MAPPING AND ANALYSIS OF CORAL REEF DAMAGE RELATED TO BOATING IN KĀNE‘OHE BAY WITH UNMANNED AERIAL SYSTEMS

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE UNIVERSITY OF HAWAI‘I AT MĀNOA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF ARTS

IN

GEOGRAPHY

DECEMBER 2016

By

Robert C. O’Conner

Committee Members:

Mathew McGranaghan, Chairperson
Everett Wingert
Cynthia Hunter

ABSTRACT

Low-cost unmanned aerial systems have been underutilized in mapping damage to coral reefs due to recreational boating activities. The need for fast and accurate mapping is important when making sense of situations where coral reefs require emergency restoration and damage assessments.

With coral reefs under increasing stress from global climate change and other anthropogenic factors, the need to protect them is more important than ever. There are inherent challenges in mapping benthic habitats with typical methods such as scuba surveys and satellite photo interpretation. This study aims to use unmanned aerial vehicles to map damage to coral reefs related to boating in Kāneʻohe Bay. Images were taken at relatively low altitudes from an unmanned aerial vehicle and then mosaicked together using commercially available software. The image orthomosaics were georeferenced and digitized into vector files for further analysis. The vector files can reveal patterns and concentrations of vessel related damage to coral reefs in the bay. Continued data collection can serve to monitor damage and predict future locations of boat interactions with these important marine resources.

ACKNOWLEDGEMENTS

This project would not have been possible without partnering with Josh Levy in field work, boat support, data analysis, and data sharing.

I would like to thank Dr. Matthew McGranaghan for over 18 years of GIS support and guidance both within and outside academia, and for providing funding for an unmanned aerial vehicle which made this paper possible.

Thank you to the State of Hawaiʻi, Department of Land and Natural Resources, Division of Aquatic Resources for in water photography support.

Anne Rosinski deserves praise for her collaboration and insight into the project, and for continued research in this field of study to quantify coral reef damage at the study sites.

Finally, thank you to NOAA's Gerry Davis for professional support, and NOAA Fisheries for providing funding for my graduate school studies.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ATON	Aids to Navigation
AUV	Autonomous Underwater Vehicle
DAR	Division of Aquatic Resources
DJI	Dà-Jiāng Innovations
DLNR	Department of Land and Natural Resources
ESRI	Environmental Systems Research Institute
FOV	Field of View
GCP	Ground Control Points
GIS	Geographic Information System
GPS	Global Positioning System
HIMB	Hawai‘i Institute of Marine Biology
LIDAR	Light Imaging Detection and Range
NOAA	National Oceanic and Atmospheric Administration
TNC	The Nature Conservancy
UAS	Unmanned Aerial Systems
UAV	Unmanned Aerial Vehicle
UH	University of Hawai‘i

INTRODUCTION

With coral reefs under increasing stress from global climate change and other anthropogenic factors, the need to protect them is more important than ever (Jameson et al. 2007). The coral reefs of Kāneʻohe Bay are no different and serve as a microcosm of the state of coral reefs worldwide: devastated and damaged by increasing human population (Waddell 2008). Increased research and focused restoration efforts could lead to an improved ecosystem in the Bay, and coral reefs globally.

There is an abundance of boat traffic in Kāneʻohe Bay and there is evidence of related coral reef injury. This is a result of the number of public and private marinas that have been developed in the bay over the years, and the presence of a recreational boating destination, Ahu O Laka, also known as the "Kāneʻohe Bay Sandbar" (Figure 1). A majority of this traffic is located adjacent to the Ahu O Laka, with up to 60 boats visiting the site on a given day (KGMB 2011). Historically, the use of thrill craft, recreational boating, and tour group activities has produced congestion on the Bay's waterways as well (Lowe 1995). There has yet to be a study that attempts to map this specific anthropogenic impact on coral reefs in this Bay.

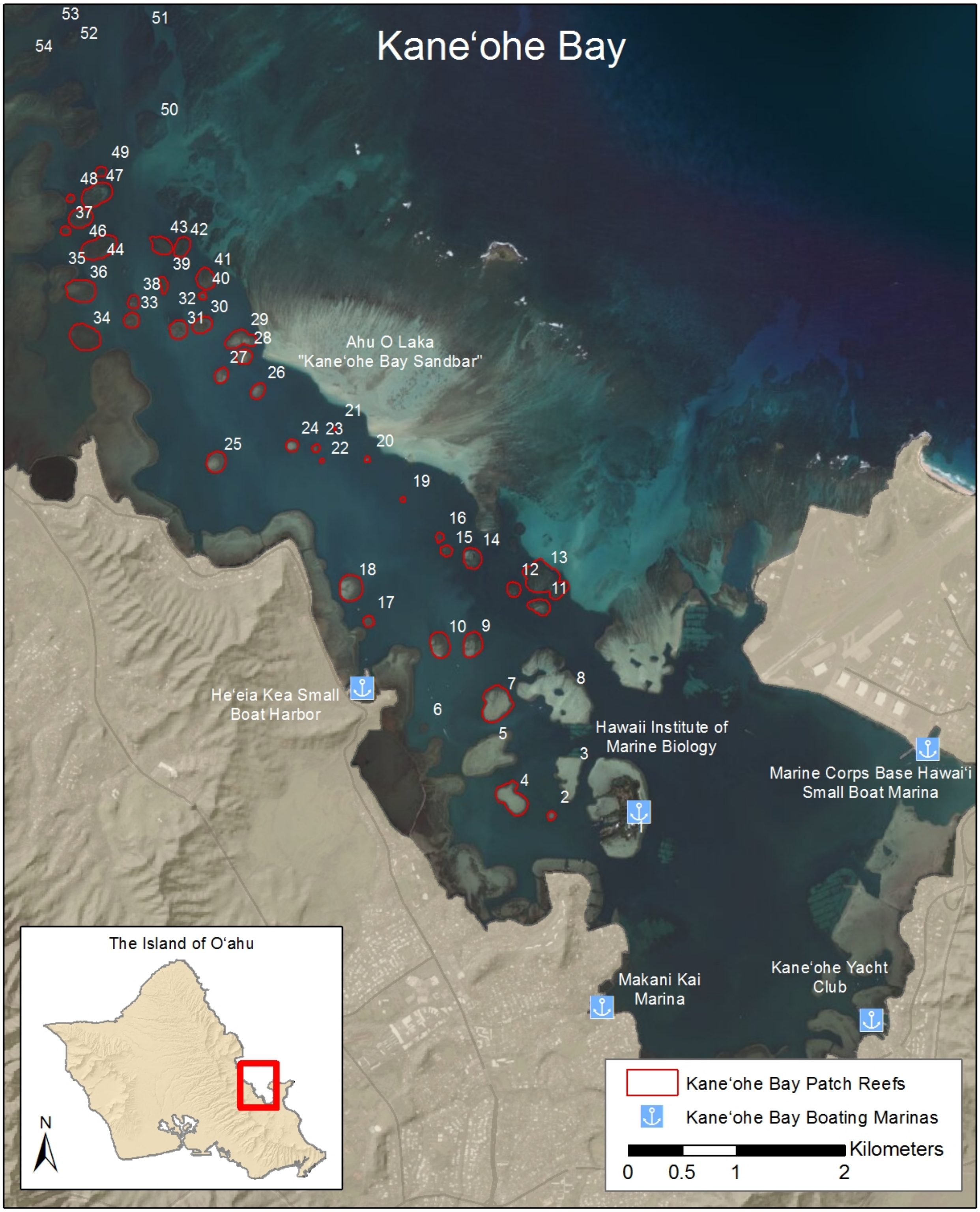


Figure 1: Map of Kāne‘ohe Bay patch reefs and marinas

Figure 2: Typical boat volume at Ahu O Laka (the Kāneʻohe Bay Sandbar)

Figure 3: Grounded boat on patch reef #20 in Kāneʻohe Bay

This congestion is a result of Kāneʻohe Bay containing the highest concentration of private marinas, public harbors, and piers in the State of Hawaiʻi including Heʻeia Kea Small Boat Harbor, Marine Corps Base Hawaiʻi, Kāneʻohe Yacht Club, Makani Kai Marina, and the Hawaiʻi Institute of Marine Biology. Inevitably, boats will run aground (Figure 3) on a monthly if not weekly basis. This occurs mainly on the unmarked patch and fringing reefs that are naturally dispersed throughout the bay. Reasons for groundings vary, but generally are due to human error, environmental conditions such as tides or winds, mechanical error related to the vessel, or a combination of these factors (Chauvin 1972). To compound the problem, there has been evidence of consumption of alcohol at Ahu O Laka (the Kāneʻohe Bay Sandbar) that has led to impaired drivers on the bay, and more recently a ban of drugs and alcohol (KHON2 2015). This is a natural resource issue because boat groundings lead to broken and crushed corals, the creation of bare substrate for colonization by invasive species (Rodgers 1999), and elimination of marine habitat complexity and structure (Precht 2001). The most dominant coral in the bay is *Porites compressa* (Hunter and Evans 1995) which is characterized as a finger coral due to its branches that grow to look similar to a human finger and are approximately one to two centimeters in diameter (Figure 4).

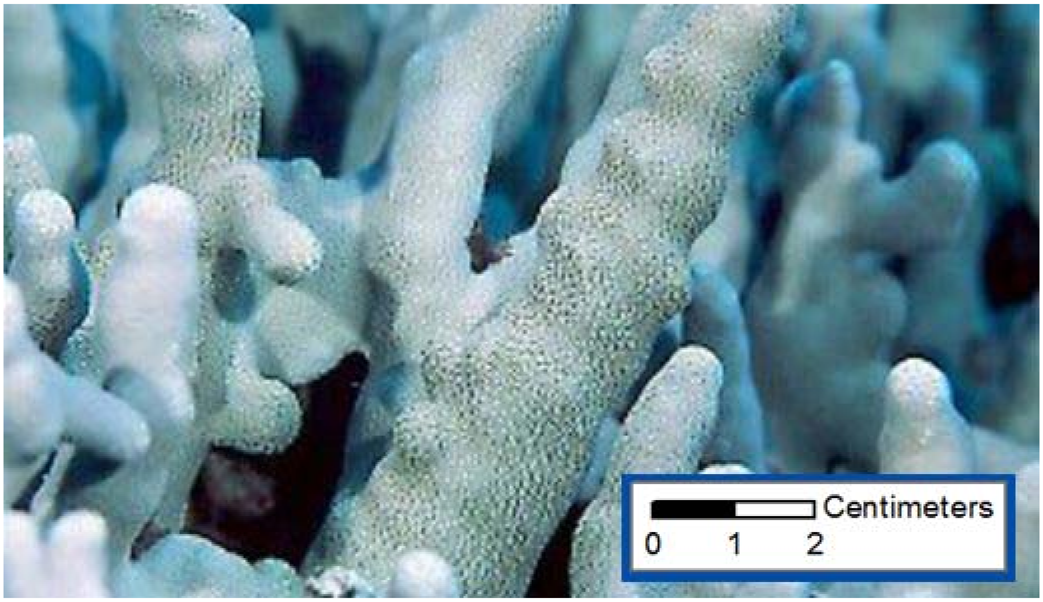


Figure 4: *Porites compressa* coral with scale bar for reference. Photo by: Yuko Stender.

Kāne‘ohe Bay is also a popular boating destination because its coral reefs are ideal for fishing, snorkeling, and scuba diving. This is because the Bay's waters are habitat for commonly harvested reef fish (Smith 1993) and the endangered green sea turtle (Balazs 1991). There is a high frequency of anchoring at the various patch reefs in the bay for these various recreational activities. The amount of fishing that takes place in the bay is exemplified by the declining catch rates of herbivorous fish (Smith 1993). Anchoring related to these activities can cause direct coral reef injury during deployment, retrieval, and while at anchor. To exacerbate the issue, the chain attached to an anchor itself often causes further damage by wrapping around and dislodging of individual coral colonies (Francour et al. 1999).

Perhaps if the injury to this natural resource could be effectively mapped and monitored something could be done to raise more awareness of this issue, and ultimately decrease the amount of boats that run aground on coral reefs. Reef #20 may be more susceptible to injury due to its close proximity to Ahu O Laka. The orientation of injury may follow the path of boats leaving Ahu O Laka and heading back to their respective marina (i.e. North to South). Considering the reefs have finger-like coral structures of one to two centimeters it may be necessary to collect imagery with a pixel size equivalent of one centimeter in order to see broken fragments as well as larger sites of injury.

LITERATURE REVIEW: METHODS FOR MAPPING CORAL REEF INJURY

Benthic habitat maps allow for a better understanding of the seascape, ecosystem function, and species habitat utilization patterns in coastal areas, and are most useful when they are created on a scale that is relevant to management actions (Wedding 2006). Mapping of coral reefs and fish habitats is also important for maintaining sustainable fisheries (SFA 1996). Mapping techniques used in a terrestrial setting are not always easily transferred to a marine setting. Diver limitations of depth and time underwater as well as oceanographic and weather conditions provide unique challenges. Furthermore, global positioning system (GPS) units that benefit most geographers in the field do not directly aid the researcher in collecting data below the surface because the satellite radio waves do not penetrate water.

Geographic information systems (GIS) are useful for answering critical research questions of fishery biologists related to benthic landscape features (Rahel 2004). Coupling GIS and spatially explicit benthic data has proven useful in examining coral reefs and fish habitat utilization patterns (O'Conner 2010).

Researchers and scientists have historically used many different techniques to map nearshore benthic environments. When discussing benthic mapping techniques for analyzing vessel related coral reef injury specifically, it is important to differentiate between 1) purely bathymetric data 2) habitat specific data that define the substrate types (e.g. coral reef, sand, rubble), and 3) habitat condition. Substrate type has been described as the major factor that defines benthic habitats (Coyne et al. 2003). The sensors and platforms referenced in this section may acquire one of these three types of data, but cannot acquire all simultaneously.

Autonomous vehicles, boat-based sonar, remotely-sensed imagery, laser bathymetry and diver surveys are methods most commonly used for benthic mapping projects (Basu and Saxena 1999; Moore 2008; Jokiel 2008). The following is a discussion of these techniques and their limitations.

AUTONOMOUS VEHICLES

Autonomous vehicles are a recent advance in benthic mapping technique that are relatively safer, more stable, and less expensive than other methods of benthic data collection (Beck 2009), but still have their own limitations. For example, the Seaglider is a small autonomous underwater vehicle (AUV) used for shallow water mapping (Eriksen 2001). This device can be equipped with a multibeam sonar (discussed later) as well as a recreational-grade GPS, and is capable of collecting data with 0.5 meter vertical accuracy (Beck 2009) and three meter horizontal accuracy (Garmin 2003). The vehicle is operated by remote control and does not require a diver in the water. However, most autonomous vehicle applications require a support vessel which can significantly increase costs of data collection.

SONAR DATA COLLECTION

Sonar is a widely used shallow water mapping technique. This method involves collecting data using sound propagation from a surface platform such as a large ship, small boat, towed sled, or autonomous vehicle. There are four main categories of sonar systems used for shallow-water mapping: single-beam echo sounders, multibeam beam-forming sonars, multibeam interferometric sonars, and side-scan sonars (Basu 2013).

The least expensive and least complex form of sonar based bathymetric mapping is the single beam sonar. Single beam sonar data can be processed into either depth profile data (such as fish finder) or as a raster for use in a GIS. Resolution varies by the point cloud density and depth, but most systems today can achieve sub-meter vertical resolution (Riegl 2005). These systems can be used to both gather depth information and detect bottom types via backscatter (Freitas 2008). Backscatter data evaluate the strength of the return signal of the sonar beams which can be used to estimate hard versus soft substrates. With this functionality, it is possible to detect distinct coral communities (Freitas 2008), but not distinct corals. Researchers have also worked with traditional recreational grade fish finder/depth finder devices which employ single beam sonar technology (Turk 2013). More recently, small lightweight acoustic mapping systems have been developed that can map waters at 1-10 meters depth (Suka and McCoy 2016).

Multibeam sonar systems are more efficient in collecting bathymetry data as the swath width of the data gathered is wider than single beam systems (up to 7 times the depth of the water). These systems vary widely in cost and functionality, but are generally more expensive, yet more efficient, than single beam systems. A typical system is mounted on the bottom of a vessel and is able to collect both depth information and the return signal strength data (backscatter data), which allows for simultaneous data collection of both bottom topography and rugosity. The resolution of these data sets is typically in the 5 to 20 meter range and does not lend itself well to sub-meter analysis of individual coral reef colonies.

