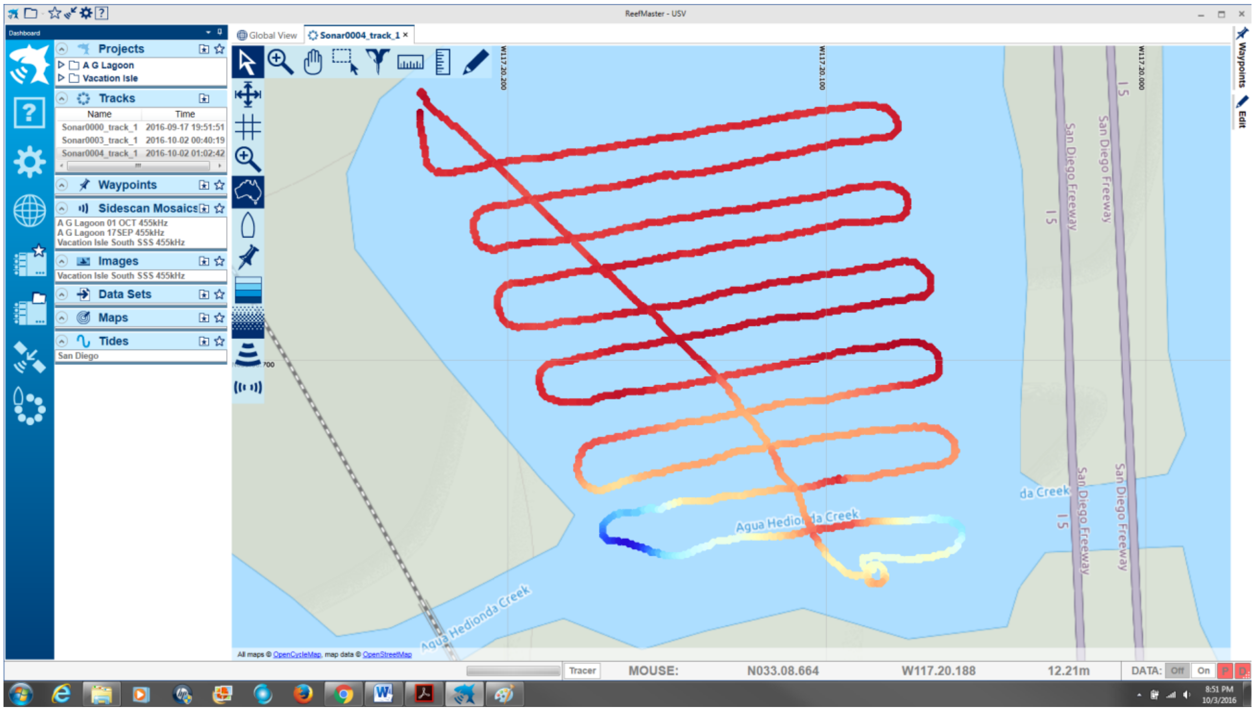


Figure 3.7 USV Collected single beam sonar soundings.

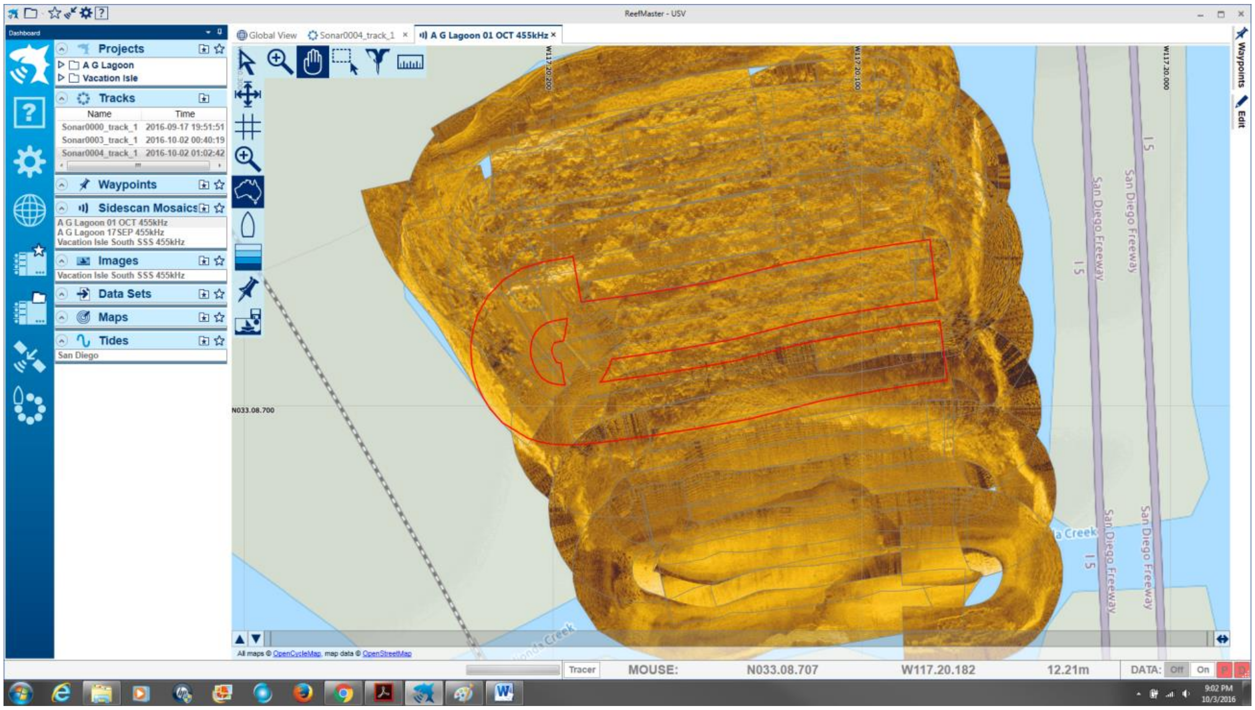
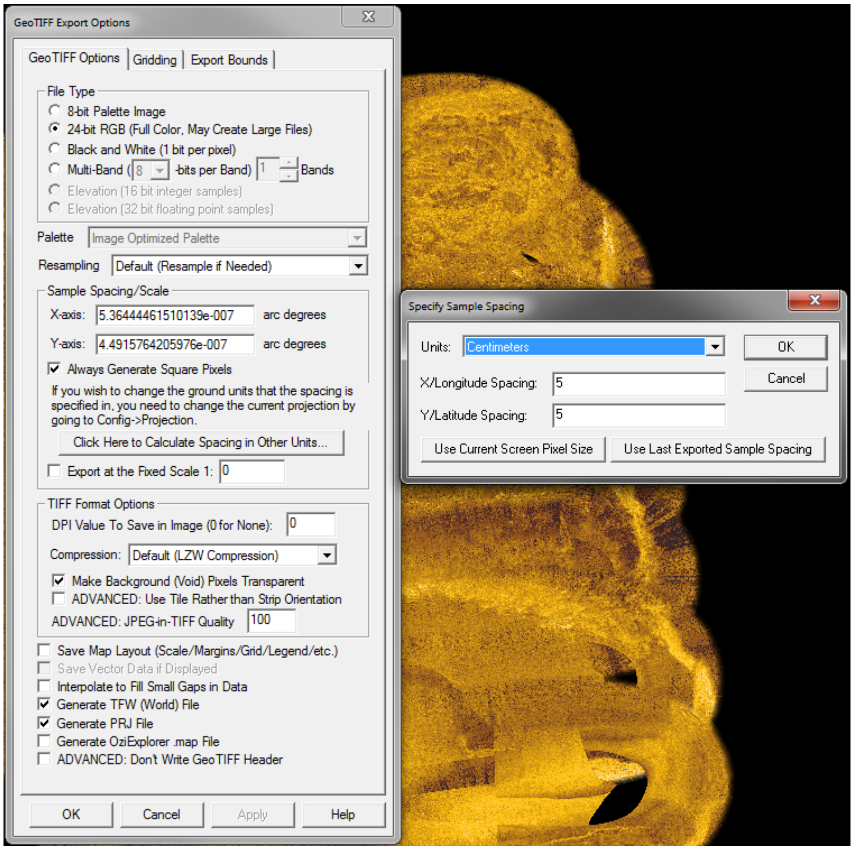


Figure 3.8 Adjusted sidescan swaths in Reefmaster. The red highlighted segment is an adjusted row section.