SIDE-SCAN SONAR

Side-scan sonar is a category of sonar system that is used to efficiently collect depth data of large areas of the sea floor. This type of hardware is typically boat mounted or towed behind a boat on a surface or sub-surface sled platform. It is most commonly used to conduct surveys of the differences in material and texture type of the seabed. It's suitable for discerning hard versus soft substrate types (Walker, 2008).

Coupling multi-beam sonar and side-scan sonar in a GIS can be an effective tool for mapping habitats including depths and bottom type (O'Conner, 2010). Combining both backscatter and bathymetric data provides more insightful visualization of benthic features (Kendall 2004). However, this technique has only been proven to be viable in deeper waters (100-400 meters depth), and not in nearshore environments due to the shallow water depth limitations of larger boats (O'Conner 2010).

Although these techniques have their own varying hardware and software costs, the common cost factor is the need for a vessel which can vary from a relatively inexpensive small boat to a large ocean-going research vessel (NOAA vessels cost ~$35K per day to operate).

AERIAL AND SATELLITE IMAGERY

Aerial imagery has been around nearly since black and white photography was invented, and has quickly advanced over the last hundred years. Advancements in cameras, sensors, and platforms have assisted the geographer in mapping anything visible on the surface of the earth from the first efforts of Gaspar Felix Tournachon using hot-air balloons in 1858 (Colwell 1997) to advancement in smaller cameras that later allowed for platforms such as kites or unmanned balloons (Aber 2004). Eventually planes and helicopters became the mainstream techniques for gathering imagery and now satellite imagery is a common application in GIS science.

Visual interpretation of remotely collected imagery is also used as a shallow water benthic habitat mapping technique (Jokiel 2008). The limitations of this technique vary widely by type of camera used, oceanographic conditions, and depth. Common problems with this technique include cloud cover, turbidity in the water column, and a lack of available imagery

(Jokiel 2008). Therefore, these techniques are generally reserved for shallow (10 to 20 meters depth), clear waters (Stumpf et al. 2003), with reported success as deep as 30 meters in some cases (Mumby 2004). There have also been limited uses of imagery for bathymetric data collection (i.e. pseudo bathymetry) with less vertical accuracy than sonar sensors. More often, visual interpretation of imagery is used to define habitat types and not depth (Jokiel 2008).

The scale and resolution of aerial and satellite imagery varies by sensor and platform utilized. The scale is defined by the size of a digital image, and when scaling a raster graphics image, a new image with a higher or lower number of pixels is created (Reddy 2013). Image resolution is defined by the number of pixels in an image and can be described by the size of a pixel in the real world (i.e. one meter pixel size).

The latest satellite imagery was evaluated as part of this literature review to assess the viability of using it to identify coral reef injury due to boating in Kāneʻohe Bay. World View 2 (WV2) imagery was obtained from a commercial vendor, Digital Globe, for the study site (described in detail later). The resolution of the available WV2 imagery for Kāneʻohe Bay obtained was 0.5 meters pixel size (Figure 5).

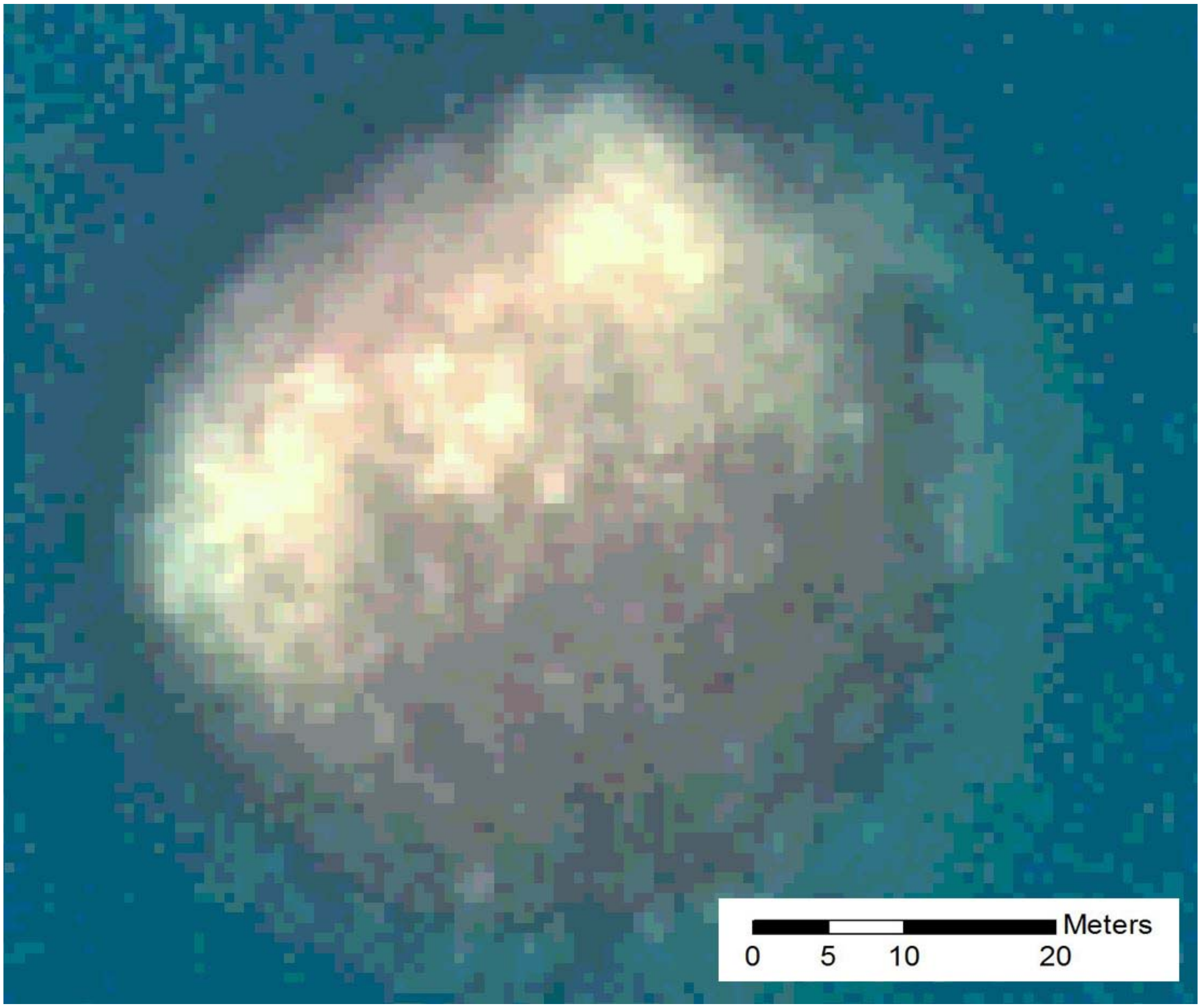


Figure 5: WV2 Imagery of patch reef #20 with 0.5 meter image pixel size

The highest resolution imagery available at the study site other than WV2 was provided by the United States Geological Survey (USGS) and was found to be 0.3 meters pixel size (Figure 6). Unfortunately, this was still not suitable for detecting scars on the coral reefs of the bay as the scars themselves are often under 0.3 meters in width. As previously mentioned, imagery needed to see vessel injury patterns must be much higher, and possibly one centimeter (or 0.01 meters) resolution range, based on the diameters of coral fragments.

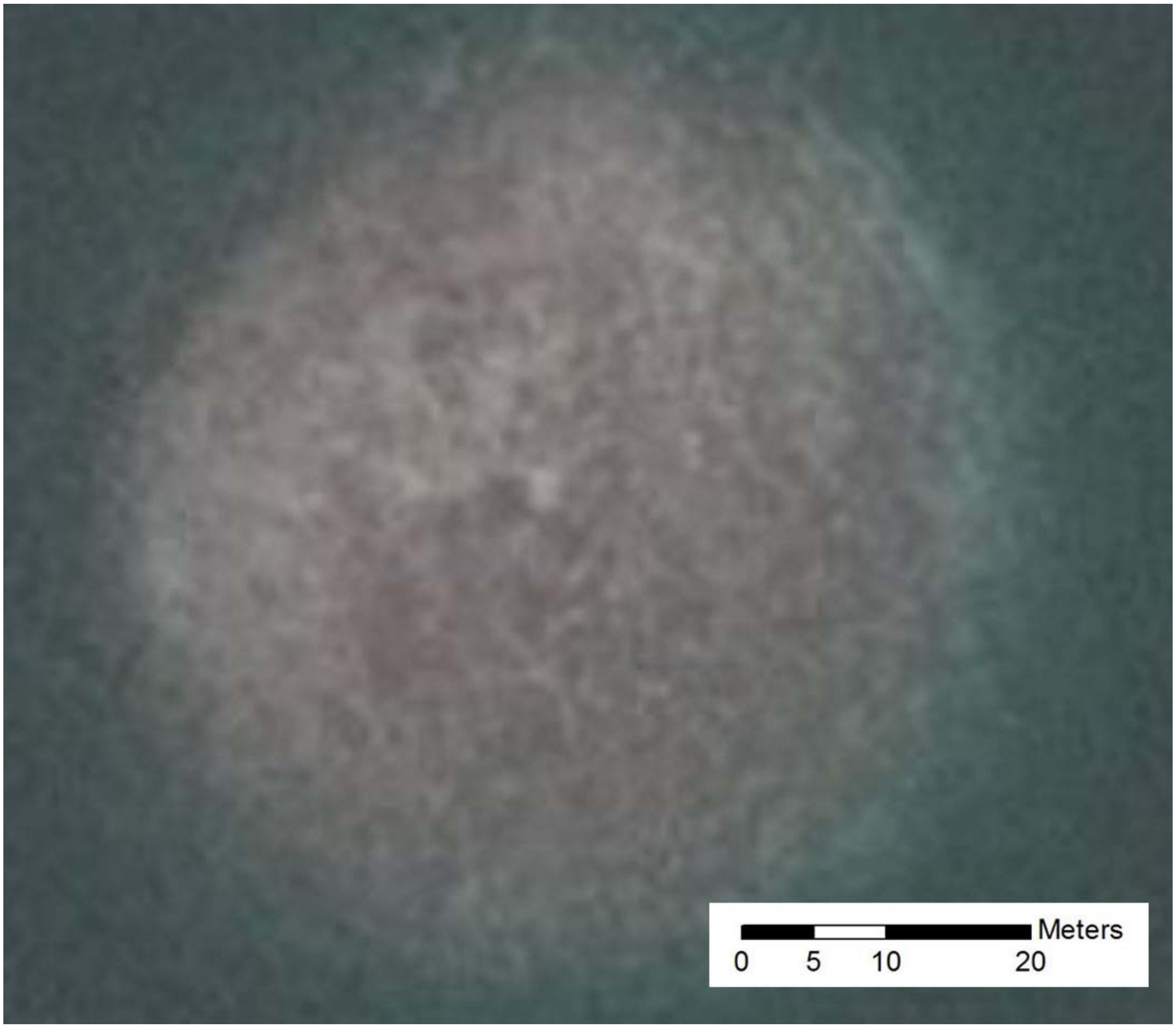


Figure 6: USGS Imagery of patch reef #20 with 0.3 meter image pixel size

Additional sources of imagery were researched from the University of Hawaiʻi (UH) School of Ocean and Earth Science and Technology and the UH Library's Maps, Aerial Photographs, and GIS Department, but both sources of imagery did not have coverage at the study sites (SOEST 2016 and MEGIS 2016).

It is important to note that even with the inability to identify coral reef injury in the aforementioned satellite and aerial imagery, that the collection of these remotely sensed images is inherently expensive, as satellites and manned aircraft are required to gather the imagery.

LASER BATHYMETRY

LIDAR (light imaging detection and range) is used to map the shallow water environment using laser beams. This sensor directs a laser pulse toward a target from an aerial platform and, by studying the returned light, may be used to retrieve information about the objects that come in contact with the laser (Houldcroft 2005). It is practical in waters with a depth of 35 meters or less, with varying rates of accuracy at approximately 1 meter or less depth (Walker 2008). The depth limitations can be increased with turbidity and surface waves. The return strength of the signal can further be used to detect bottom substrate type and theoretically discern coral reefs from sand habitats. Rugosity can be measured, but is done typically at larger grid sizes such as 4 meters (Wedding et al. 2008). Furthermore the resolution cited in the literature is typically resampled to approximately one meter and would be insufficient for detecting coral reef injury on individual coral colonies.

DIVER SURVEYS

Underwater photography and videography collected by divers or remotely deployed cameras are utilized for local-scale mapping of benthic habitats (Stevens 2005). Divers are able to tow a surface float with a mounted GPS and later link photos or video to the track log of the GPS on the surface. This technique typically involves photographing areas at randomly stratified points and not for creating orthomosaics.

NOAA employs the towed diver method (Figure 7) which is ideal for fish counts and habitat mapping at depth. This method is ideal for rapid ecological assessments for coarse scale habitat mapping (i.e. one acre), but offer little in the way of bathymetry data collection. Data collected by this method are not suitable for mosaicking, as divers are towed at up to two knots, and there is no overlap in the imagery collected. In addition, imagery is not always taken at nadir because the tow boards are constantly angled in order for the diver to steer underwater.

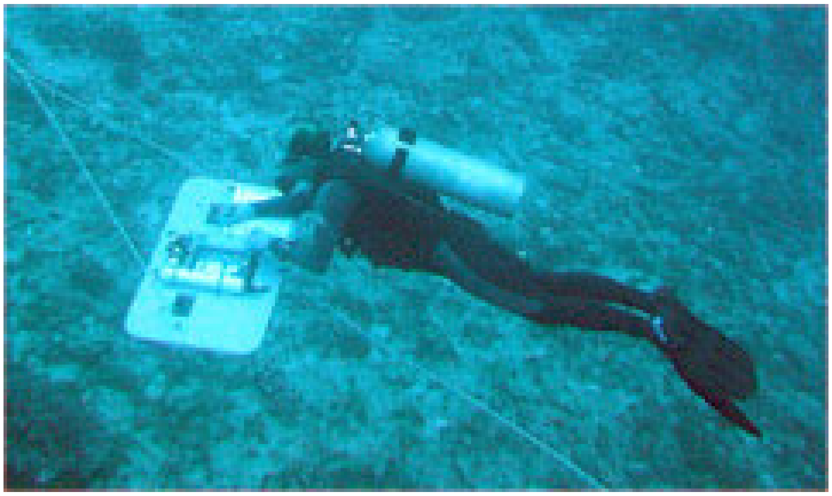


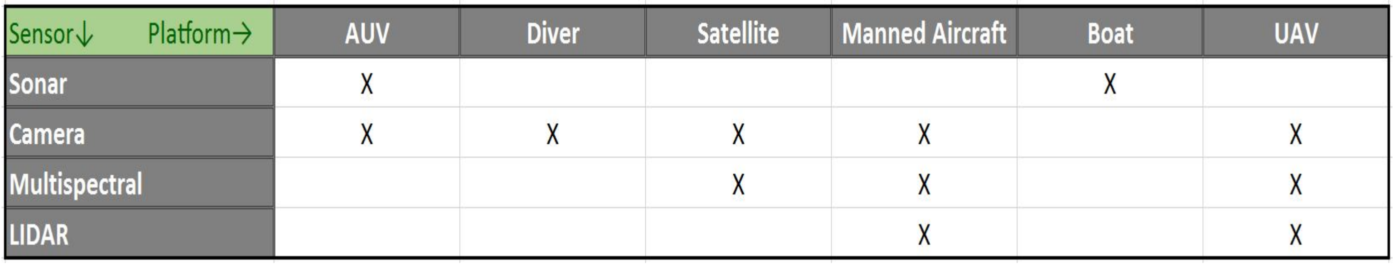
Figure 7: Towed diver survey. Photo by: NOAA Fisheries

Underwater photography has been employed in mapping coral reef injury, but is both labor and time intensive as divers must swim over the affected areas. These techniques can involve large vessels that require many personnel on board, are expensive to operate, and are limited by the draft (depth) of the vessel. Smaller vessels are easier to operate, less expensive, and can work closer to shore, but have less room for the needed equipment and are more vulnerable to oceanographic conditions such as waves, currents, and tides (Beck 2009).

Video-mosaic survey technology is a relatively new method for creating fine scale benthic habitat maps (Lirman 2007). This method requires divers to collect digital video of the benthos which are later stitched together into a static image mosaic. The added benefit of digital video is that divers are able to capture a large number of digital frames in a limited amount of time, thus decreasing the amount of time a diver spends in the water (Lirman 2007). The digital video data also allow for interpretation in the lab as opposed to *in situ* data documentation. The major downside of this technology is that it is not easily transferable to a GIS as there is no georeference capability. Towing a GPS on the surface would introduce large (~10 meter) positional variations when towing at depth, because of the length and angle of the tow line. Additionally, no GPS control points were mentioned in the studies found in the literature reviewed.

Altogether, the need for trained divers and a research platform compound the costs, risks, and complexity of diver surveys.

CORAL REEF INJURY MAPPING CONCLUSIONS



Sensor↓ Platform→	AUV	Diver	Satellite	Manned Aircraft	Boat	UAV
Sonar	X				X	
Camera	X	X	X	X		X
Multispectral			X	X		X
LIDAR				X		X

Table 1: Cross tabulation of platforms verses sensors

Coral reef injury is mapped with a combination of platforms and sensors (Table 1).

These surveys can employ sonar and/or laser data collection based methods with varying degrees of vertical depth accuracy. Both boat based and autonomous vehicles have been used to gather sonar based data, but generally these methods collect bathymetry data, and rarely habitat feature data which is necessary for coral reef injury identification. Additionally, these methods are not applicable in waters of less than 1 meter depth.

The resolutions of the data collected by other methods are insufficient for identifying discrete coral reef scars and identifying the species of corals impacted. Most cited applications of sonar result in data that is of 5 to 20 meters in image resolution or pixel size and too coarse for mapping an area 2,000 to 3,000 square meters (the average size of a patch reef in Kāneʻohe Bay). Remotely sensed imagery has resolution limitations and accuracy issues with the main source of error being based on weather and oceanographic conditions. Altogether shallow water benthic habitat data is limited to coarse resolutions and costs associated with data acquisition platforms (i.e. satellites, large research vessels, manned aircraft, etc.). In-water photography and videography is a viable solution to the fine-scale mapping problem, however, the literature reviewed lacks an avenue for GIS compatibility.

It is important to note that there is a lack of published literature on how any of these systems have been applied to mapping coral reef injury in Kāneʻohe Bay. The methods referenced that involve boats or divers would not work at the study sites as the reefs are less than one meter deep, and at the lowest of low tides these reefs are actually above the water surface.

PROBLEM STATEMENT

There is a gap in the literature related to how UAV surveys can be performed to obtain one centimeter image resolution imagery and GIS-compatible coral reef injury data. Can the use of a relatively inexpensive and easy to operate unmanned aerial vehicle (UAV) coupled with a high resolution camera be utilized to map coral reef injury due to vessel groundings? Is there a pattern to the vessel scars that can be predicted based on the geography of Kāneʻohe Bay?

PILOT STUDY

A pilot study was conducted to see whether the project was feasible considering budget restrictions, weather variables, and the need for multiple complex software programs. The pilot study had several major goals: 1) determine the appropriate UAV and become familiar with flying a UAV and using the appropriate camera settings 2) determine what weather variables were appropriate and inappropriate for flying UAVs and collecting imagery in a marine setting, and judge whether the imagery gathered by a UAV could be processed in available software 3) build and test an underwater camera array and assess if this is a more appropriate way of gathering high resolution imagery of injured coral reefs 4) determine if vessel grounding scars could be visible in the imagery acquired from a UAV and what the resolution requirements would be for mapping such targets 5) compare data acquisition and processing times to ensure that this is the quickest yet most efficient way to map boat grounding events after they happen, compared to other techniques.

Originally there was suspicion that the scars may be invisible because of quick algae growth and/or because perhaps they were too small to identify unless one were physically in the water snorkeling on top of them. I suspected that the weather/wind conditions of the windward side would make it difficult to acquire adequate imagery. There was also a possibility that a relatively inexpensive ($479) UAV would not be sufficient for this type of data collection (NOAA uses a $25K UAV that obtains slightly higher resolution imagery with more endurance and reliability). Finally, the image resolution needs were still completely unknown prior to the study.

DETERMINATION OF THE APPROPRIATE UAV, BECOMING FAMILIAR WITH FLYING A UAV, AND USING AN APPROPRIATE CAMERA/CAMERA SETTINGS

Several UAV platforms were researched in a previous thesis done by Charles Devaney of the UH Geography Department. His literature review compared multiple UAVs and concluded with a determination that a custom fixed wing was suitable for his study (Devaney 2015). In general, fixed wings are used for high endurance flights at relatively higher altitudes. This is because UAV battery power is preserved when a UAV has the ability to glide on wings as opposed to a rotary type copter that needs constant upward thrust to keep it at altitude. Fixed wing systems can also use the wind for additional lift while rotary copters must fight the wind and consume more battery power in the process. However, for the purpose of my study, there was no requirement for long endurance flights as my study sites are relatively small (~2,200 square meters), and could be effectively mapped within one battery or 15 minutes of flight time. The relatively small study site and needed resolutions dictated that the UAV for mapping coral reefs should have the maneuverability of a rotor craft. In addition, a long range aircraft was not needed as the study site is easily accessible by small boat.

In any pilot study cost is a major consideration, as UAVs with photographing capabilities can range in price from just under $80 to $30 million dollars (as is the case with a Predator B drone). Coral reef mapping applications by graduate students specifically need to be relatively inexpensive, and even somewhat expendable, because of the inherent danger of flying over water by an inexperienced pilot. I found that employing a DJI Phantom was the best option based on ease of use, reliability, price ($479.00), and the ability to mount a GoPro Hero 3 camera. Larger and more expensive UAVs have their own useful characteristics such as longer flight times, ability to carry larger payloads, and thus other sensors or higher resolution cameras.

The GoPro Hero 3 camera was found to be useful in the initial flights as it was adequate for obtaining the 1 centimeter resolution imagery of the coral reefs at the proposed study sites. It is ideal for UAV work because of its small size and light weight at 135 grams. This is important because lighter payloads equate to longer flying times with any UAV. The horizontal field of view (FOV) of the camera can be adjusted and the options vary from 64.4 to 125.3 degrees. A medium FOV was chosen for this study as it was a compromise between the image distortions found in the wide FOV settings verses the small footprint of imagery acquired with the narrow FOV settings. The camera has an automatic shutter mode that can be set so that the camera takes an image at regular intervals chosen by the photographer (i.e. 0.5 seconds, 1 second, 2 seconds, 5 seconds, etc.). A 32 gigabyte memory card is used which is capable of housing over 1,000 12 megapixel images. Images collected were found to be high in resolution at one centimeter pixel size when flown at 20 to 30 meters. The individual images themselves measured 4,000 by 3,000 pixels. Flying at lower altitudes offered higher resolution imagery (i.e. 0.5 centimeter pixel size), but increased the need for longer flight times to acquire imagery over the same amount of area.

Three test flights were flown over land to assess ability to manually fly the UAV with no formal pilot training. The flight times were recorded in order to know how long I could safely fly a UAV over water before needing to bring the UAV back to the boat. The UAV proved to be relatively easy to fly and was able to be maneuvered in the needed pattern for adequate imagery overlap and sidelap.

Flight times ranged with different batteries because of battery type (some were aftermarket brands), and battery maintenance. The lithium ion batteries that power this and other UAVs need to be cared for in a specific manner in order to maintain optimum performance. The main variable in battery maintenance of utmost importance is storing the battery at approximately 20% battery charge. Storing at any other level will decrease the life of the battery and flight times. The need for precise battery maintenance was exemplified during the next phase of testing: flights over the ocean in Kāneʻohe Bay.

Phase two of test flights was performed in conjunction with research off of a small boat (17 foot Boston Whaler) in Kāneʻohe Bay by the State of Hawaiʻi's Division of Aquatic Resources (DAR). The location of the study was reef #20 (Figure 1). Although weather conditions were not perfect (there were light trade winds and passing cloud cover) it was important to obtain practice in piloting the UAV in conjunction with working with the DAR staff. The initial test flight proved successful as the team was able to successfully hand launch and recover the UAV from the small boat. Unfortunately, during the second flight of this field day the UAV malfunctioned and seemed to appear to try to return to the boat. The DJI Phantom has a return to home feature, should battery power be too low to sustain any additional flight time. However, the boat was anchored with one anchor which allowed the boat to move slightly and did not provide the same landing location as the original take off location. Therefore, the UAV landed on the water adjacent to the boat and descended to the bottom in approximately 5 meters depth. Upon recovery of the UAV, attempts were made to rinse the UAV with fresh water and dry it out. These attempts proved unsuccessful and the UAV was returned to the manufacturer for repair where it was later determined that it needed to be completely replaced. Fortunately, the GoPro Hero 3 camera was housed in the original waterproof housing and did not sustain any damage, and the photos taken during the field day were recoverable.

WEATHER VARIABLES

Kāne‘ohe Bay’s weather is characterized by consistent trade winds blowing predominantly from the northeast (Leopold 1949). Wind conditions were checked the night before UAV operations to ensure that the atmosphere would be relatively stable the next day. It was assumed that light wind conditions would be ideal for high resolution mosaic producing imagery (discussed later). Typical optimal weather conditions were found in early to mid-morning before winds increased in velocity due to the heating of the surface of Oahu Island and the associated convection.

DATA PROCESSING

A number of conclusions could be drawn after looking at thousands of sample photos from both the flights done over a terrestrial setting and flights done over the waters of Kāne‘ohe Bay. The most important conclusion drawn was that it was important to have at least 60% overlap and sidelap in the imagery. This value is also cited in recent UAV imagery acquisition publications (Rango 2009 and Gonçalves 2015). However, it was found that upwards of 90% overlap and sidelap is needed in more homogenous habitat areas such as sand or coral rubble zones.

Initial imagery was processed using a free version of image mosaicking software, Microsoft’s Image Composite Editor. The terrestrial images were mosaicked successfully using this software with only minimal artifacts (Figure 8). However, the marine photos did not successfully mosaic in Image Composite Editor, and thus a more robust program for mosaicking software was researched. The most widely used software for creating orthomosaics from aerial imagery was determined to be Agisoft Photoscan (Green 2014). Other mosaicking software packages were in development at the time of the authoring of this manuscript, but had yet to be proven as viable alternatives in the available published literature.

Figure 8: Sample terrestrial image mosaic.

The numerous settings (i.e. resolution, mesh density, etc.) within the Agisoft PhotoScan software had to be tested before finding the optimum work flow for mosaicking sub-surface coral reefs. All published applications of Agisoft PhotoScan software had been applied in a terrestrial setting, so there was little previous knowledge to draw upon when setting up the work flow. The previous work by Devaney (2015) , while focused more on a terrestrial humanitarian search and rescue mission, did include artifacts over the water. His work suggests that the settings used by the terrestrial scientist using Agisoft PhotoScan are not applicable to the marine scientist working in the marine environment. Eventually, the optimum settings in the software where found in order to produce an orthomosaic (Figure 9).

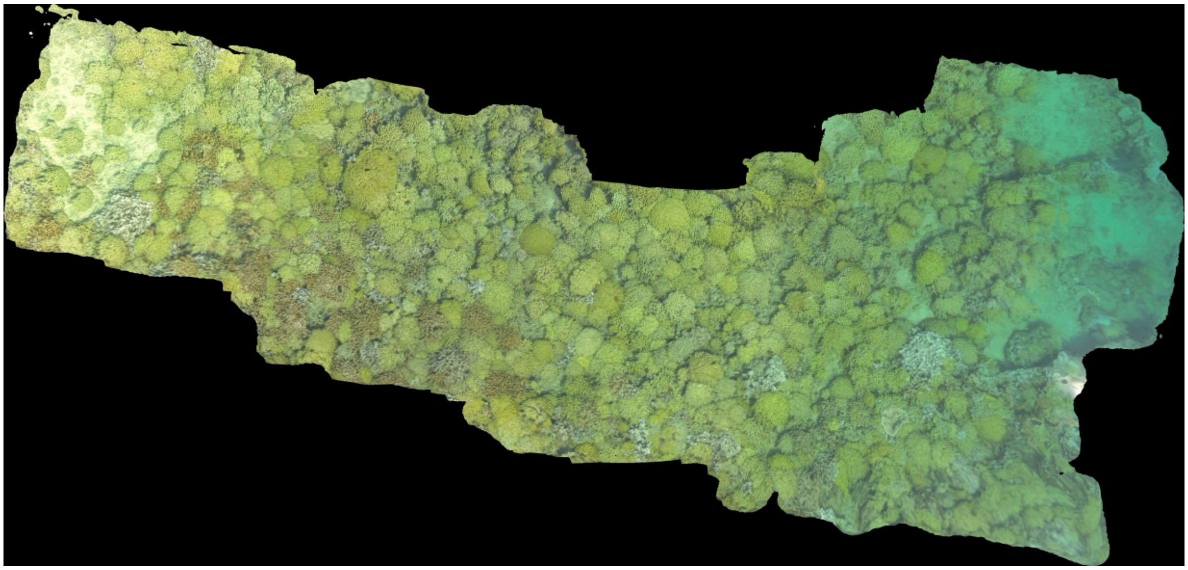


Figure 9: Sample image mosaic created with Agisoft PhotoScan

When flying over the waters of Kāneʻohe Bay, it was determined that sun glint (Figure 10) was too centered on the images if taken after approximately 10:00 or 11:00 am, depending on the time of year, as the sunrise varies in Hawaiʻi by about 1 hour and 21 minutes throughout the year (NOAA 2016). The use of a polarized filter made little difference with respect to sun glint. If glint were centered in the image, it was found that the mosaicking process would fail.

Figure 10: Image of a coral reef taken from UAV with sun glint evident in center of image

Wind was another major factor in the ability to acquire quality imagery of coral reefs for mosaicking. Imagery that had been collected when there were any noticeable wind waves on the surface (Figure 11) proved to be insufficient for mosaicking in either software package. The distortion in the photos made the pixel values inaccurate and thus impossible for the software to effectively mosaic any imagery with wind waves in them. Thus the aforementioned camera mounted kite method described in the literature would have proved ineffective.

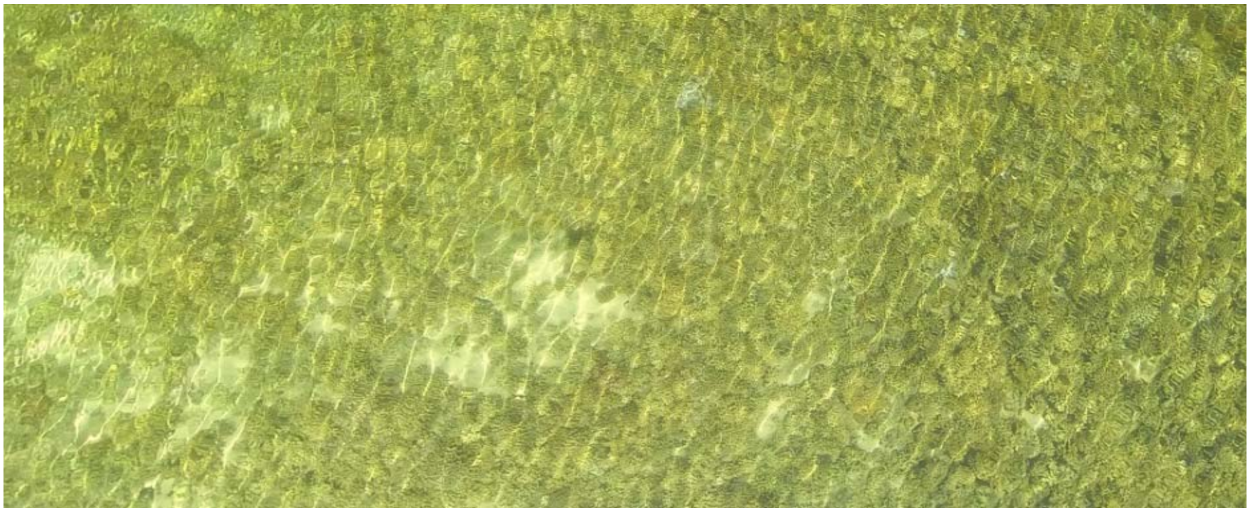


Figure 11: Sample image with visible small wind waves on the surface of water

EXPERIMENTAL UNDERWATER CAMERA ARRAY

As part of the study, an experimental underwater camera array was assembled and tested. Previous studies seen at the most recent International Coral Reef Symposium utilized custom built underwater camera arrays for benthic habitat mapping, and more recently for three dimensional modeling of coral reefs (Guo 2016).

The camera array built for this pilot study was built using the same design parameters which included the use of three meters of one inch diameter PVC piping and four PVC joints (Figure 12). Three GoPro Hero 3 cameras were placed one meter apart on the array in a configuration that pointed them straight down at roughly nadir, and allowed for 60% overlap in the photos from the three cameras when taking photos of the seafloor bottom from 1 meter above it. These parameters were chosen because the typical depth of the reef flats in Kāneʻohe Bay is approximately one meter (Hunter and Evans 1995). Experiments were conducted to assess necessary overlap in a lab before testing in the water. It was found that with complex underwater landscapes, that upwards of 90% overlap was needed in order to obtain a quality mosaic (i.e. no major artifacts). The overlap was especially important on the reef edge where the majority of artifacts were found.