The final sidescan mosaic was then exported from Reefmaster into a PNG image file with an associated KML calibration file. The export settings selected were 20 pixels per meter (resulting in a 8136x7696 pixel image) and the “Fade swath edges” box was checked. In its newly exported form, ArcGIS is unable to open the PNG file correctly, therefore, it needed to be converted into a GeoTiff format. Global Mapper 14, another GIS software program, was selected and the PNG image was loaded and then converted into a GeoTiff raster. See Figure 3.9 for the export raster settings used in Global Mapper 14.



File Type
○ 8-bit Palette Image
● 24-bit RGB (Full Color, May Create Large Files)
○ Black and White (1 bit per pixel)
○ Multi-Band (8 -bits per Band) 1 Bands
○ Elevation (16 bit integer samples)
○ Elevation (32 bit floating point samples)

Palette: Image Optimized Palette
Resampling: Default (Resample if Needed)

Sample Spacing/Scale
X-axis: 5.36444461510139e-007 arc degrees
Y-axis: 4.4915764205976e-007 arc degrees
☑ Always Generate Square Pixels
If you wish to change the ground units that the spacing is specified in, you need to change the current projection by going to Config->Projection.
☐ Export at the Fixed Scale 1: 0

TIFF Format Options
DPI Value To Save in Image (0 for None): 0
Compression: Default (LZW Compression)
☑ Make Background (Void) Pixels Transparent
☐ ADVANCED: Use Tile Rather than Strip Orientation
ADVANCED: JPEG-in-TIFF Quality 100

☐ Save Map Layout (Scale/Margins/Grid/Legend/etc.)
☐ Save Vector Data if Displayed
☐ Interpolate to Fill Small Gaps in Data
☑ Generate TFW (World) File
☑ Generate PRJ File
☐ Generate OziExplorer .map File
☐ ADVANCED: Don't Write GeoTIFF Header

Units: Centimeters
X/Longitude Spacing: 5
Y/Latitude Spacing: 5

Figure 3.9 GeoTiff raster export settings for Global Mapper 14.

3.4 Data Classification

Sidescan imagery for mapping purposes is typically not very useful until it is classified with attributes of the bottom composition. In order to be useful for researchers, sidescan imagery containing eelgrass locations needs to be classified quickly. There are typically four methods of classifying remote sensing data, manual, supervised, unsupervised, and object oriented. For this study, only manual and unsupervised classification techniques are examined. Supervised classification did not function correctly in ArcGIS when it was trialed on the sidescan imagery and object oriented classification would have required an additional program purchased outside the SSI program. Therefore, the sidescan mosaic was classified in ArcGIS both manually and unsupervised with the Iso Cluster tool. Additionally, it was trialed in Clark Labs’ TerrSet (IDRISI).

3.4.1. Classification in ArcGIS

The following subsections detail classification techniques in ArcGIS. The first method outlines the Iso clustering utility with the stock image and then running it again with Principal Component Analysis (PCA) conducted beforehand. The second method involved manually digitizing the sidescan image according to what an observer viewed.

3.4.1.1. Iso-Clustering Classification

The GeoTiff raster image was imported into ArcMAP, the Image Classification toolbar was opened, the image was loaded in the toolbar and the Iso Clustering classification was selected from the drop-down menu. Eight classes were chosen and the program was run. See Figure 3.10 for the resulting image of the straight Iso-cluster. The same classification process was followed with the image first being run through the Principal Component Analysis (PCA) utility. See Figure 3.11 for the resulting image run with PCA.

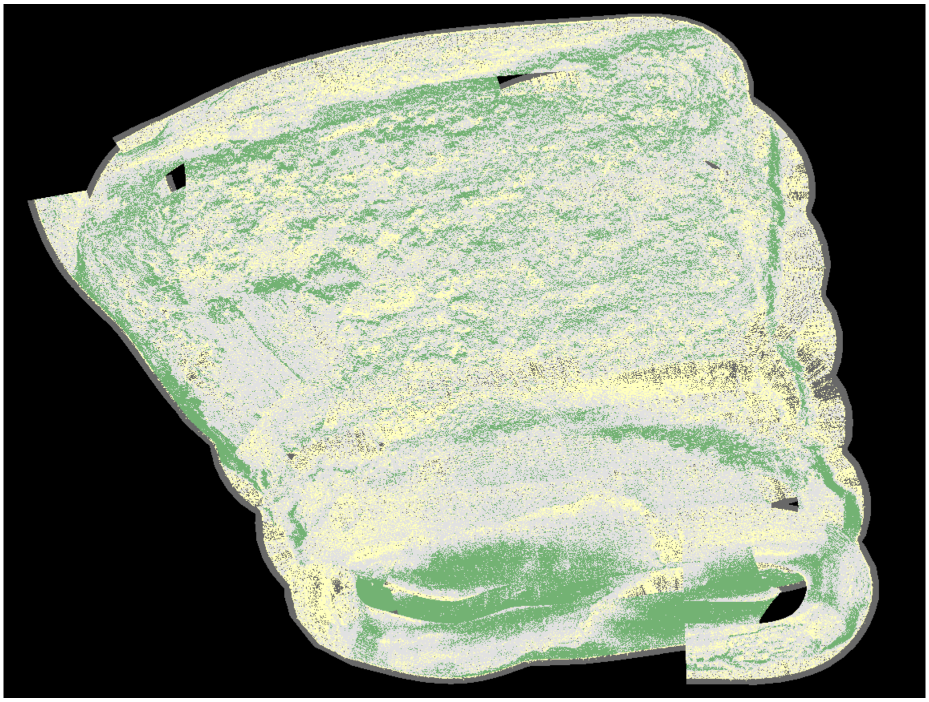


Figure 3.10 Iso Clustering raster of bottom composition.