Figure 12: Testing of the experimental camera array

Ultimately, the resolution of the camera array mosaics proved to be too fine (2 millimeters) for detection of reef scars. Broken fragments can be seen in the fine resolution imagery, but overall patterns of vessel are better seen at coarser scales such as 1:240. However, the individual photos did prove to be suitable for ground truthing injury, as coral reef fragments were visible and could be distinguished from small sand patches.

Acquisition of imagery from the camera array was time consuming as the diver must swim very slow (less than one meter per second) in order to get the needed 60-90% image overlap. Therefore mapping a reef the size of 2,200 square meters would take approximately 42 minutes and result in approximately 2,500 individual photos needing to be processed, which could take upwards of 10 hours.

This technique requires an average of 84% more of images to be collected (i.e. 2,500 compared to 400), and increases image processing times, compared to the number of images collected from a UAV over the same area.

APPROPRIATE RESOLUTION FOR IDENTIFYING CORAL REEF INJURY

One centimeter image resolution was determined to be appropriate for vessel related coral reef imagery. Aside from making it possible to see injury patterns, one centimeter image resolution imagery assists biologists to identify distinct coral reef species in addition to accurately mapping benthic habitat features such as sand patches and zones of coral rubble. Finer scale resolution imagery did not appear to aid in injury identification and only increased processing times and opportunities for the mosaicking process to be interrupted by a computer malfunction, power outage, etc.

PILOT STUDY CONCLUSIONS

There was no guarantee that the use of a small UAV would be suitable for mapping injured coral reefs, but this pilot study provided assurance that it could be done. Piloting a UAV while taking imagery requires practice. UAVs can be unpredictable to the novice, especially when experimenting with varying life expectancy of batteries, and thus flight times. Specific weather conditions are needed to obtain suitable imagery (winds must be extremely calm), or the mosaicking process fails. Ideal weather conditions exist approximately five weeks out of the year or ~10% of the time. Passing boats create short wind-wave distortion in the imagery and adequate imagery could only be obtained in the morning hours prior to the sun introducing glint into the imagery. Budgetary concerns needed to be considered when flying UAVs over the water as there is a real possibility of the UAV coming in contact with the ocean which will make the UAV inoperable. For this reason, it is also useful to utilize a lightweight waterproof camera when flying UAVs over the water. The experimental camera array took longer to acquire imagery and produced imagery resolution that was too fine for identifying vessel scarring patterns.

The final conclusion of both the literature review and the pilot study is that one centimeter resolution aerial imagery has only recently been possible to collect at a relatively inexpensive price, frequency, and speed.

STUDY SITE

Kāne‘ohe Bay is located on the east side of the Island of Oahu and is the largest embayment of the Hawaiian Archipelago encompassing approximately 39 square kilometers (Holthus 1986). This bay is unique in that it contains 60 independent patch reefs that have been studied intensively with over 1,000 scientific journal articles citing the bay in various topics of research (Hunter and Evans 1995). The various patch reefs and fringing reefs in the bay vary in size and structure (Roy 1970). However, most of these patch reefs are circular in shape and less than 1 meter in depth at their shallowest locations at mean low tide. The predominant species of coral in the bay is *Porites compressa* (Figure 13) followed by *Montipora verrucosa* (Hunter and Evans 1995).

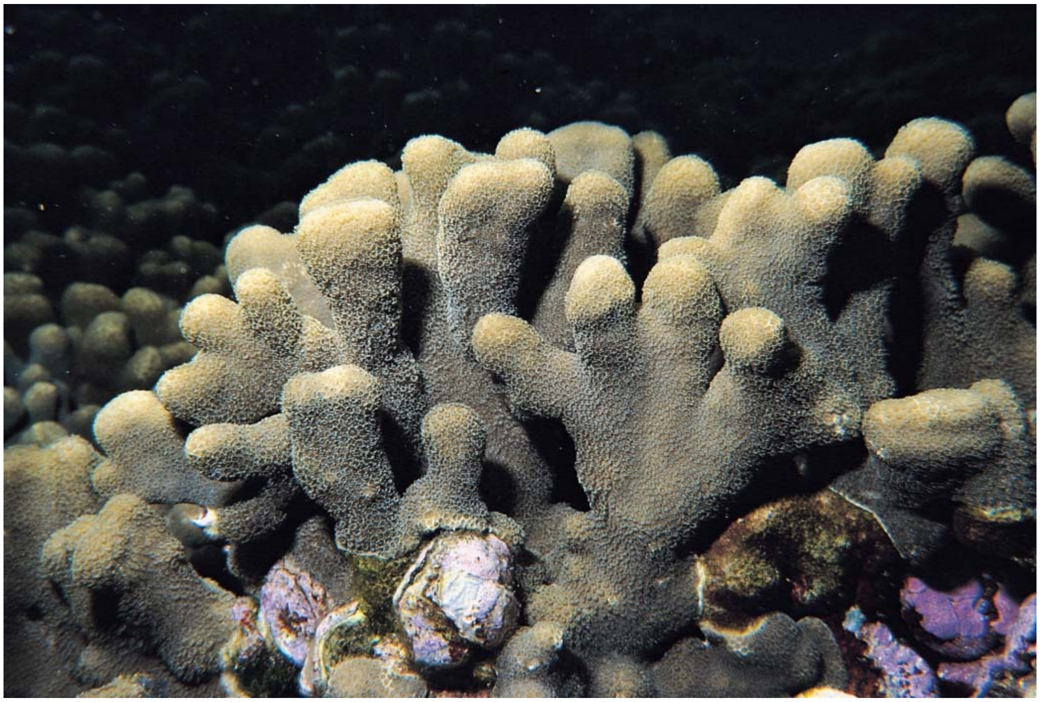


Figure 13: *Porites compressa coral colony. Photo by C. Hunter*

There are numerous marine conservation efforts already taking place in Kāne‘ohe Bay. The He‘eia Kea fish pond is being restored by a nonprofit group, Paepae o He‘eia, and in turn is raising awareness about the importance of coral reef resources. The DLNR Division of Aquatic Resources (DAR) has recently developed a sea urchin hatchery in an effort to out-plant the young urchins on the patch reefs of Kāne‘ohe Bay, to eat the invasive algae that has plagued the area for decades. DAR has also been conducting the so-called super sucker project, which involves a custom developed vacuum for physically removing the invasive algae. Additional coral reef research is ongoing to protect these reefs, but there is little being done to prevent boats from running aground, destroying live reef colonies, and counteracting the conservation efforts taking place. The agency responsible for the natural resources, DLNR, should be informed of the fact that efforts to protect and study these coral reefs are being reversed by unreported vessel groundings in Kāne‘ohe Bay.

The primary study site chosen by the author was reef #20 (Figure 14). This reef was selected because it is the site of the aforementioned coral reef conservation measures and because of its geographic location in the Kāne‘ohe Bay. This reef in particular lies in between the popular boating destination, Ahu O Laka (Kāne‘ohe Bay Sandbar), and the numerous boating marinas in Kāne‘ohe Bay: He‘eia Kea Small Boat Harbor, Marine Corps Base Hawai‘i, Hawai‘i Institute of Marine Biology, Makani Kai Marina, and Kāne‘ohe Yacht Club. These marinas are the source of the majority of vessel traffic in the bay which may ultimately injure reef #20. The area of the reef is approximately 2,200 square meters, with a paremeter of 170 meters, and an average diameter of 54 meters. The average depth is approximately one meter at mean high tide.

The secondary study site chosen for the study was reef #22. It was important to choose two reefs in different proximity to the Ahu O Laka, as the initial prediction was that there is an inverse correlation between the distance to the sandbar and the number of vessel scars identified (i.e. more scars should be found on the coral reef closest to the Ahu O Laka).

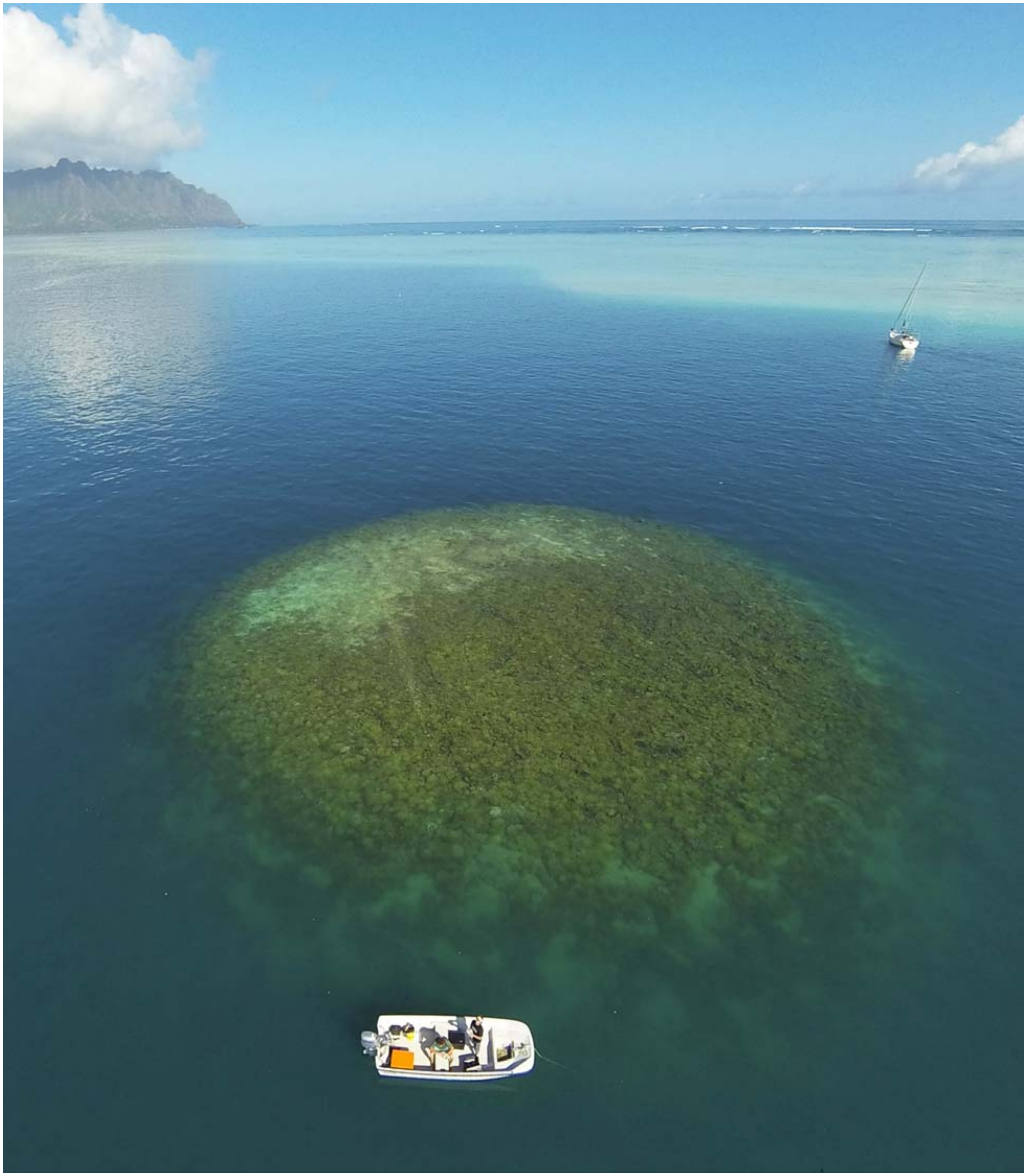


Figure 14: Reef #20 in Kāne‘ohe Bay with visible injury and Ahu O Laka in the background

The geographic location of this reef situates it between the various marinas in the bay and the Ahu O Laka. The predicted orientation of the scars is thought to be in a relatively north to south orientation (Figure 15).

The size of the patch reefs are of appropriate size to be mapped with a UAV in less than 15 minutes, which is often necessary because of flight time restrictions and changes in conditions. Weather in Kāneʻohe Bay can change quickly, and any changes in surface waves or cloud cover during data collection of one individual reef will decrease image quality.

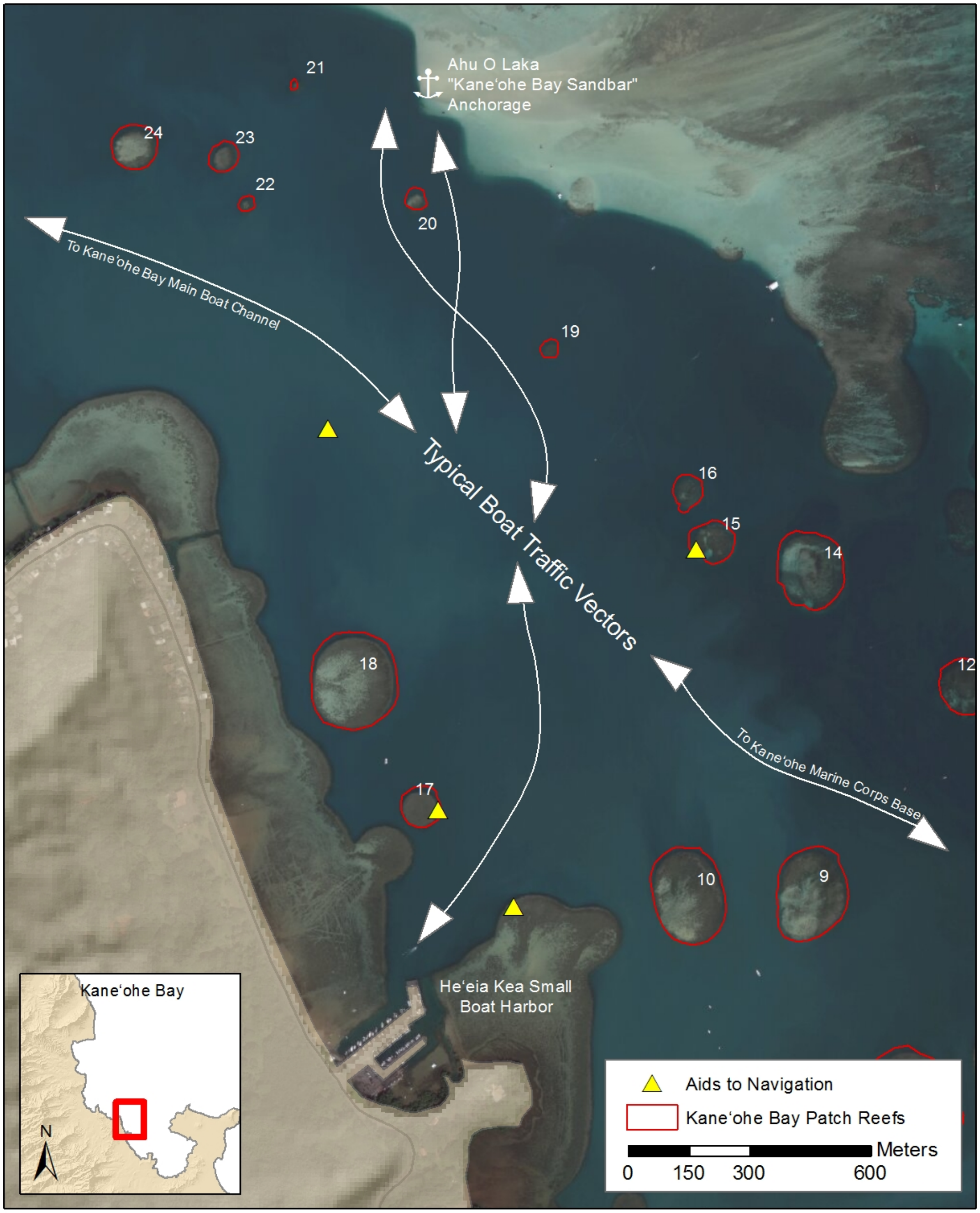


Figure 15: Typical boat traffic vectors based on geography of bay and ATONs

Previous studies on these reefs have been done by NOAA and the State of Hawai‘i. NOAA’s biogeography program created shallow water benthic habitat maps based on satellite imagery, but with a minimum mapping unit of one acre. The reefs of the bay were also the site of a sea urchin outplanting project to combat invasive algae. The super sucker program has used a large vacum to remove the algae off of the coral reefs at these sites. The State of Hawai‘i’s algae nursery program, which operates out of Sand Island in Honolulu, provides native juvenile urchins to be outplanted on these reefs in an effort to have them feed on the invasive algae and further reduce possible impacts to coral such as smothering. Numerous fish surveys have been done at these two reefs, and studies have been undertaken to examine correlations between fish biomass and coral reef health. Therefore, baseline data exist, and these coral reefs are of importance to natural resource agencies.

MATERIALS AND METHODS

HARDWARE

The industry of small unmanned aerial systems (UAS) has exploded with affordable options for sensor carrying platforms (Devaney 2015). The DJI Phantom UAV (Figure 16) was used in this case study because of its relatively low cost (less than $1K), and its sufficient functionality to fly both autonomously (with a ground control station) and manually if needed. The flight times were consistent with the project area size, necessary flight altitudes, and proximity to anchoring locations near the study site. This UAV is also well suited for carrying small portable waterproof cameras such as the GoPro brand of digital cameras (discussed below).

The GoPro Hero 3 Camera was chosen for this case study because it is relatively inexpensive at $300. These cameras come equipped with a waterproof housing which is preferred when flying over the ocean, or in trade wind weather when unexpected rain episodes can arise with short notice. The camera takes 12 megapixel imagery, and can be set to automatically take photos at regular intervals such as every 0.5 seconds. Additionally, it has the ability to take high resolution video (4K), which could be used for additional photo analysis.

The camera was positioned to point vertically straight down in order to reduce distortion in imagery, and thus improve the mosaicking process. The camera lens introduces distortion proportionally as you move from the center of an individual image, but the mosaicking process takes the center portion of the photo, and thus the amount of distortion is negligible for the purposes of this study (discussed later). Distortion was partially removed by post-processing in Photoshop CC which has a GoPro lens correcting function built in. Additionally, the keypoint matching algorithm in Agisoft PhotoScan reduces distortion from photos taken at slightly different altitudes (i.e. 14 meters verses 16 meters), and photos taken near, but not at, nadir

(Devaney 2015). Any remaining distortion was assessed by comparing known features in the water (i.e. existing cinder blocks on the reef at the study cite) with the processed image mosaic. These comparisons proved that image distortion was less than 1% of actual targets.

A 10 megapixel Canon Powershot SD 1200 IS digital camera combined with a water proof housing was used for taking *in situ* photos of injured sites in order to ground truth data taken from UAV (discussed later).

Figure 16: DJI Phantom UAV with GoPro Hero 3 Camera at Ahu O Laka

A recreational grade GPS (Garmin 76cx) was used to collect latitude and longitude coordinates during the data gathering phase of the project. The unit was chosen as it is relatively inexpensive at $300, water resistant, and buoyant. The accuracy of the GPS varies based on conditions such as the satellite constellation at the time of data acquisition, and the amount of cloud cover. Typical positional accuracy estimates for this unit range from three to five meters, which was adequate for positioning the final orthomosaic in a GIS. Actual positional accuracy estimates where closer to three meters, when comparing GPS data collected the same day at a known geodetic marker.

SOFTWARE

Comparisons were made between a freeware version of photo mosaicking software (Microsoft ICE) as well as a commercially sold software program (Agisoft PhotoScan version 1.2.6). Initial tests of mosaicking aerial imagery demonstrated that while the free software was capable of producing mosaics of terrestrial imagery (i.e. a tropical jungle) it did not perform well in the marine environment (i.e. over a submerged coral reef). A third software, Pix4D, was also well cited in the literature, but Agisoft PhotoScan had the best performance as it was the fastest, the easiest to use, and had the best spatial accuracy (Turner 2014). Therefore, this study abandoned use of the freeware and utilized the commercially sold software. Other software packages (i.e. ESRI's Drone2Map) were being released during the data processing phase of this project, and may prove to be more effective at creating mosaics from aerial images of submerged reefs, such as those at the study site.

Image editing, georeferencing, digitizing of injury into shapefiles, and additional GIS analysis was done using ESRI's ArcGIS 10.3. Additional batch image processing was accomplished in Adobe Photoshop CC.

GROUND CONTROL POINTS (GCPs)

Before the data collection process was conducted, it was necessary to place ground control markers (colored buoys) across the study area. These markers were used to assist the mosaicking software to identify image overlap, and to georeference the mosaic in a GIS. A minimum number of two and a maximum of three floats were used so that the orientation of the final mosaic could be spatially aligned accurately in the GIS. Specifically, one float was used to position the image in a GIS, while a second float was used to adjust the orientation of the orthophoto. Since the study area is over water it was better to use small floats on the surface that were anchored by small two ounce fishing weights. Smaller floats (10 centimeters or less in diameter) allowed for more precise GPS data collection, as the location of the floats is more precise than using a typical small boat mooring buoy that can be 0.5 meters in diameter in most cases. The length of the anchor line was within 0.1 meters of the depth of the water to ensure that there was not too much scope on the anchor line which would have allowed the location of the float to change with any winds or currents on the surface of the ocean. The length of the anchor line also had to be long enough to account for any minor tide increase which would have served to sink the float below the surface or cause the float to float away. Ultimately, this led to a variation in the float position of approximately 0.2 meters (Figure 17).

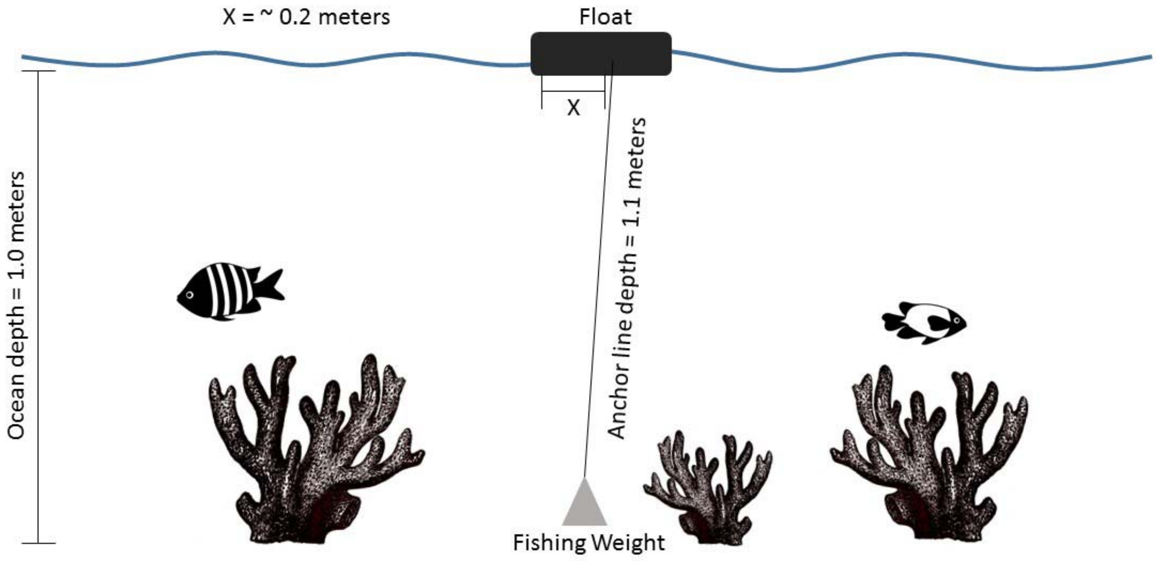


Figure 17: Diagram of float, anchor, and anchor line.

The floats were spread apart more than the assumed positional accuracy of the GPS (three to five meters). Otherwise, there may have been overlapping locations of the floats once brought into the GIS. It is also useful to use different colored floats so that they can be named within the GPS unit to avoid confusion later in the GIS. Once in place a GPS point was taken directly over the float. Increased horizontal accuracy of the GPS location was achieved by using the average points feature on the GPS and/or by taking three or more GPS points at each float, and later manually averaging those latitudes and longitudes in a spreadsheet program such as Excel.

The floats also served the purpose of allowing precise measurement of image resolution, as they were of a known length and width.

IMAGE DATA COLLECTION

Specific regulations were in place at the time of image data collection including the requirement to fly within line of sight of the UAV, maintaining an altitude of 400 feet or less, and maintaining a 5 nautical mile buffer from any airport unless with prior approval. Approval was received from the nearby Kāneʻohe Marine Corps Base to fly on Sundays when the base does not perform aircraft operations.

The image data collection process included locating the study site, placing the GCPs, and collecting imagery with UAV and camera. A small boat was employed to get near the reef being studied. All flights were done within line of sight and at approximately 15 meters of elevation. Flights were flown both manually and autonomously with a ground control station and pre-programmed waypoints. Images were collected at one second intervals (which is a standard setting on the camera) while flying for approximately 15 minutes. Altitude and flight time were chosen based on needed resolution of imagery (in this case approximately one centimeter), and were also dependent on weather conditions (i.e. windy conditions decrease flight time).

Once the GCPs were in place it was time to fly the UAV over the study area. Weather conditions should be assessed at this point to attempt to predict consistent weather conditions during the scheduled flight. Special care should be taken not to fly when rain squalls or low clouds are approaching the study site. Inconsistent cloud cover or wind velocity can hamper the consistency of the imagery (i.e. low light and high light), and thus the ability of the mosaicking software to accurately match overlapping photos. It is imperative to fly in early morning hours (i.e. 7:00 a.m. to 9:00 a.m.) because of the typically light winds during this time in Kāneʻohe, as well as to avoid sunlight glint. During mid-day hours the sun will create a reflection that makes it difficult to see the coral reef being mapped in the imagery, as well as confusing the photo processing software program during the stitching process. Afternoons are characterized by low level clouds that build up on the adjacent Ko‘olau Mountain Range due to orographic lifting, and thus imagery is typically hampered by low light conditions.

The UAV can be flown manually or autonomously depending on the type of UAV and presence or absence of a ground control station for flight programming. Careful attention must be paid in making sure that there is adequate overlap (60-90%) of the photos being taken, and ground control software is effective in assuring appropriate image overlap. To ensure proper overlap, during individual flight lines, the camera is set to take a photo every 0.5 seconds. It was determined that a relatively slow horizontal speed is necessary to ensure adequate overlap. For the purpose of this study the UAV was flown at approximately one to two feet per second. The flight pattern is important as well, and the pilot must fly in parallel flight path lines or in a “mow the lawn” pattern to ensure the entire reef is photographed. This pattern is flown across the reef in one orientation (i.e. north/south) and then again perpendicular (i.e. east/west). The frequency of photos taken, the horizontal speed of the UAV, and the pattern of flight must all be taken into account for a complete mosaic of the study area to be produced by the photo-stitching software. Ultimately, the photo-stitching software was not hampered by flight path orientation as long as adequate coverage was accomplished. Several oblique photos were taken after a successful mapping mission for reference in the injury identification process.

IMAGE PROCESSING

The photo processing begins by uploading photos from the camera and importing them into files to be organized by individual flights. The imagery is processed in order to prepare them for the image mosaic software (discussed in the next step). If needed, the imagery is first processed in Adobe Photoshop CC in order to brighten photos if taken during periods of cloud cover or inconsistent lighting, remove glint or glare from the sun, and/or crop out edges of photos where distortion from lens may be apparent. Batch processing is set up in Photoshop in order to automate the process and to ensure consistency across photos from each individual flight. It is necessary to set up individual parameters in Photoshop for each individual flight, because cloud cover, sun angle, and oceanographic conditions such as wind waves can vary across individual flights. Furthermore, certain flights require additional processing in Photoshop to correct for color and contrast variations based on the type of habitat being mapped (i.e. coral versus sand).

The mosaicking process begins by importing the photos into Agisoft PhotoScan, and allowing the program to align the photos. This is the stage in which the photos are aligned with one another based on similar cues in the photos. For example, similar patches of pixels in an area of sand are automatically recognized and overlaid with each other. Alternatively, similar patches of pixels of specific species of coral colonies are matched based on patches of similar pixel values in the corresponding images. Multiple publications that explain how this process matches the geometry of pixels, and it is shown that using the color histograms of individual object representations can assist in differentiating among a large number of objects (Swain 1991). When using GoPro imagery, segments of imagery with a minimum of 500 pixels (or an area of 22 by 22 pixels) were needed in order to match the same feature in different images (Schmidt 2012).

During the alignment process PhotoScan also found the camera position and orientation for each photo and built a sparse point cloud model. Settings for this step included choosing a level “medium” accuracy for best performance and processing time. The “generic” option was enabled when mosaicking a few photos (i.e. 20 or less) or a small area of reef. It was best to disable this option when processing hundreds or thousands of photos.

The next step in the process was building the dense cloud. Based on the estimated camera positions, the program calculated depth information for each camera to be combined into a point cloud. The point cloud represents the estimated three dimensional surface of the seafloor. Due to factors such as poor texture of some elements of the scene, or noisy or badly focused images, there can be some outliers among the points. To sort out the outliers Agisoft PhotoScan has several built-in filtering algorithms that improve the elevation information (Agisoft 2013).

Once the cloud was built, the “build mesh” function was employed, which involved aligning the photos along the three dimensional surface created in the previous step. It was important to use the “height field” function as opposed to the “arbitrary” setting, because this surface type is optimized for modeling of planar surfaces, such as terrains or sea floor surfaces. “Height field” should be selected for aerial photography processing as it requires a lower amount of computer memory and allows for larger data set processing (Agisoft 2013). Thus, since a three dimensional surface was of less importance than the two dimensional mosaic, this setting allowed for expedited processing times.

The next step was to build the texture with the “build texture” function, and create the orthophoto output, by using the mapping mode of “orthophoto”. Orthorectifying the image preserves the scale of the photo mosaic across the entire area photographed. The texture mapping mode determines how the object texture will be packed in the texture atlas. Proper texture mapping mode selection helps create a more accurate image of the sea floor. In the orthophoto mapping mode the whole surface is textured in the orthographic projection. The orthophoto mapping mode produces even more compact texture representation than the Adaptive orthophoto mode, at the expense of texture quality in vertical regions (Agisoft 2013).

The final step was to export the orthophoto by using the File command then “export orthophoto”. The projection settings are ignored in this step, because the spatial reference will be added in the next step, when the mosaic is georeferenced within a GIS. Alternatively, the photo can be exported as a three dimensional Adobe PDF if it is not needed in a GIS and just to be used for visualization purposes.

A note on processing times: when processing less than a dozen photos the average time it takes to process the photos is approximately an hour, but when processing hundreds of photos (most likely the case) then the entire mosaicking process can take several hours or need to run overnight. For example, 400 photos took 2.5 hours to process. Computer crashes, power outages, and network errors were all responsible for the process needing to be repeated at least one time during this research. Therefore, it was imperative to ensure that more imagery was not collected than needed.

GEOREFERENCING MOSAIC

Once a complete one centimeter image resolution orthophoto is produced of the study site, the process of georeferencing can begin. The georeferencing toolbar within ArcGIS was utilized to accomplish this task. The mosaic is first added to an ArcMap project using the add data tool. The photo is then roughly aligned with the actual spatial location of the study site by comparing the image to background imagery that is included with the software package. The average GPS points of two GCPs are also brought into the GIS as a point layer. This point data is used to further tie the image mosaic to the actual geographic location using the Georeferencing Toolbar within ArcGIS. Additional GCPs are not used to avoid any rubber sheeting of the original orthophoto.

DIGITIZING SCARS

The orthophoto was visually examined in a GIS to identify possible injury targets such as individual damaged coral colonies, scarring from boats, and other anomalies that were assumed to be related to boat grounding (Figure 18).