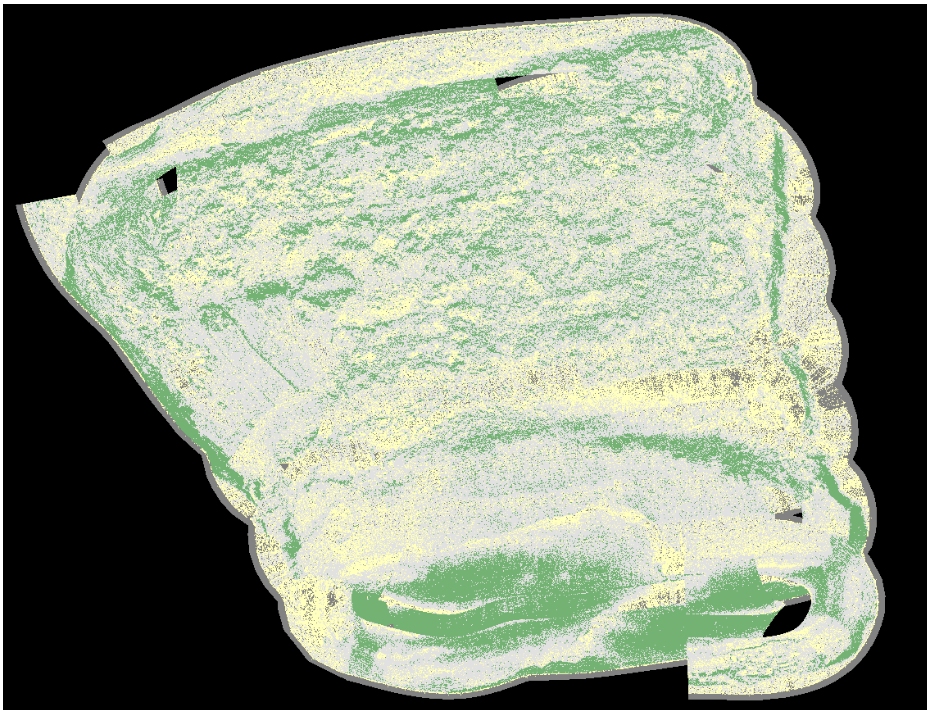


Figure 3.11 Iso Clustering raster with PCA of bottom composition.

3.4.1.2. Manual Digitization Classification

Manual digitization of the GeoTiff was accomplished through visually interpreting the raster image. A new feature class was created and a construction template was used with values for the bottom type , either eelgrass or sediment. “Fuzzy” areas were classified as eelgrass polygons and “smooth” areas were classified as sediment.

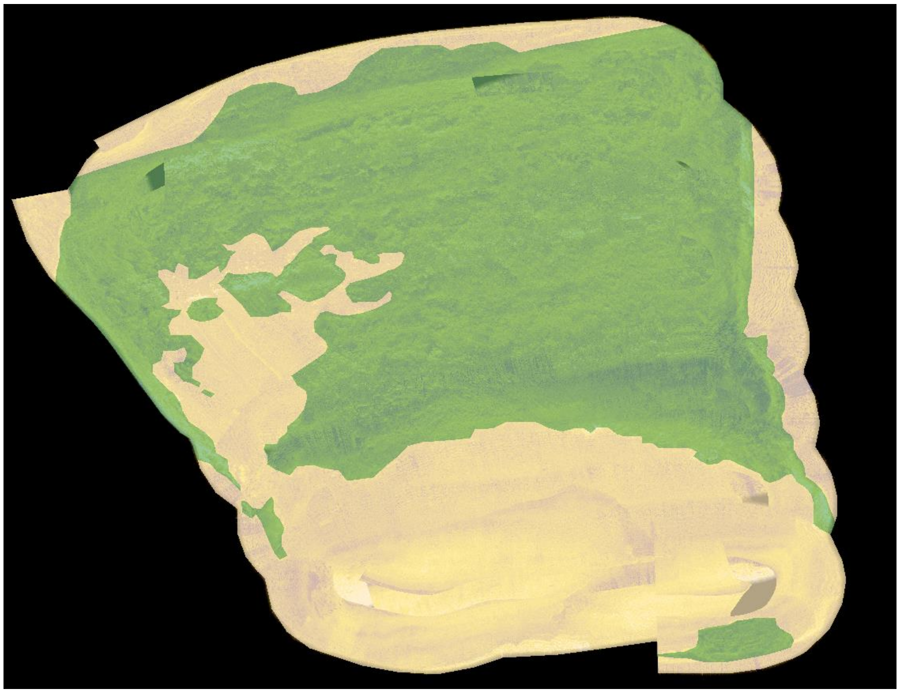


Figure 3.12 Manual digitization of side scan image. A 50% transparency was used to show the side scan image beneath. Green is the location of eelgrass.

3.4.2. Classification in Clark Labs’ TerrSet (IDRISI)

The GeoTiff raster image was imported into IDRISI through the GDAL Conversion Utility tool in IDRISI. The output format “RST (RW+v): Idrisi Raster A.1” and Bands 1-4 were selected. A false color composite image was made through the COMPOSITE image compositing utility with Band 1 specified as the Red image band, Band 2 specified as the Green image band, and Band 3 specified as the Blue image band. Band 4 is a “no data” area image and was not selected. See Figure 3.13. for the false color composite image of the sidescan mosaic. A raster group was then made of Bands 1-3.

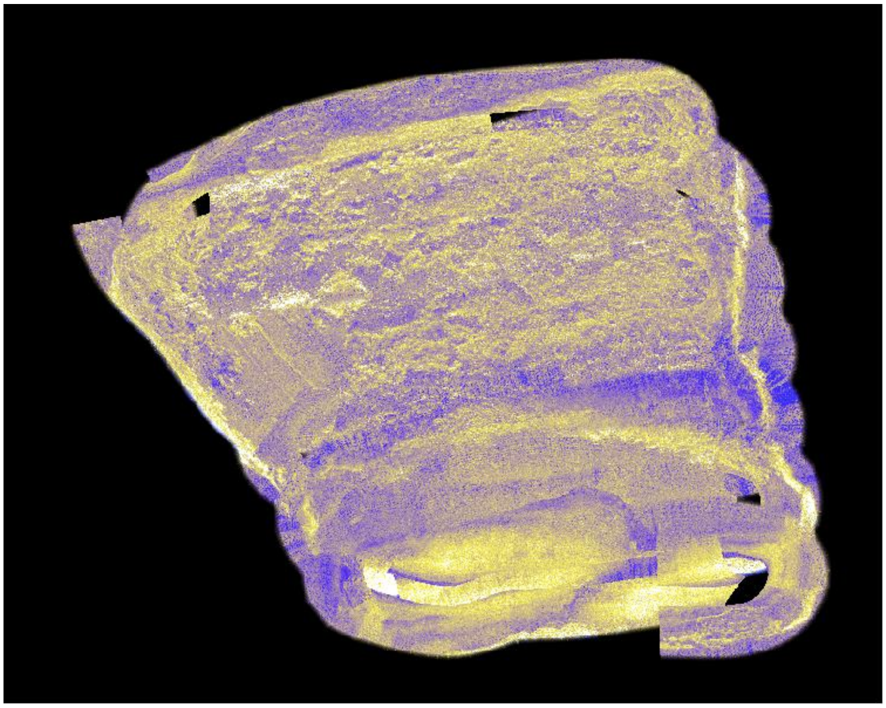


Figure 3.13 Sidescan mosaic as a false color composite image.