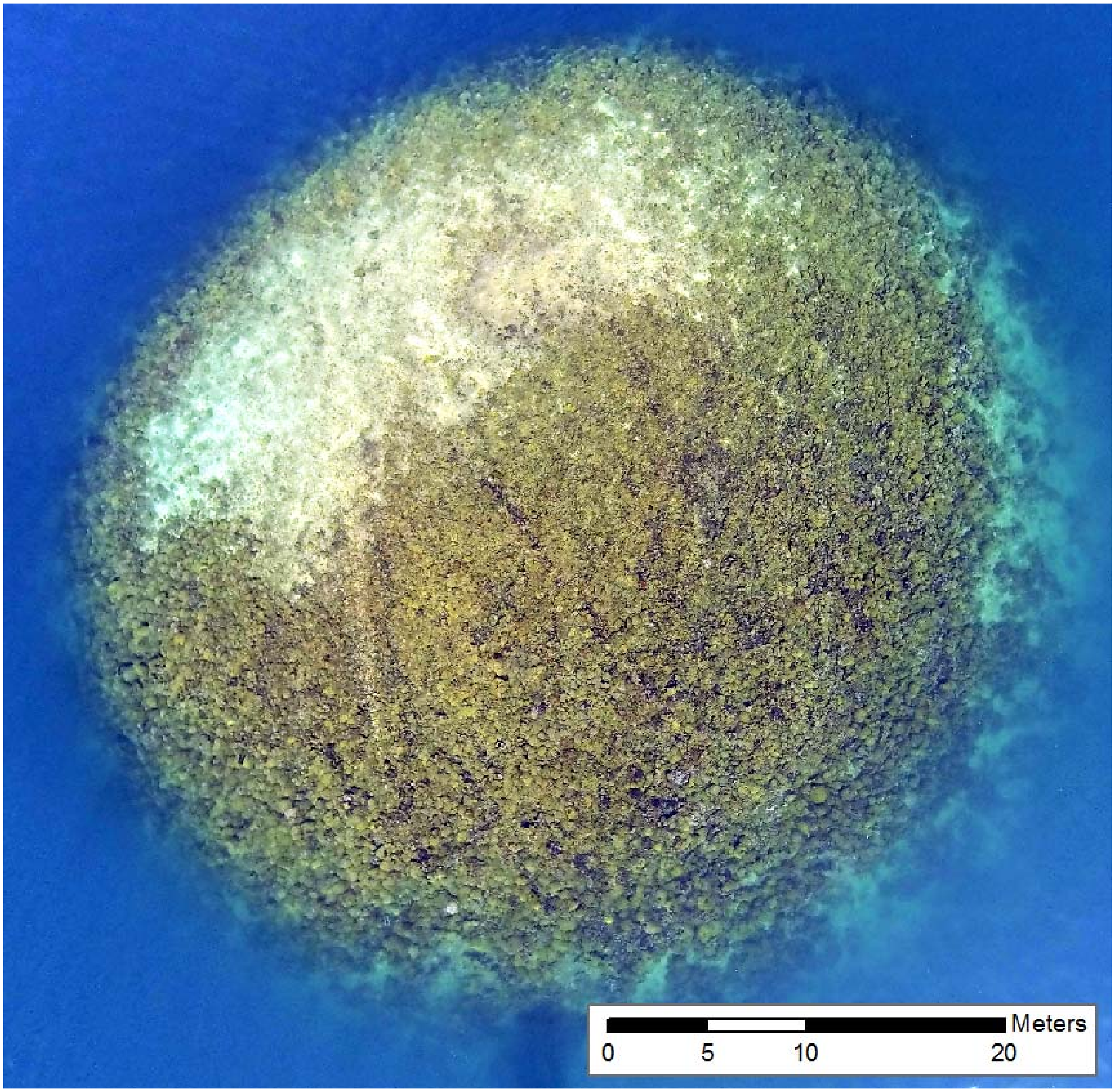


Figure 18: Orthomosaic used for digitizing coral reef injury with visible injury

Initially, efforts were made to automate the injury detection in the orthophoto by using image classification software and attempting to use injury as a class. Image classification using eCognition software is well-cited in published literature, but used in a terrestrial setting where obvious classes can be successfully created, such as distinguishing between water, forest, and urban landscapes (Flanders 2003). The image classification toolbar within the ArcGIS software package was used in an attempt to automate the process of scar identification and digitization. Attempts to train the software to identify scars by assigning a training set of scar data resulted in inaccurate results based on field validation data. A related study was done at the time of authoring this paper by University of Hawaiʻi researcher, Josh Levy, who attempted a similar image classification exercise of the same study site using the a well cited image classification software, ENVI. He found that the variability in the imagery and similar spectral signatures of features on these patch reefs made it difficult to differentiate between similar looking features such as a fresh scar and a small patch of sand. This is due to the fact that sand by definition is a fragment of a coral reef, and when a vessel comes in contact with a coral reef and injures it the result is coral fragmentation. These fragments are identical in color and spectral signature as a patch of granular sand. In other words, the similar visual characteristics of bleached coral, sand, and injured corals make it difficult for image classification software to discern the difference between these three common elements of a coral reef in Kāneʻohe Bay. Additional work has been done in specifically trying to classify benthic features from in-water imagery, but has had limited success when used with aerial imagery (Soriano 2001).

Ultimately, coral reef injury was manually digitized in a GIS using ESRI's ArcMap software (Figure 19).

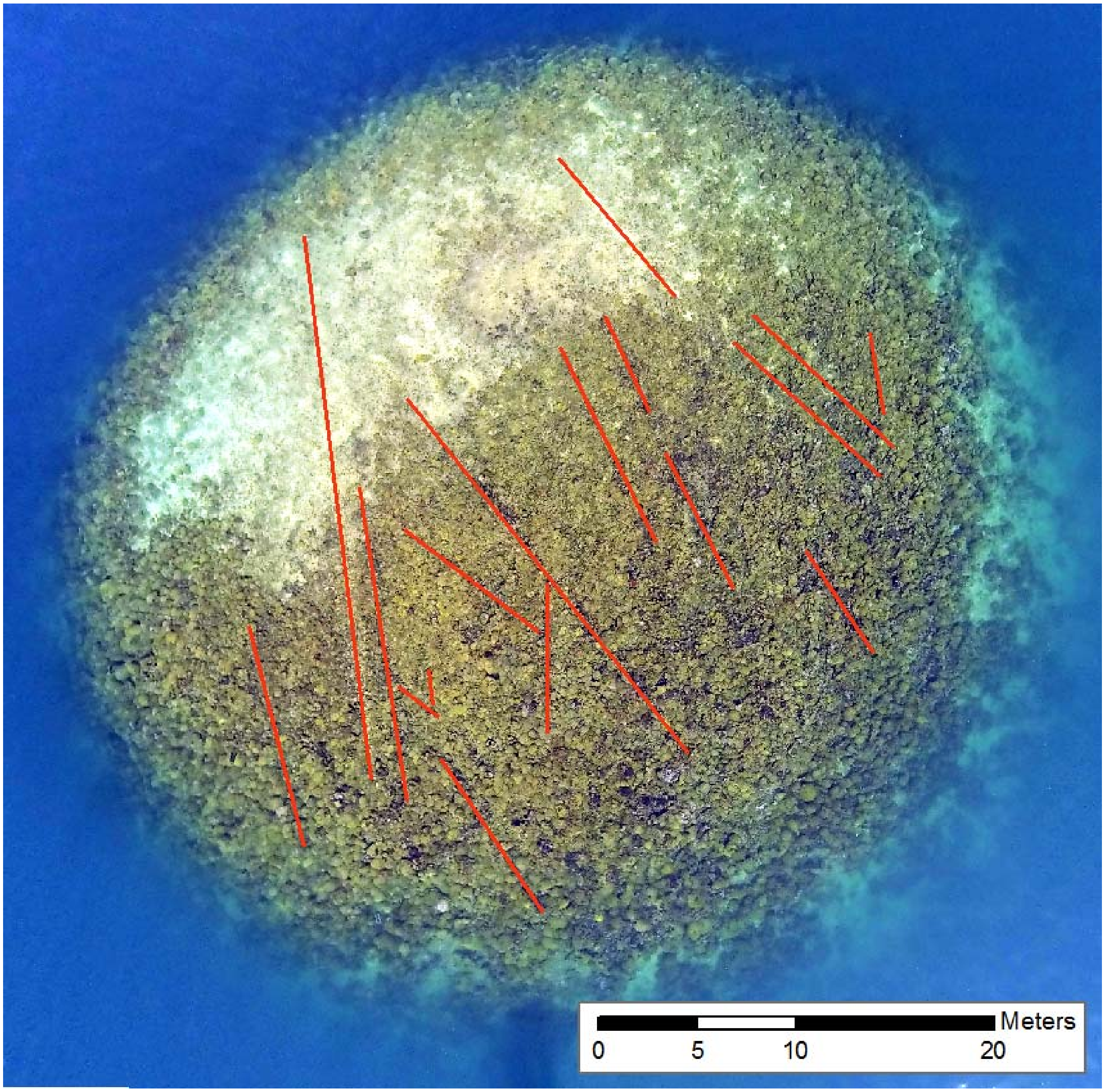


Figure 19: Digitized injury vectors overlaid on orthomosaic

The scars were most easily identified when viewing the orthomosaic at scales between 1:24 and 1:240. It is of interest to note that not all scars seen at the 1:24 scale were necessarily identifiable at 1:240 scale and vice versa. It was important to look at both oblique and nadir imagery for comparison of injury areas as some injury was easier to identify in the oblique verses the nadir mosaic and vice versa.

A shapefile was created of the 17 identifiable coral reef injury locations (Figure 20).

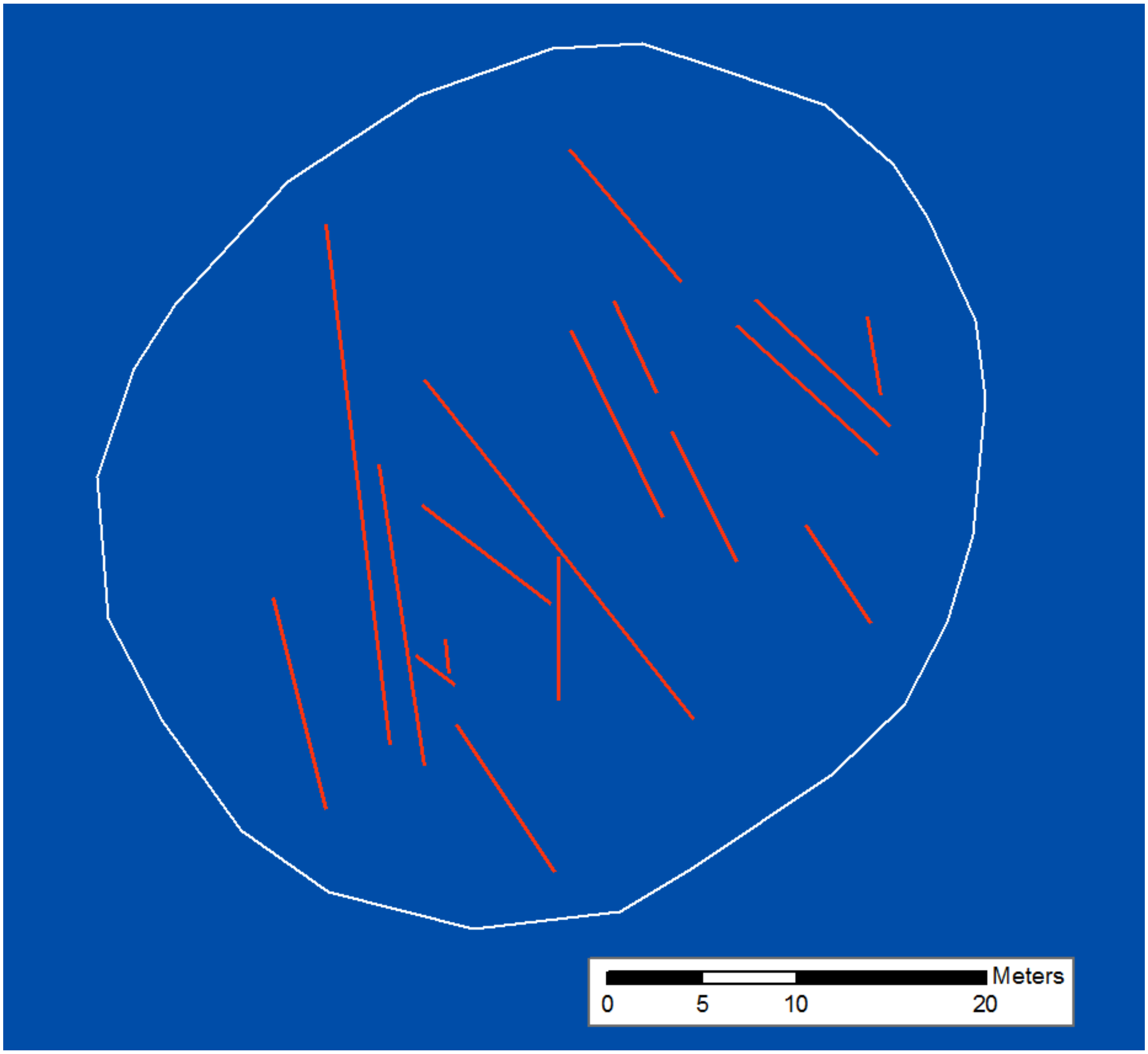


Figure 20: Digitized injury with outline of Reef #20 included for reference.

This data set was later confirmed with *in situ* photos of injured areas. Two separate researchers (the author of this paper and Anne Rosinski, a biologist from the University of Hawai‘i) digitized scars on the reefs independently for comparison and to ensure accuracy. Informal discussions and a subsequent day of snorkeling at the site revealed congruence with injury mapped at reef

#20. A separate GIS line shapefile was created with associated attribute data for all scars identified. Data was recorded in the attribute table for each scar that included a unique identifier, length, and azimuth.

FIELD VALIDATION

Field validated injury area vectors were photographed *in situ* (Figure 21) and linked to latitude and longitude coordinates in the GIS. The results included an ArcMap project with linked photos of all 17 injury sites. A subset of six injury site locations were analyzed for patterns in injury including scar length, width, geographic alignment, and frequency distribution on the individual patch reef. Length estimates from aerial imagery versus *in situ* measurements with a measuring tape were averaged to be within 6% of each other when analyzing the data collected *in situ* (i.e. a scar measuring 10.1 meters in the imagery was measured *in situ* to be 9.5 meters). It was interesting to note that all values measured *in situ* were less than the values measured in the GIS. The most likely source of this error was due to the fact that many of the beginning and end of the vectors in the image mosaic were not easily identifiable while snorkeling, but obvious when viewed at smaller scales in the GIS. This was most likely due to the scale at which one sees the scars *in situ* versus in the GIS. Injury seen from a meter away while snorkeling is not necessarily as visible when analyzing the orthomosaic.

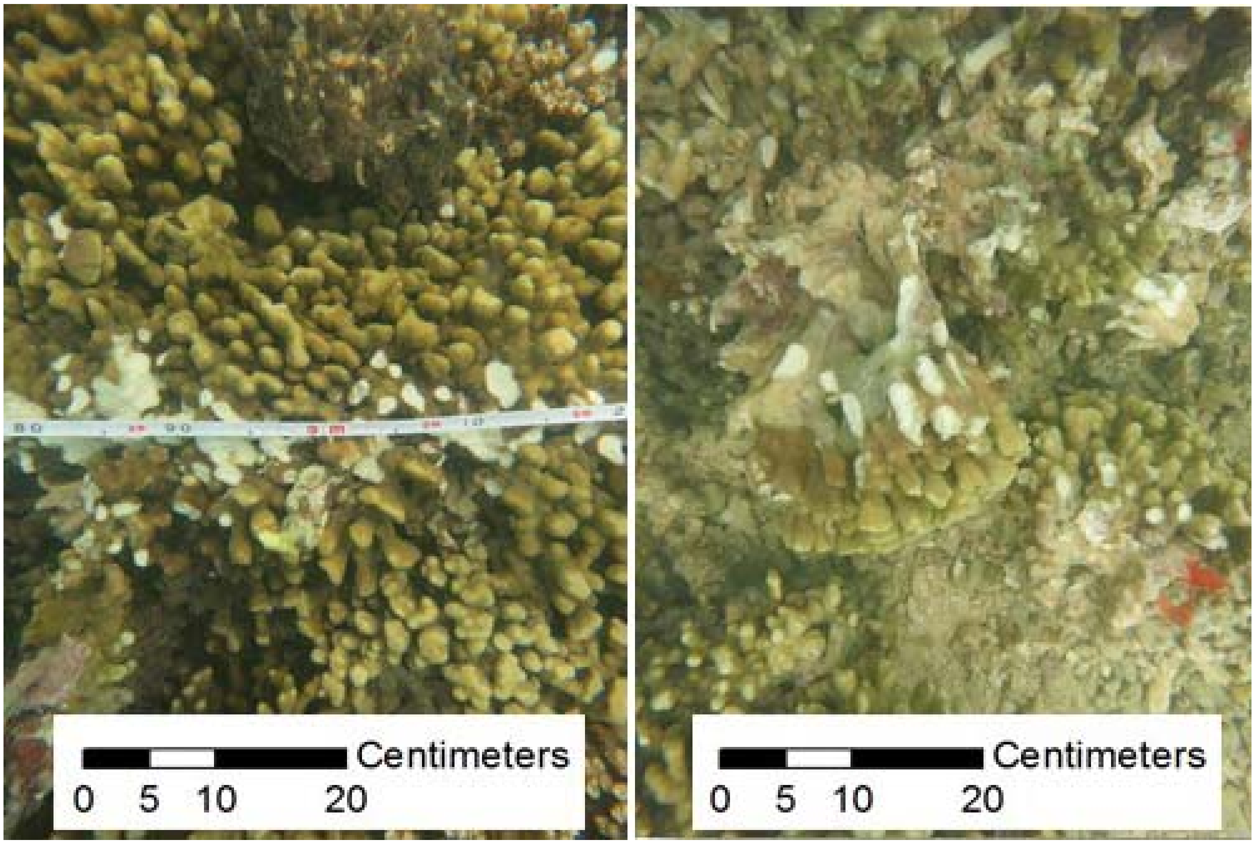


Figure 21: Example imagery of field validated injury with injured corals showing in white

RESULTS AND CONCLUSIONS

The UAV-collected photo mosaics revealed injury and interesting patterns of injury to coral reefs not seen in previous imagery or data acquisition efforts. UAV collected imagery was processed through Agisoft PhotoScan to produce a high resolution georeferenced orthophotos of two patch reefs in Kāne‘ohe Bay. The pixel size of the final image was one centimeter (0.01 meters), and superior for coral reef injury identification as compared to commercially available imagery (Figure 22).