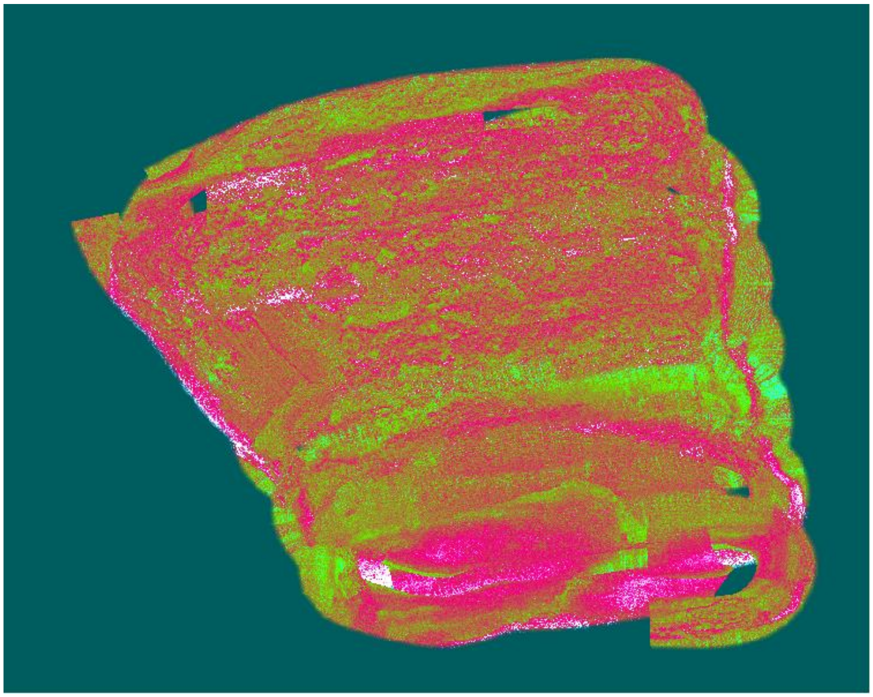


Figure 3.14 Sidescan mosaic as a false color composite image with PCA.

The raster group was then inserted into the Principal Component Analysis (PCA) utility and run in Forward T-Mode with the option for Covariance matric (Unstandardized) selected. A false color composite image was made from this PCA analysis through the COMPOSITE image compositing utility with Band 1 specified as the Red image band, Band 2 specified as the Green image band, and Band 3 specified as the Blue image band. See Figure 3.14 for the false color composite image with PCA.

The ISOCLUST utility was then run on the raster group with PCA analysis and the one without. After the histogram was generated of each, the dialog box was specified to conduct: 3 iterations, 8 output clusters (based on the diminishing returns from the histogram), and a minimum sample size of 30 pixels. After the ISOCLUST utility was completed on each of the rasters, they were visually reclassified, creating classes for no data areas, sediment and eelgrass. See Figure 3.15 and Figure 3.16 for the results of the reclassification.

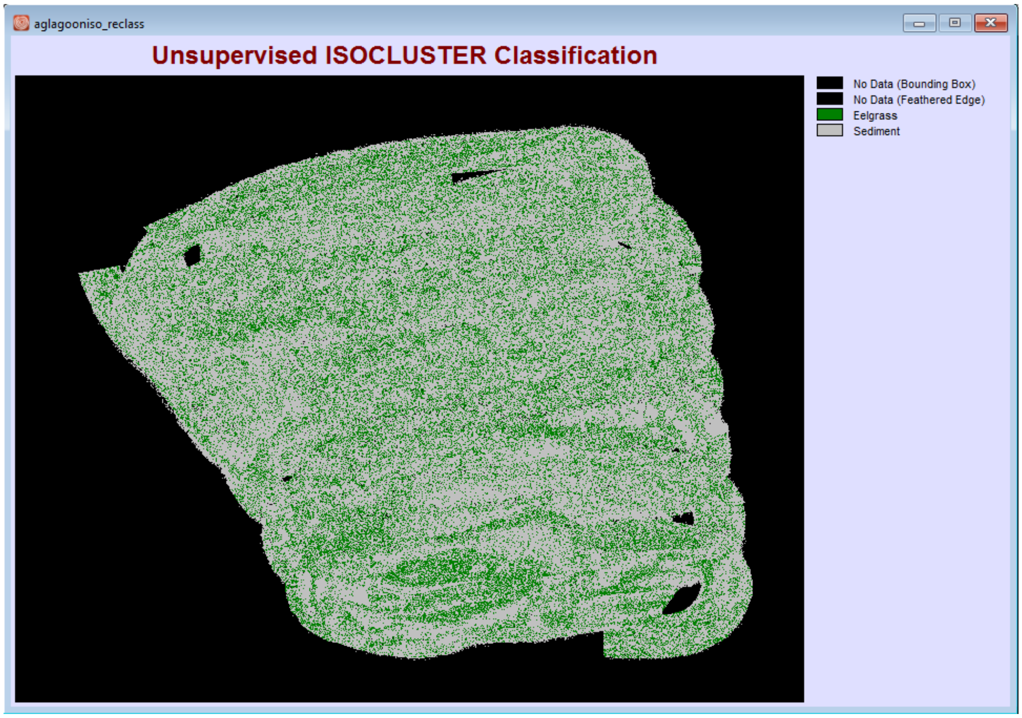


Figure 3.15 IDRISI Unsupervised IsoCluster classification.

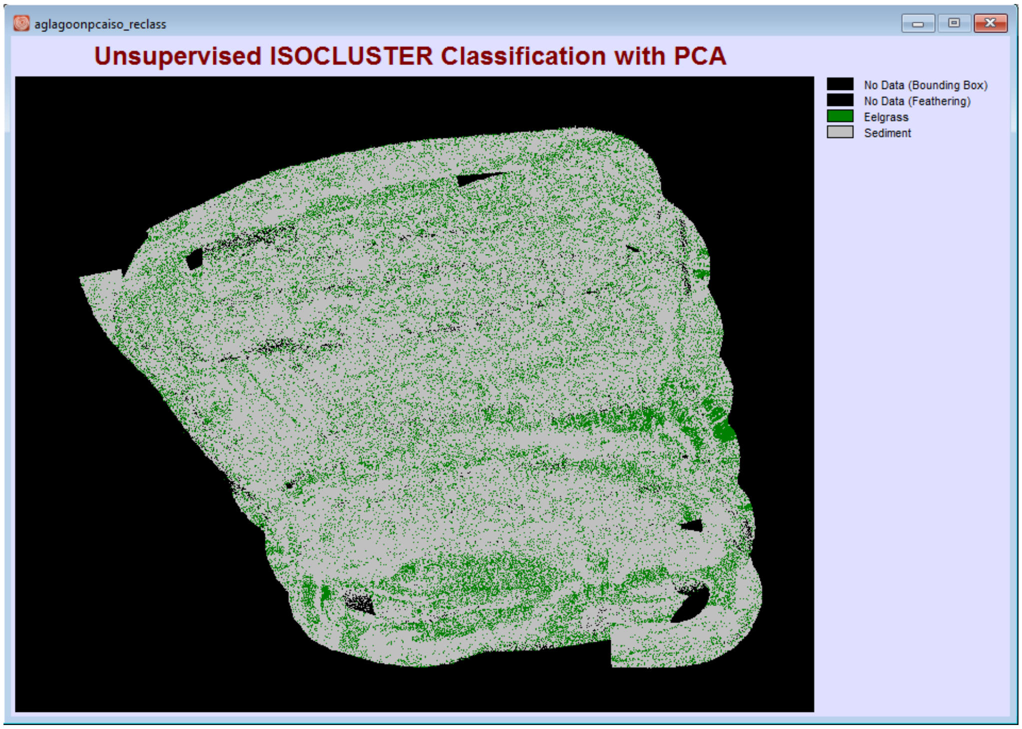


Figure 3.16 IDRISI Unsupervised IsoCluster classification with PCA.

3.5 Depth Processing

After importing the GPS assets from Section 3.3, a new map project was created and the tracks were uploaded into that new map project file. Next, the Define Map tool was selected and a box was drawn around the entire middle lagoon. The Define Map tool automatically generates a bathymetric map with the soundings. The map was changed from vector to raster to show the gradual bathymetric curves better. The map was then exported as a PNG file to be opened in ArcGIS. Exporting the bathymetric map was trialed as a shapefile, but only contours were available, and as an ESRI Grid (.arc) file, but no spatial reference was assigned to it. This is a known error and is intended to be corrected in the next Reefmaster release.