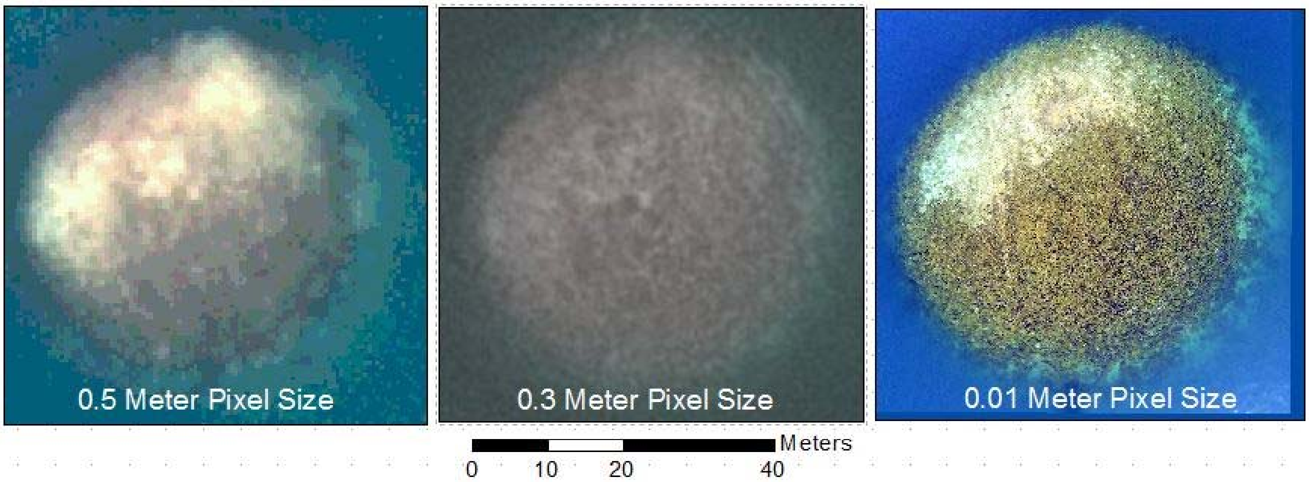
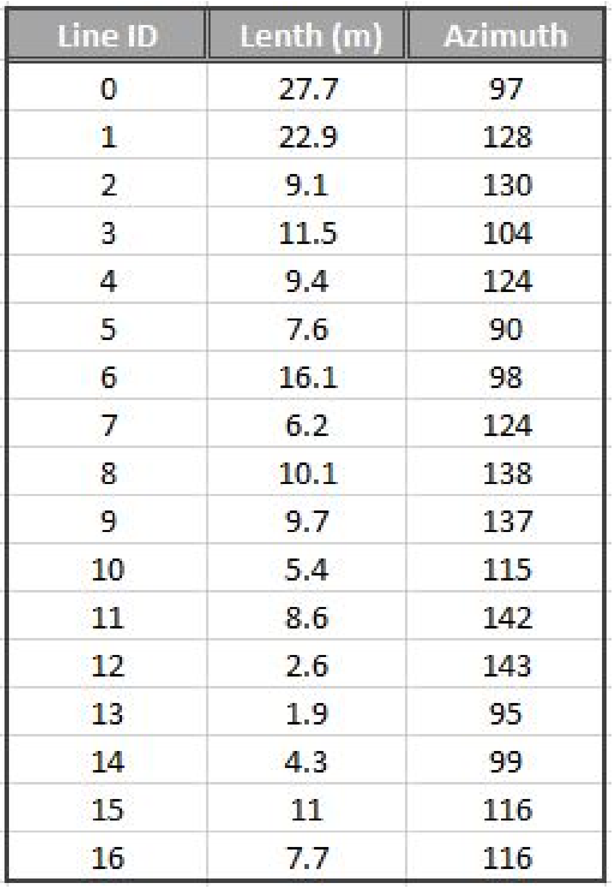


Figure 22: Image resolution comparison



Line ID	Lenth (m)	Azimuth
0	27.7	97
1	22.9	128
2	9.1	130
3	11.5	104
4	9.4	124
5	7.6	90
6	16.1	98
7	6.2	124
8	10.1	138
9	9.7	137
10	5.4	115
11	8.6	142
12	2.6	143
13	1.9	95
14	4.3	99
15	11	116
16	7.7	116

Table 2: Details of the mapped 17 injury vectors

Coral reef injury was visually identified and digitized in ArcGIS. Overall, 17 individual scars were located in the orthophoto associated with reef #20 and converted to GIS compatible files. Attributes for the scars were exported from the ArcGIS COGO tool, and then recorded in a table (Table 2) including length and azimuth. GIS derived azimuths were assigned values from 0 to 180 degrees based on their orientation with 90 representing north. The actual data values were distributed from 90 degrees to 143 degree range (Figure 23) indicating a northeast to southwest alignment, and similar to the predicted vectors. A chi squared goodness of fit test was performed against a uniform distribution of values. The test revealed a value of 0.0029 indicating that the data is not uniformly distributed which is seen in the histogram of the data (Figure 24).

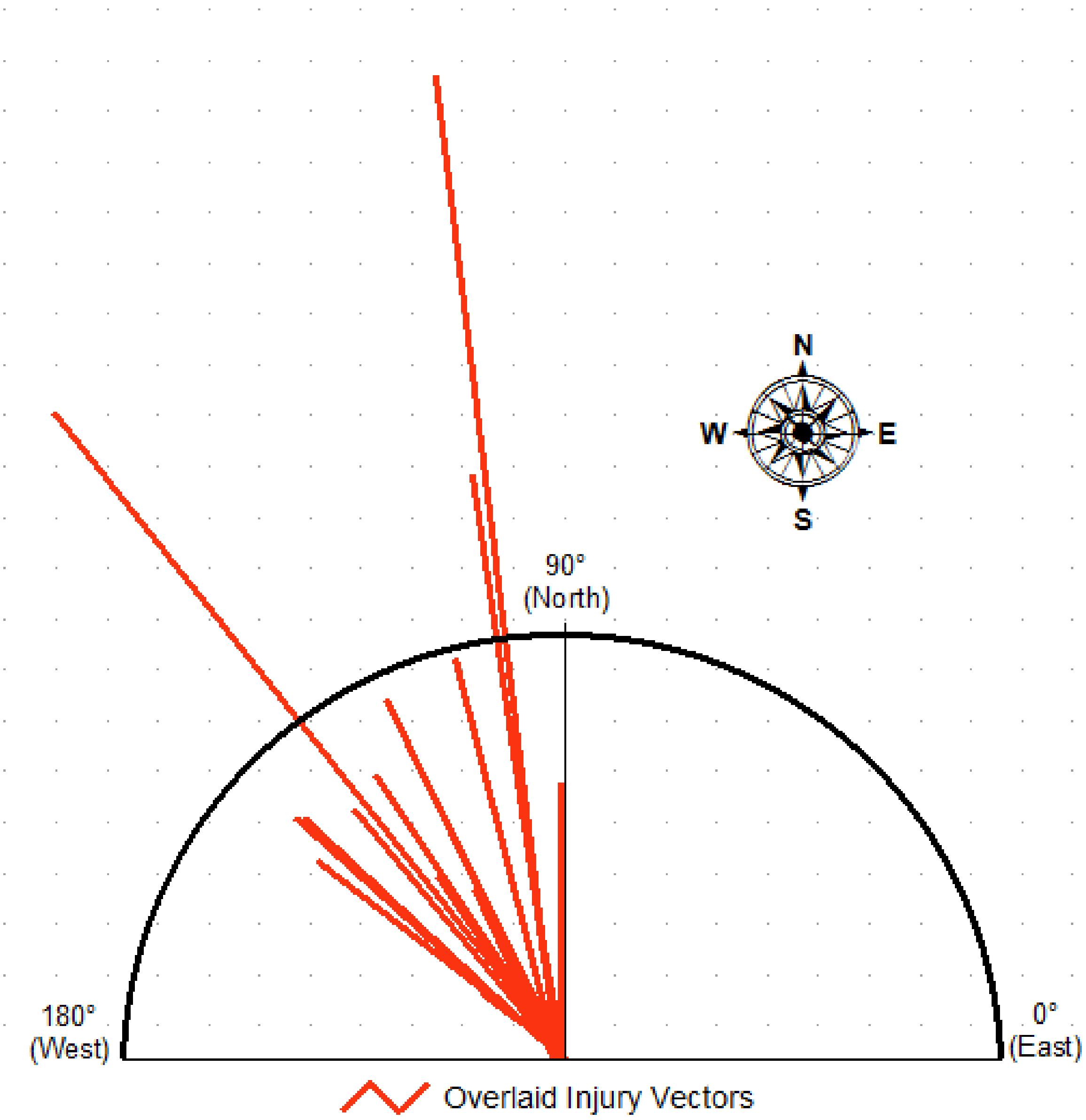


Figure 23: Graph of injury vectors overlaid on each other

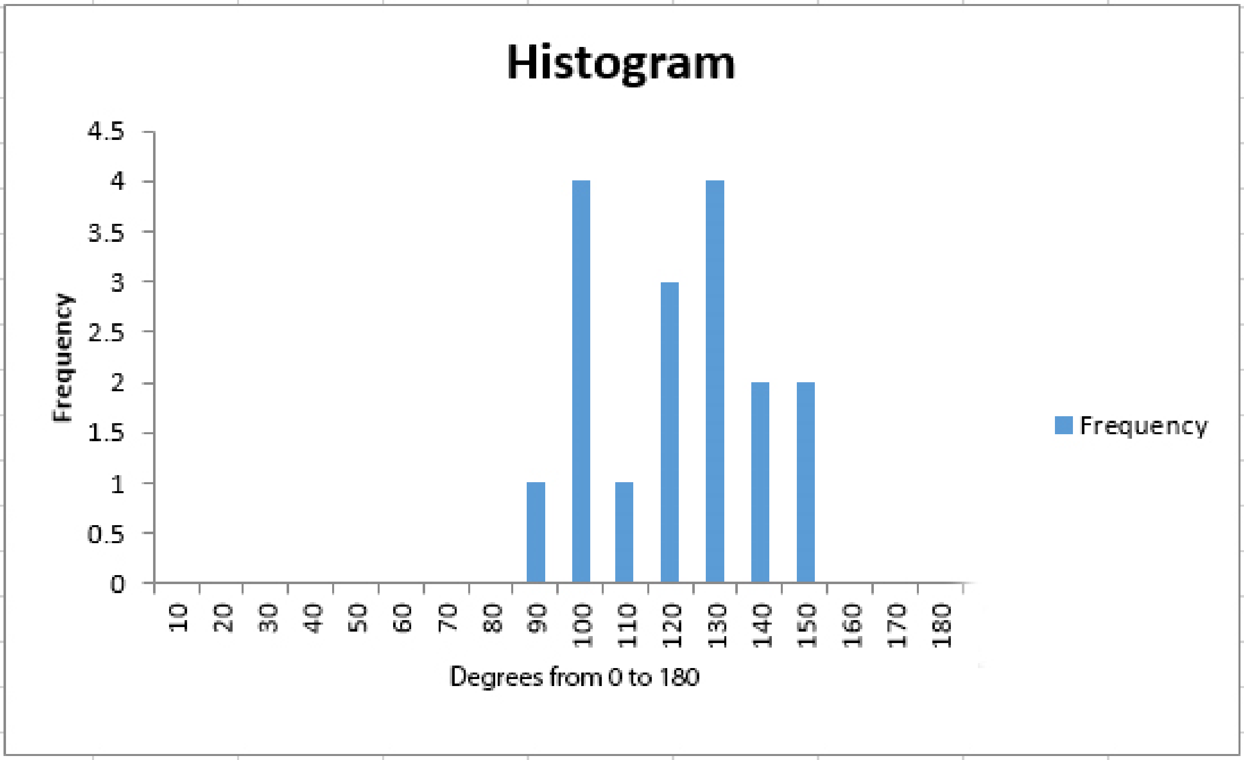


Figure 24: Histogram of injury vector data

There was no visible coral reef injury on reef #22 (Figure 25), which was originally predicted, as it is not situated in the path of usual boat traffic (Figure 15). This was verified *in situ* on subsequent snorkel surveys.

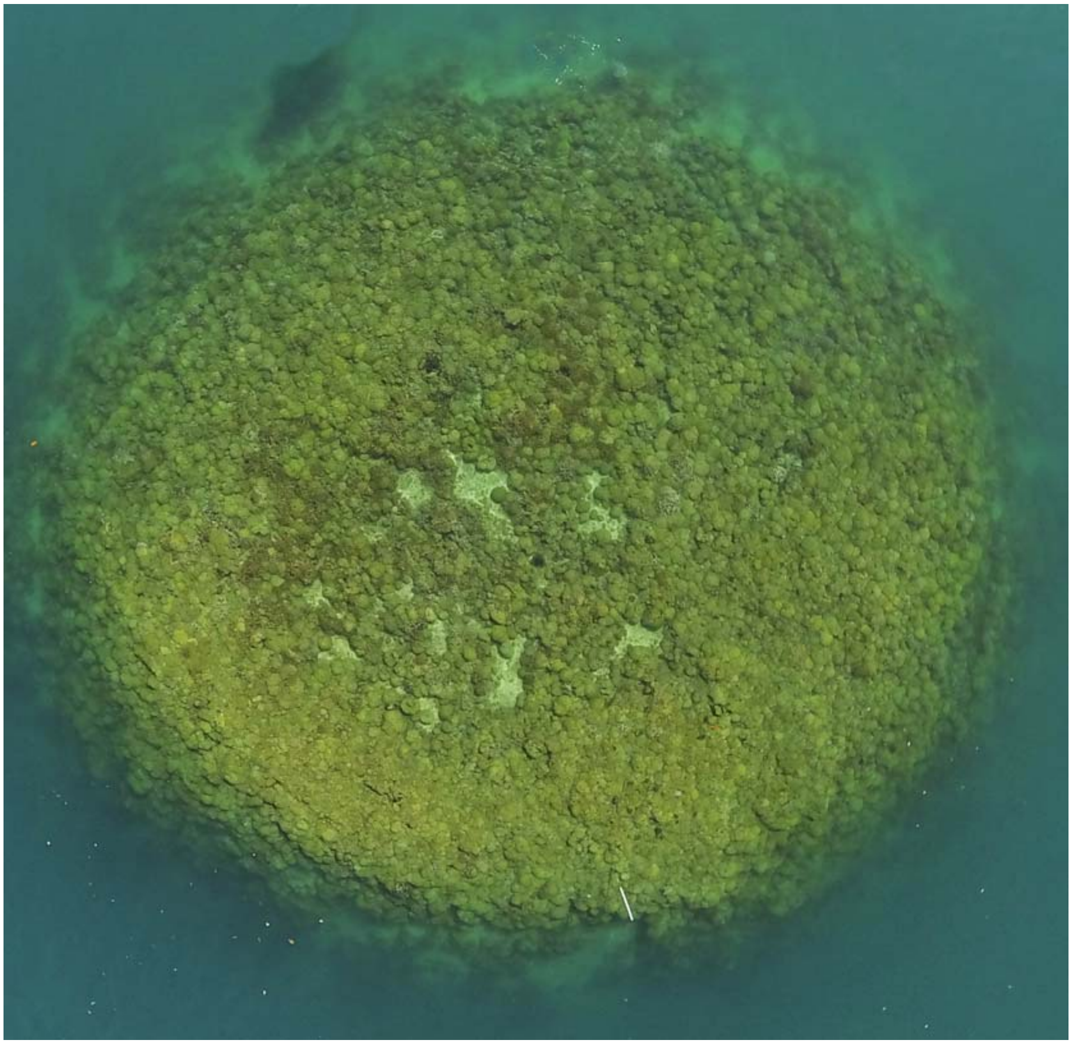


Figure 25: Reef #22

The results also showed that the pattern of injury was oriented in a roughly northwest to southeast direction, which is close to the initial prediction that vessels travel in a roughly north to south orientation, and typical of boat traffic in the area (Figure 15). *In situ* imagery verified these results, and ongoing studies at the University of Hawai‘i’s Institute of Marine Biology (HIMB) are analyzing the rates of recovery at these specific locations. The resolution of the photos was one centimeter pixel size, which, when compared to available coarser resolution imagery (i.e. WV2 or USGS imagery), was necessary for the goal of this study. Areas of injury with individual fragmented corals in the one to two centimeter diameter range were visible in the one centimeter pixel size orthomosaic. Coarser resolution imagery (i.e. one to two centimeters) could be collected to accomplish the same goal by conducting higher altitude flights, and this would enable the ability to acquire more imagery in a shorter time frame. However, for the two study sites used for this study, the flight time was a minimal factor as these reefs covered only approximately 2,200 square meters. Future studies of larger reefs may find flying at higher altitudes to be useful for covering more area, but it should be understood that coarser data allow for less analysis of coral species level identification. That is, it is possible to see injury, but less likely to see what specific species of corals and other benthic habitat features are affected.