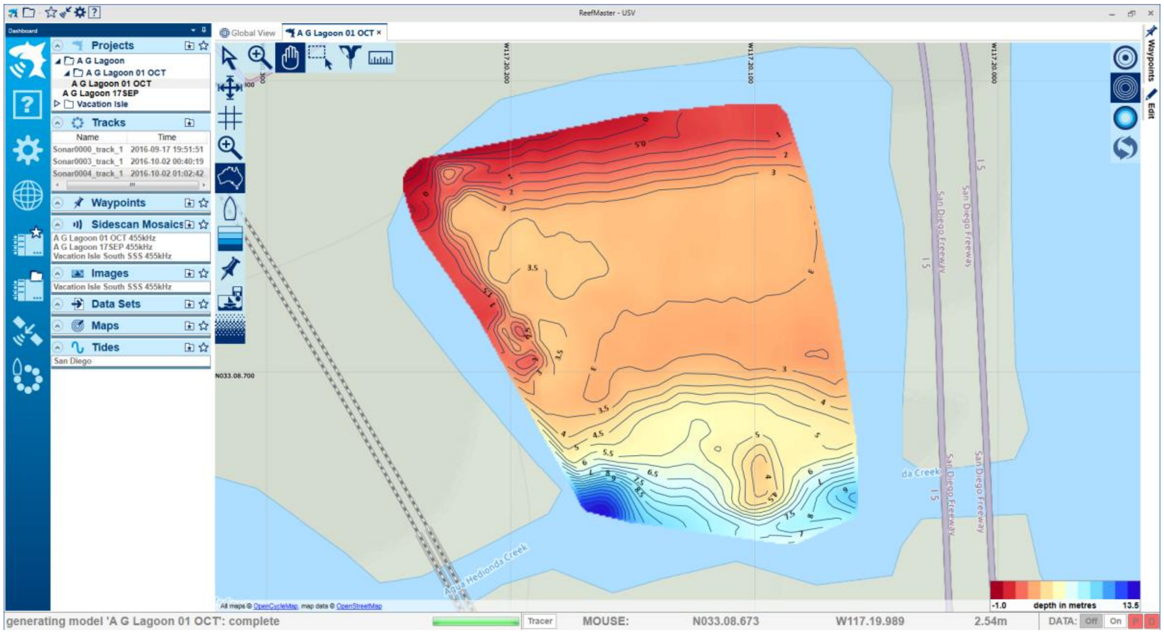


Figure 3.17 Bathymetric map made from soundings collected by the USV.

Chapter 4 Results

This chapter presents results from recording sonar imagery of eelgrass using a USV. The results of the data determine whether an inexpensive USV can be used for identifying eelgrass in very shallow water. Findings compare the USV collected data against existing data sources via a manual classification in polygon format (Section 4.1), automated classification in raster format (Section 4.2) and depth data (Section 4.3).

4.1 Comparison of USV Sonar and Existing Data (Manual Classification)

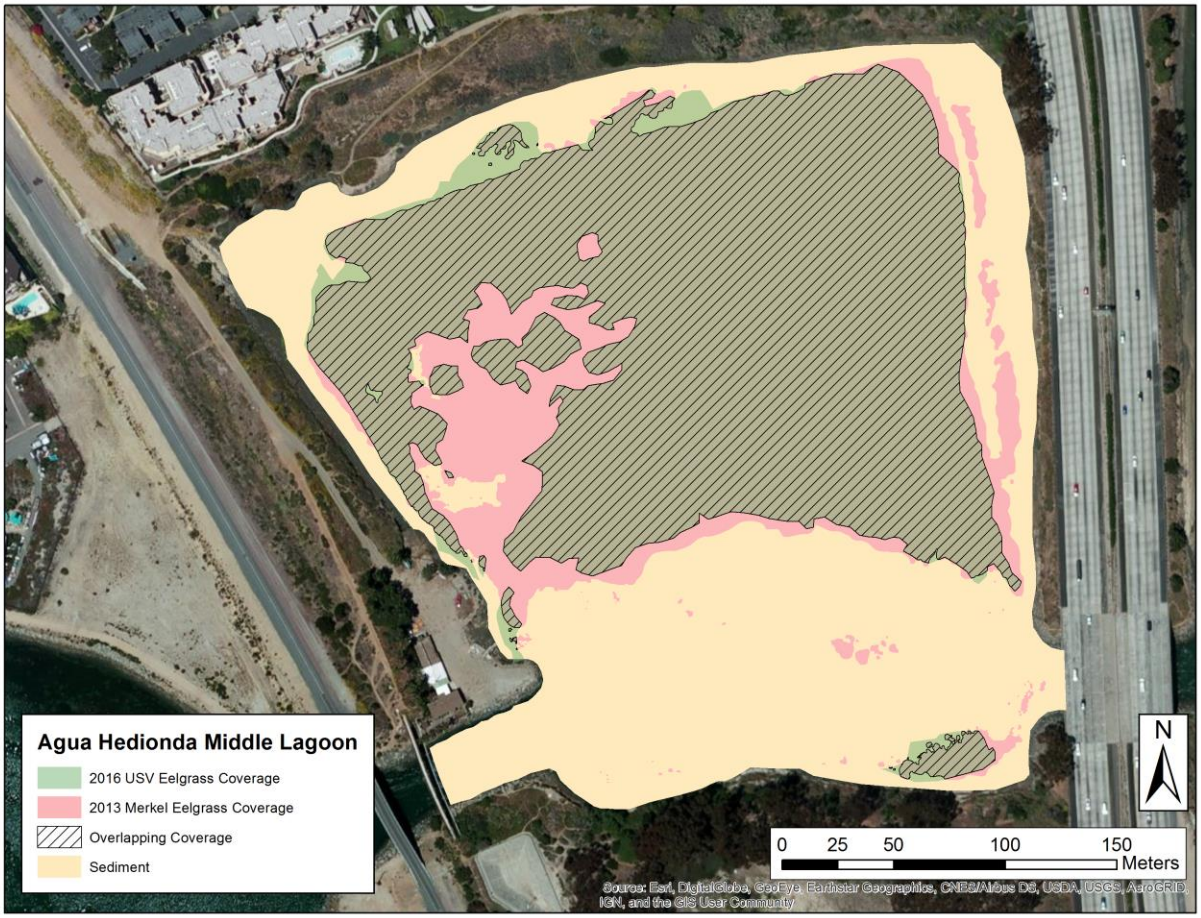
The USV collected imagery is visually compared to processed polygon data from Merkel & Associates. To compare relevance, the dates the imagery sets were collected are listed in Table Table 4.1.

Table 4.1 Dates imagery were taken by the two surveys. The table reveals a three year difference in age between the surveys while sonar frequency was comparable.

Imagery Source	Date(s) Collected	Collection Equipment
USV	01 October 2016	455 kHz side scan sonar
Merkel & Associates	19 April, 15 and 19 July, 20 September 2013	468 kHz side scan sonar and aerial photography

The USV side scan imagery was collected over a single day in October 2016, and is the most recent dataset of the bottom composition of the middle lagoon in Agua Hedionda Lagoon. The Merkel & Associates dataset, when it was captured and processed in 2013 is the most recent and relevant professional data compared to previous mapping efforts. From reviewing the history of the middle lagoon, very little has changed physically since 2013 and there have been no dredge operations to deepen the channel in the middle lagoon. The only dredge operations to occur have been in the outer (western) lagoon to clear sand away from the intakes of the Encina power plant.

In order to determine how closely the USV collected and manually classified polygon matched the Merkel & Associates processed polygon, the intersect tool in ArcGIS was run with both datasets revealing the area of overlap where there was eelgrass in both datasets. See Figure 4.1 to see a visual of both datasets and the area of overlap.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 4.1 Map showing the eelgrass coverage areas of the 2016 USV data, the 2013 Merkel data and where the datasets overlap.

In reviewing the individual polygon shape areas from their respective attribute tables in ArcGIS, there is a reasonably large difference between the 2016 USV polygon and the 2013 Merkel polygon (7500.57m^2) that is assessed in Figure 4.1. With another review of Figure 3.12, it is clear the decrease in area from 2013 to 2016 is not due to the recreational side scan sonar missing the western section of the main eelgrass bed, but instead due to a physical loss of eelgrass in the bed itself. The factors of why this occurred are topics for marine biologists to investigate and outside the scope of this project.

The areas where the USV missed collecting data were in the northeast corner and the very southern border. The northeast corner was missed due to a fear of the operator of bio-fouling entanglement and grounding the vehicle in extremely shallow water. The portion of the southern border was missed due to an entanglement hazard that the vehicle had to be worked free from and a depleted battery from running continuously for nearly 1.5 hours.

Table 4.2 Respective polygon area coverages.

Polygon Shapefile	**Shape Area (m^2)**
2016 USV Eelgrass Coverage	47,633.64
2013 Merkel & Associates Eelgrass Coverage	55,134.21
Overlapping Coverage	45,787.85
Total Area of Agua Hedionda Middle Lagoon	93,208.71

4.2 Comparison of USV Sonar and Existing Data (Unsupervised Classification)

In addition to the manual bottom classification, an automatic classification approach was tested in ArcGIS and Clark Labs' TerrSet (IDRISI). In order to reduce redundancy in the raster datasets, the principal components analysis (PCA) tool was run in each of the programs on the input raster before the final Iso Clustering tool.

4.2.1. Unsupervised Classification in ArcGIS

Figure 4.2 and Figure 4.3 show the results of using the Iso Clustering Classification tool in ArcMAP. Visually inspecting the images yielded little to no visual change between the standard image and the one run with PCA. Although the method worked for delineating the eelgrass bed as in the manually classified polygon, the majority of the eelgrass bed was only lightly classified as eelgrass, signifying that spectrally differentiating eelgrass from sediment is difficult for the system to handle and most likely not what the tool was intended for. Another area of concern is the large patches of green that the tool classified as eelgrass, but in reality are areas of sediment. At this time, it is unknown why ArcMAP classified these regions as eelgrass.

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 4.2 Unsupervised Iso Cluster Classification in ArcMAP.

Figure 4.3 Unsupervised Iso Cluster Classification with PCA in ArcMap

4.2.2. Unsupervised Classification in IDRISI

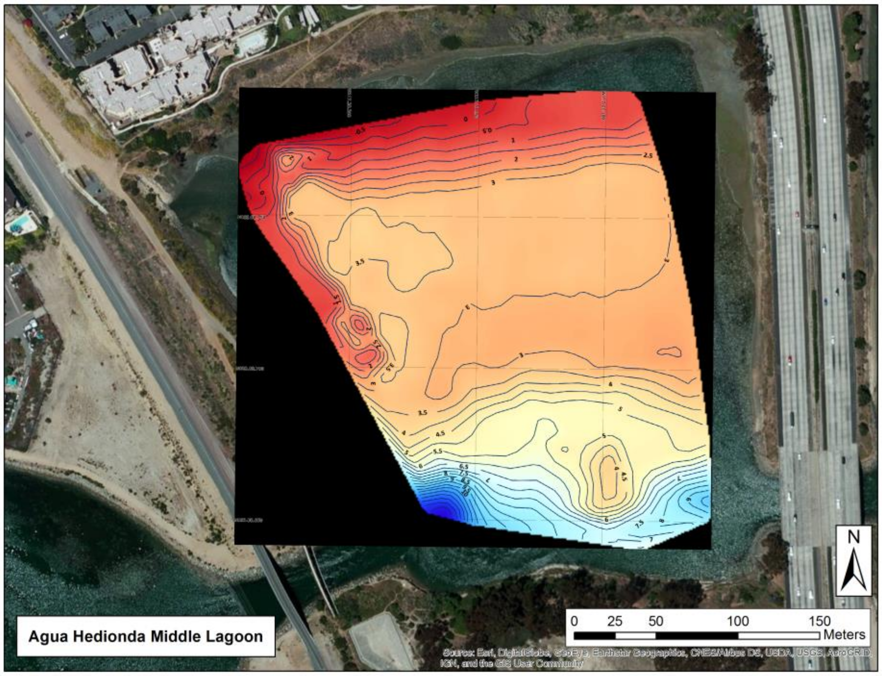
Automatic image classification was also conducted in IDRISI, which yielded a different set of results. Figure 4.4 shows the result of running a straight Iso Cluster classification. It is apparent the program had difficulty spectrally differentiating eelgrass from sediment and there is no delineation between the two in known locations. Figure 4.5. shows the raster with PCA run before the classification process. The results show some delineation between eelgrass and sediment, but not enough to be conclusive. It should be noted that the large patch of what IDRISI classified as eelgrass in the southern region is not actually eelgrass. Similarly to ArcMAP, this area must have been spectrally similar to eelgrass IDRISI classified it as such.

Figure 4.4 Unsupervised Iso Cluster Classification from processing in IDRISI.

Figure 4.5 Unsupervised Iso Cluster Classification with PCA from processing in IDRISI.

4.3 Single Beam Depth Data

The single beam sonar from the USV yielded a fairly detailed, bathymetric map with tidal corrections (Figure 4.6) as compared to the bathymetric map from the 2005 hydrodynamic study conducted by Coastal Environments. However, there are limitations in only that a PNG image file could be exported for use in ArcGIS. As was later found out, the software creator does not have a copy of ArcGIS, so functionality was rather limited. This precludes importing information for a legend and other supporting information. In the future, the developer is working on additional export options for shaded relief rasters and ESRI Grid files.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 4.6 Bathymetry from single beam sonar from USV. Note: Unable to import depth legend from Reefmaster.

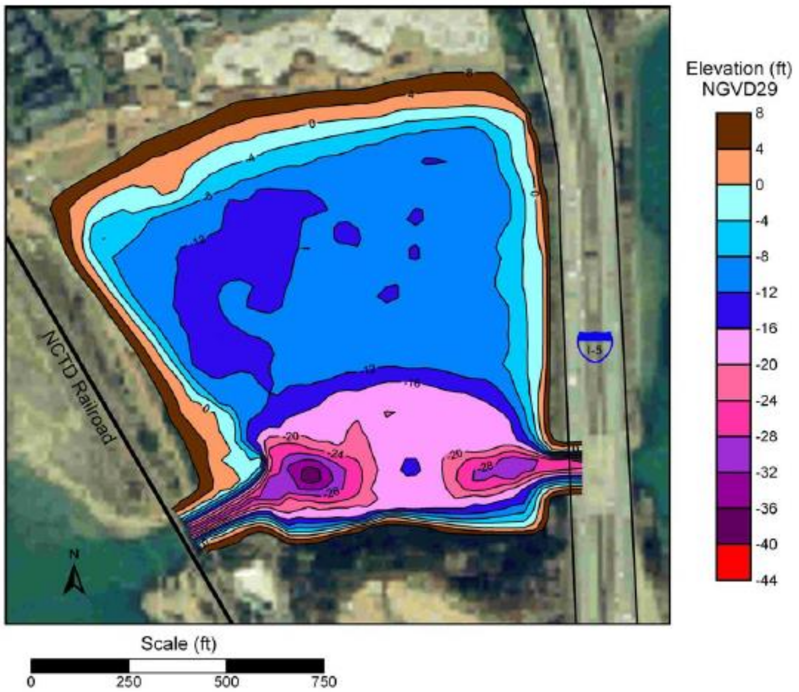


Figure 4.7 Bathymetry of Agua Hedionda Middle Lagoon (Source: *Coastal Environments 2005*)

Chapter 5 Discussion and Conclusions

This chapter discusses results and conclusions of the use of an inexpensive USV for mapping eelgrass. The findings from the results of the GIS imagery from Chapter 4 will be discussed first. Next, ascertainable sources of error will be examined before looking at the Strengths, Weaknesses, Opportunities and Threats (SWOT) of the overall projects. The rest of the chapter will discuss possible future improvements for the vehicle and software to achieve better results.

5.1 Findings

The methodology utilized in Chapter 3 and displayed in Chapter 4 provided three significant findings: 1) accuracy and differences in eelgrass coverage between 2013 and 2016, 2) utility of auto-classifying in ArcGIS and IDRISI, 3) applicability of bathymetry information.

The accuracy in comparing the 2013 Merkel & Associates polygon of Agua Hedionda Lagoon and the polygon created in 2016 from USV side scan data is a bit difficult to compare. From a visual analysis, the edges between the two polygons are nearly identical with very little of the 2016 data not overlapping with the 2013 polygon. The difference comes in comparing the difference between the two areas. The 2013 polygon contained 7500.57m^2 more eelgrass area than the 2016 polygon. By only looking at the polygons and not the sidescan data, an observer would conclude that the USV was inadequate at collecting the eelgrass coverage. However, a closer examination of Figure 3.12 where the manually digitized polygon was set to a 50% transparency reveals that the polygon conforms to the sidescan data of where the eelgrass was in 2016 and there is clearly more exposed sediment than in 2013. Thus, the conclusion from this is that the USV was not inadequate at collecting data, but that there was a recession of the eelgrass bed from 2013 to 2016. Although a loss of eelgrass in the lagoon is unfortunate, these results can be confirmed via a ground truth of the bottom or when the lagoon is professionally rescanned in

2018 by Merkel & Associates. It will be interesting to note the change and see if this 2016 data acts as a “midpoint” between 2013 and 2018 or if the eelgrass grows back.

Although auto-classifications using the Iso-Cluster tool were run in both ArcGIS and IDRISI, neither of the programs yielded satisfactory results that could discernably be used to classify and eelgrass bed from sediment. The best result came from using the Iso-Cluster tool in ArcGIS (running PCA was irrelevant), however, a false classification of known sediment as eelgrass in the southern area of the lagoon called this method into doubt. The same false classification was discovered when classifying in IDRISI was attempted. In comparison to ArcGIS, IDRISI did have a discernably better result in identifying the eelgrass edge when PCA was run on the sidescan image before the Iso-Cluster tool. It should also be noted that a supervised classification was unable to be conducted in ArcGIS due to an error in attempting to create a signature file. In conclusion regarding auto classification of sidescan images, it is determined the software in ARCGIS and IDRISI is not mature enough to handle accurate processing at this time. Although more time consuming, manually classifying the data yielded more accurate results that could be supported by sidescan imagery.

The examination of the 2016 bathymetry data in comparison to the 2005 data is difficult to determine. There was no GIS bathymetry data that could be located for the 2005 report, thus any sort of analysis in ArcGIS is not possible. Further, Reefmaster was only able to output a single PNG image of the depth raster. This complicated import into ArcGIS and no Legend could be accurately created showing what the colors corresponded to in the raster. Another issue with the single beam sonar itself is that due to the narrower beam as compared to the sidescan sonar, depth data was unable to be collected on the far extents of the lagoon leaving large data gaps along all the edges. This could possibly be remedied by conducting surveys at high tides and driving the USV closer to shore.

5.2 Sources of Error

The primary source of positional error comes from the GPS receiver on the Lowrance HDS-7 Gen 3 chartplotter. The GPS on the USV is for vehicle navigation only hand has no connection to the Lowrance charplotter. In order to mitigate the positional error of the side scan, the chartplotter was mounted on top of the sidescan sonar transcoder so that no offsets would need to be entered. No GPS accuracy information is given in the Operator Manual for the internal GPS and the previous informational screen that displayed satellite data was removed from the GEN 3 models. Therefore, it is unknown what the positional accuracy of the Lowrance charplotter is. With that said, the GPS is rated at a 10Hz high speed update and capable of using GPS & GLONASS, WAAS, MSAS, EGNOS for corrections. These methods usually result in position fixes of less than 1m.

The other likely source for error is the multiple data format transitions that had to occur to get the sidescan and depth data to display correctly in ArcGIS. ArcGIS 10.4 did not have any tools or extensions to support importing the Lowrance SL2 files directly, so they had to be imported and processed in Reefmaster software. Sidescan mosaicking is not completely automatic and there is a high level of direct operator intervention to add relevant sections to a final mosaic. Once a mosaic is completed, it is exported into a PNG format, which ArcGIS can’t import either and had to be exported as a GeoTIFF in GlobalMapper. There are many settings for creating a raster GeoTIFF and while the end result worked in ArcGIS, some of the settings may be incorrect for a multiband monochrome raster image. Additionally, once the images were imported into ArcGIS, the raster had to be projected into the California State Plane VI in order to get accurate polygon shape length and area.

In manually digitizing the sidescan image between sediment and eelgrass errors could be made in interpreting areas of eelgrass due to the single color of the image. The only way to differentiate is to determine which areas are smooth (sediment) or rough/fluffy (eelgrass). Due to the failure of auto classifications, manually digitizing often leads to errors and creating polygons that are not precise enough to capture all the data.

5.3 SWOT Analysis

A SWOT analysis of the many lessons learned in this study show that although there strengths to using this method, there are also weaknesses and threats that should look at being addressed. See Table 5.1 for the attributes that have been identified. As has been discussed in Section 5.1, using a small USV that was built with off-the-shelf parts allowed the operator to keep costs low while still collecting relevant data that could be processed in affordable commercial software to create GIS imagery and products. As long as the mission profiles are saved, another mission could be run at any time and the same spatial data could be collected with a different temporal date.

With the USV running on battery power, the endurance was limited to around 1.5 hours with most of the power going to the thrusters. For larger areas, a higher endurance time will be mandatory and there are some opportunities using Lithium Ion (Li-Ion) battery packs or Sealed Lead Acid (SLA). Due to the shallowness of the water medium and the nadir region, the swath width was limited and was often adjusted to actually have useable data. Imagery on the fringes tended to be of low quality and the nadir region was highly compressed. To overcome this, an overlap in the side scan imagery was mandatory and even then some areas were missed. Another consideration was that there had to be a minimum of 20cm of water depth for the vehicle to operate without striking the bottom. This often led the operator to be overly cautious in where he or she was driving. One aspect of the vehicle that was never fully developed was the tuning of the autopilot module. Although it was in a working state, further tuning is required to ensure it tracks properly along a path of waypoints. This is a time consuming process, but once complete, the vehicle will have the capability to complete its mission fully autonomously.

Table 5.1 SWOT analysis of using a USV for shallow water mapping.

Strengths	1. Man portable system 2. Cost effective (Hardware and software) 3. Provides up to date sidescan imagery 4. Easily repeatable
Weaknesses	1. Limited endurance 2. Limited useable swath width 3. Requires at least 20cm of water under the keel 4. Limited side scan sensors available 5. Autopilot requires configuring 6. Line of sight communications
Opportunities	1. Can be used to map other types of submerged vegetation or features 2. Technology advancements will lower the cost of sidescan sensors and improve quality 3. Better autopilot features 4. 4G Cellular or Iridium satellite communications for longer range
Threats	1. Vessel Traffic 2. Propulsion fouling 3. Future government regulations on USVs

An exciting prospect for this USV is that is can be used to map other types of submerged vegetation that may be invasive or require monitoring. This vehicle can be used in lakes, slow moving streams or even in the open ocean if the wind waves are low. It will only take the keen eye of an analyst to determine the what different sonar returns are imaging.

The two most difficult threats facing the USV during mapping operations were human powered vessel traffic and propulsion fouling. Human powered vessels (paddleboards and kayaks) are common in Agua Hedionda Lagoon and there were a few instances during initial navigation tests that the USV was brought to a halt to allow the traffic to pass. The solution to this was to wait until dusk when all the vessels were off the lagoon and a complete run could be conducted without interference. The other physical problem, propulsion fouling, was a very difficult issue with the BlueRobotics thrusters. Ironically, floating eelgrass that was detached from its base in the sediment was easily sucked into the thrusters and caused them to seize up. See Figure 5.1 for an example of a fouled thruster. Since the thrusters were of a brushless design, no damage done, but eelgrass did cause a number of propulsion failures and the vehicle had to be manually retrieved and cleaned out. The solution was to utilize a 3D printer and manufacture thruster guards. These dramatically cut down on the amount of eelgrass sucked in and allowed for the survey to be completed.

Figure 5.1 Image of fouled thruster with eelgrass.

Unlike the use of UAVs which have been heavily regulated, there are no United States Government regulations regarding the use of USVs. In the International Regulations for Preventing Collisions at Sea 1972 (COLREGS), a USV has no definition and is not refined as a "vessel" because it is unable to carry people or cargo. However, COLREGS is routinely updated for new legal definitions as technology is updated. It is expected that there will be a definition for USVs in the regulations in the future. If the vehicles must conform to the collision regulations that manned vessels must obey, then USVs may lose their appeal and utility.

5.4 Future Improvements

Many lessons were learned on this project and although a few rapid innovations were implemented such as 3D printing, there are still many that will take some time to research and develop. The following remaining sections highlight how a USV for mapping eelgrass in very shallow water may be improved starting with physical vehicle improvements and then looking at other software packages.

5.4.1. USV Improvements

The USV was built over a period of 6 weeks in August and September 2016 with the intention of being a platform that could adequately maneuver a sidescan sonar around the lagoon. While this basic premise was successful, there are a few improvements that are being implemented on the next revision of the vehicle.

In November 2016 the successor to the Pixhawk 1, the Pixhawk 2.1 was finally brought to the consumer market and reviews have been good. The new autopilot features a modular design, more accurate GPS, an onboard computer and an additional Inertial Measurement Unit (IMU). The Pixhawk 2.1 is compatible with the ArduRover firmware, but so far has not been tested with it. Replacing the current autopilot will require some rework, primarily on the connector interfaces, but should offer better navigation control once the parameters are correctly tuned especially with the use of multiple GPS’.

One of the limitations of the current USV setup was that it was reliant upon the additional radio control (Spektrum DX8) for manual control. During normal operations, the radio control is only used for maneuvering near the launch and retrieval point. The vehicle is in AUTO mode for the majority of its mission. There are parameters to enable the use of a joystick in another program called MissionPlanner, but they have not yet been implemented into QGroundControl. Getting these working properly would allow the operator to do away with everything but the tablet as there is an option for a “virtual joystick” with touch controls right on the screen. This would save a fair amount of weight in the field.

A useful feature that is found on some of the more expensive USVs is the ability to see live sonar data back to a ground control station. The USV used on this project does not support this, however it is being considered for future work where the ability to see areas that have been scanned in real time is important. The communications architecture for the improvement is still being researched, but it will most likely require an onboard computer lugged into the chartplotter relaying data back to shore over Wi-Fi.

5.4.2. Reefmaster 2.0 Improvements

In October 2016, Reefmaster announced that the software package would be undergoing major upgrades for the “2.0” release by Quarter 1, 2017. Although most of the changes are directed towards bathymetry, some were for sidescan mosaics. GeoTIFF inport and export support is reported to be coming which should be easier to open in ArcGIS. It was mentioned that new blending modes including “closest signal” and “blend closest” would be implemented which blends the sidescan signal across multiple sidescan swaths, thus eliminating the need to edit port/starboard ranges that are fairly time consuming. Other features include noise reduction, real-time sharpening and fully automatic gain correction.

5.4.3. Object Oriented Classification

In researching alternative classification techniques, the National Oceanography Centre of the United Kingdom created an Esri Add-in called Remote Sensing Object Based Image Analysis (RSOBIA). The RSOBIA software is able to take multi-layered raster imagery (including sidescan imagery) and segment the data into geographic areas with similar statistical properties. This technique is a bit different than the Iso-Cluster tool and from the imagery in a presentation looks like it will do a much better job of auto-classifying sidescan data from a USV. The downside is that a license costs £100.00 for a single user.

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Appendix 1: Materials List and Cost

USV Equipment List

Component	Quantity	Cost Total
SunDolphin Bali 6 Kayak	1	$120.00
HDPE Cutting Boards	4	$10.00
Bolts, ¼”	8	$1.00
Wingnuts, ¼”	8	$1.50
Machine Screws, ¼”	24	$2.00
Loctite Marine Epoxy, tube	4	$20.00
BlueRobotics T200 Thruster	2	$338.00
1200 Pelican Case	2	$95.22
Pixhawk 1 Autopilot	1	$199.99
Quadcopter Power Distribution Board	1	$10.00
BlueRobotics 30A Basic ESC	2	$50.00
Spektrum DX8 Radio Control	1	$349.99
3DR GPS Unit	1	$89.00
RFD900+ Telemetry Radio Bundle	1	$229.95
XT-60 Connector	1	$5.00
Pack of 18AWG Silicone Wire	2	$12.00
BlueRobotics Hull Penetrators	10	$40.00
Bullet Connectors	28	$10.00
XT-90 Connectors	2	$10.00
XT-90 Y-Harness	1	$20.00
Multistar 4S 10,000 mAh LiPo Battery	2	$138.00
Lowrance HDS-7 Gen3 Chartplotter	1	$949.00
Lowance Totalscan Transducer	1	$299.00
	Total:	$2999.65

Ground Control Station

Component	Quantity	Cost Total
Microsoft Surface Pro 4	1	$899.00
MobileDemand XCase for Surface Pro 4	1	$124.95
	Total:	$1024.95

Software

Component	Quantity	Cost Total
Reefmaster PRO	1	$149.00
GlobalMapper v18.xx	1	$499.00
	Total:	$648.00