In conclusion, using UAVs for image acquisition is a suitable method for mapping vessel related injury on the shallow coral reefs of Kāne‘ohe Bay. UAV imagery can be gathered and processed more quickly, as well as with less cost than other methods for assessing injury to coral reefs. Most other methods of mapping coral reef injury are not applicable to waters shallower than one meter. Commercially available aerial and satellite imagery lack the resolution needed to identify coral reef injury related to boating in Kāne‘ohe Bay.

DISCUSSION AND IMPLICATIONS

A number of points of discussion and implications for future research were produced following both the pilot study and the research project at reef #20 and reef #22. The pilot study involved practice piloting the UAV, experimenting with image mosaicking software, dismissing an alternative technique to image acquisition (the underwater camera array), and determining optimal weather conditions for image acquisition of shallow coral reefs. The pilot also proved that one centimeter image resolution orthomosaics were appropriate for detecting coral reef injury.

It was found to be important to obtain sufficient overlap (at least 60%) in UAV imagery acquisition missions so that the mosaicking software had sufficient cues in the photos to properly align them. Specifically, there needed to be approximately 400 images taken over an area of 2,200 square meters. Higher overlap resulted in more complete and accurate orthomosaics, but also increased the processing time of the data mosaicking process as more photos were necessary. Additionally, more diverse habitats required relatively less overlap, and conversely homogenous habitats (i.e. sand patches) would require additional overlap (up to 90%).

Coral reef injury was visible in the processed image orthomosaics, and injury areas were digitized in a GIS for further analysis. Efforts to automate the coral reef injury digitizing process by conducting classifications proved to be less effective than manually digitizing scars. It was not anticipated that any oblique imagery would be of much value, but ultimately it was a good indicator of injury in the orthomosaic and used as a valuable reference. Details on injury size and orientation were recorded and analyzed for patterns.

It was not expected that the imagery would reveal a very obvious zone of rubble on the northwest facing side of the reef (Figure 26). Additional *in situ* research will be done to determine if the dead coral rubble zone on the northwest facing side of reef #20 is the result of decades of cumulative impacts of repeated boat groundings. It may be proven, too, that this coral rubble zone is continually impacted, but the impact is difficult to map because there is a lack of live coral to injure.

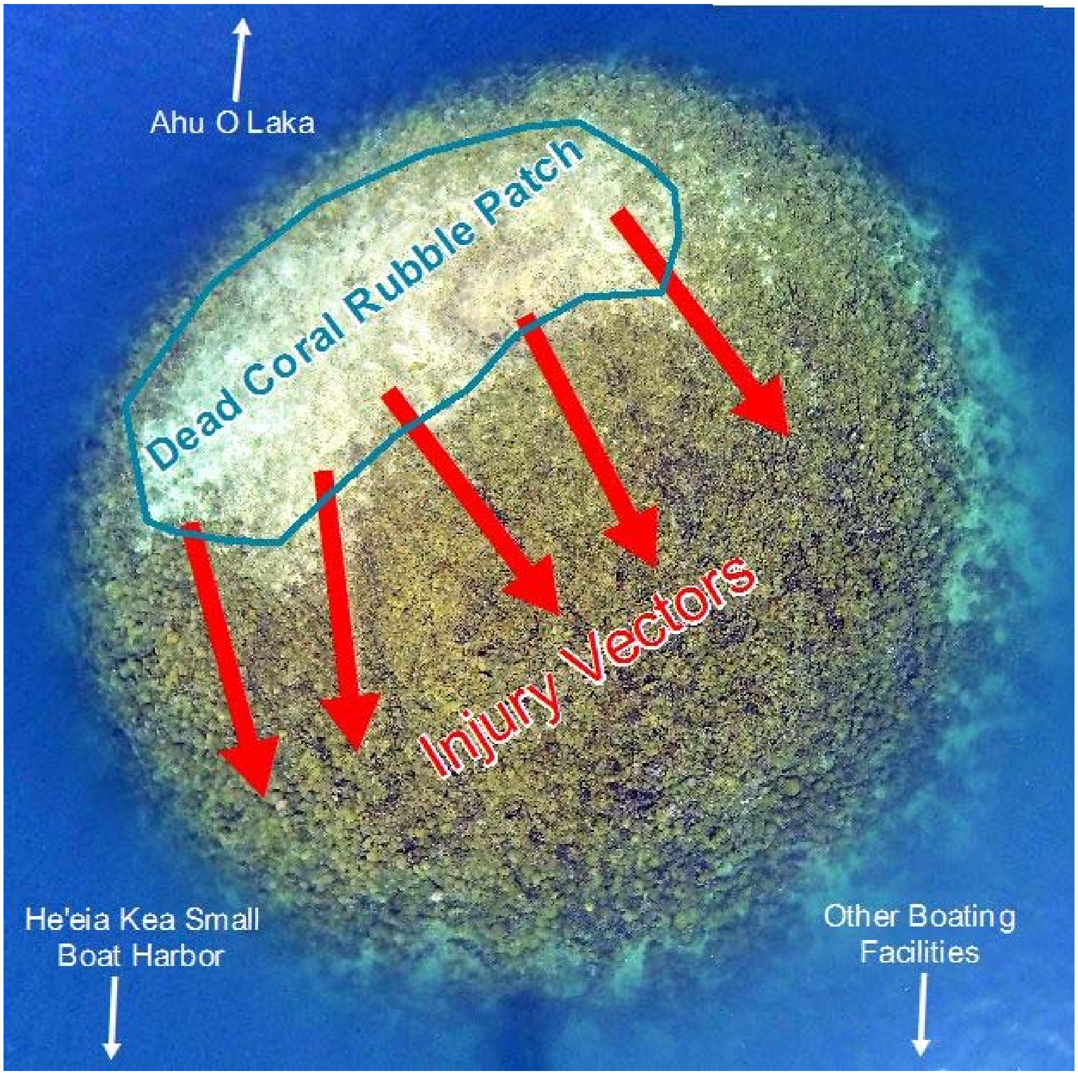


Figure 26: Map of possible cumulative impacts from vessel groundings at reef #20

The data collected is suitable for developing high resolution benthic habitat maps as it is possible to differentiate sand versus coral habitat as well as determine percentages of coral cover using this new imagery.

Agisoft PhotoScan produces a three dimensional point cloud that could be used to determine the depth of vessel grounding scars as well as coral growth rates both in areas of coral reef injury, and in areas of healthy coral reef habitat. The data would have to be adjusted to vertical accuracy standards and an appropriate mapping datum for comparison to other data being collected by researchers at DAR and HIMB.

The author would also like to transfer this method to the work that NOAA is currently conducting in its UAS program. Additionally, three dimensional printers are enabling customization of UAVs for additional functionality (i.e. more efficient propellers), and an increasing number of sensors (i.e. multibeam, LIDAR, and infrared cameras).

Coupling these emerging technologies in order to create high resolution GIS products will continue to evolve and better inform marine scientists as to the condition of coral reefs in Kāneʻohe Bay, and the world globally.

NEXT STEPS

This paper will be presented to the DLNR as a NOAA technical document along with recommendations for avoidance and minimization of continued coral reef injury in Kāneʻohe Bay. The most effective and inexpensive method for doing this would be installing additional aids to navigation (ATONs) in the bay. Small floating buoys centered on the patch reefs which are most impacted would enable boaters to better locate and avoid these obstacles. NOAA offers grants that would qualify for this type of effort. The NOAA Fisheries Office of Habitat Conservation has expressed interest in assisting the DLNR in purchasing and installing ATONs once research and development of a suitable ATON is performed, the necessary permits are in place to install an anchor on the existing coral reef, and a letter of support has been provided by the DLNR chair and district Coast Guard office.

The priority for an ATON would be reef #20 which is most susceptible to boat incursions, because of the data presented in this paper, and by the fact that it has no signage or existing ATON. Incursions have been witnessed at this patch reef both by the media, the author, and anecdotally by other researchers and boat users in the bay. This reef is a target simply due to its position in relation to the popular destination, Ahu O Laka, and the origin of most vessels in the Bay, the numerous marinas that lie south. Most of the other 58 reefs in Kāneʻohe Bay are located in areas of less traffic and/or are currently marked with ATONs. Other reefs that would seem to be in danger of being hit by boats are either marked with an ATON, or exist at deeper depths which allow for boats to simply avoid them altogether.

UAVs could be flown at periodic intervals in order to monitor the reef health and document any future incursions by vessels. Altogether, this reef would serve as the best test bed for the effectiveness of a new ATON in Kāneʻohe Bay.

REFERENCES

Aber, J. S. (2004). Lighter-than-air platforms for small-format aerial photography. *Transactions of the Kansas Academy of Science*, *107*(1), 39-44.

Agisoft, L. L. C. "Agisoft PhotoScan user manual. Professional edition, version 0.9. 0." (2013).

Balazs, G. H. 1991. Current status of fibropapillomas in the Hawai‘ian green turtle, *Chelonia mydas*. *In* G. H. Balazs and S. G. Pooley (eds.), Research plan for marine turtle fibropapilloma, December 4-6, 1990, Honolulu, Hawai‘i, p. 47-57. U.S. Dept. Comm., NOAA Tech. Memo. NMFS-SWFSC-156.

Basu, A; Saxena, N K., 1999. A review of shallow-water mapping systems. Marine Geodesy, Volume 249-258.

Beck, E., Kirkwood, W., Caress, D., Berk, T., Mahacek, P., et al., 2009. SeaWASP: A small waterplane area twin hull autonomous platform for shallow water mapping. Marine Technology Society Journal, 6-12.

Chauvin, L. E. 1972. *U.S. Patent No. 3,693,569*. Washington, DC: U.S. Patent and Trademark Office.

Colwell, R. N. 1997. History and place of photographic interpretation. In, Philipson, W.R. (ed.), Manual of photographic interpretation (2nd ed.), p. 3–47. American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland.

Coyne, M.S., Battista, T.A., Anderson, M., Waddell, J., Smith, W., Jokiel, P., Kendell, M.S., Monaco, M.,E., 2003. NOAA Technical Memorandum NOS NCCOS CCMA 152 (On-line). Benthic habitats of the Main Hawai‘ian Islands, National Oceanic and Atmospheric Administration, Silver Spring, MD, 48 pp and CD-ROM.

DAR 2014. “DAR Raises Native Collector Urchins to Reduce Invasive Algae on Hawai‘i’s Reefs”, Department of Land and Natural Resources, State of Hawai‘i pamphlet. http://dlnr.Hawai‘i .gov/ais/files/2014/01/Hatchery_Pamphlet.pdf (last accessed 02-21-2014)

Devaney, C.P. 2015. An Assessment of a Low-Cost Approach to Automate Spatial Referencing of sUAS-SFM Image Orthomosaics for Use in Denied Environments. Masters Thesis, University of Hawai‘i.

DLNR 2013. State of Hawai‘i , Department of Land and Natural Resources Administrative Rule, “DLNR - Administered Open / Accessible Sites – O‘ahu”, http://files.Hawai‘i.gov/dbedt/film/O%20&%20A%20List%20%2812-31-13%29.pdf (last accessed 02-21-2014).

Eriksen, C. C., Osse, T. J., Light, R. D., Wen, T., Lehman, T. W., Sabin, P. L., & Chiodi, A. M. (2001). Seaglider: A long-range autonomous underwater vehicle for oceanographic research. *IEEE Journal of oceanic Engineering*, *26*(4), 424-436.

Flanders, D., Hall-Beyer, M., & Pereverzoff, J. (2003). Preliminary evaluation of eCognition object-based software for cut block delineation and feature extraction. *Canadian Journal of Remote Sensing*, *29*(4), 441-452.

Francour, P., Ganteaume, A., & Poulain, M. (1999). Effects of boat anchoring in *Posidonia oceanica* seagrass beds in the Port-Cros National Park (north-western Mediterranean Sea). *Aquatic Conservation: Marine and Freshwater Ecosystems*, *9*(4), 391-400.

Freitas, R; Rodrigues, A M; Morris, E; Perez-Llorens, J L; Quintino, V., 2008. Single-beam acoustic ground discrimination of shallow water habitats: 50kHz or 200kHz frequency survey?. Estuarine, Coastal and Shelf Science, 613-622.

Garmin GPS Series 18 Technical specifications manual, http://www8.garmin.com/specs/GPS18_Series_SpSht.pdf (last accessed 10-27-2016).

Gonçalves, J. A., & Henriques, R. (2015). UAV photogrammetry for topographic monitoring of coastal areas. *ISPRS Journal of Photogrammetry and Remote Sensing*, *104*, 101-111.

Green, S., Bevan, A., & Shapland, M. (2014). A comparative assessment of structure from motion methods for archaeological research. *Journal of Archaeological Science*, *46*, 173-181.

Guo, T., Capra, A., Troyer, M., Gruen, A., Brooks, A. J., Hench, J. L., ... & Dubbini, M. (2016). Accuracy assessment of underwater photogrammetric three dimensional modelling for coral reefs. *ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 821-828.

Holthus, P. (1986). Structural reefs of Kāneʻohe Bay, Hawaiʻi: an overview. Coral reef population biology. Hawaiʻi Institute of Marine Biology Technical Report, (37), 1-18.

Houldcroft, C. J., Campbell, C. L., Davenport, I. J., Gurney, R. J., & Holden, N. (2005).

Measurement of canopy geometry characteristics using LiDAR laser altimetry: a feasibility study. IEEE Transactions on Geoscience and Remote Sensing, 43(10), 2270-2282.

Hunter, C.L., Evans, C.W. 1995. Coral reefs in Kāne‘ohe Bay, Hawai‘i: Two centuries of western influence and two decades of data, Bulletin of Marine Science, 57(2): 501-515.

Jameson SC, Erdmann MV, Karr JR, Gibson GR Jr, Potts KW, 2007. Development of biological criteria for coral reef ecosystem assessment, U.S. EPA report.

Jokiel, P.L., 2008. Biology and Ecological Functioning of Coral Reefs in the Main Hawai‘i an Islands. Coral Reefs of the USA, 489-517.

Kendall, M.S., Buja, K.R., Christensen, J.D., Kruer C.R., Monaco M.E., 2004. The seascape approach to coral ecosystem mapping: an integral component of understanding the habitat utilization patterns of reef fish Bulletin of Marine Science, 225-237.

KGMB (2011). http://www.Hawai‘inewsnow.com/story/15024028/booze-ban-brings-sobriety safety-to-sandbar (Last accessed 12-06-2016).

KHON2, 2015. http://khon2.com/2015/05/22/alcohol-drug-ban-in-effect-at-Kāne‘ohe-sandbar2/ (Last accessed 11-21-2016).

Leopold, L. B. (1949). The interaction of trade wind and sea breeze, Hawai‘i. *Journal of Meteorology*, *6*(5), 312-320.

Lowe, M. K. (1995, June). The Main Hawai‘i an Islands Marine Resources Investigation (MHI-

MRI): Integrated watershed and inshore fisheries management to conserve Hawai‘i a coastal fisheries ecosystems. In *Manuscript Collection of Country Statements and Background Papers. South Pacific Commission and Forum Fisheries Agency Workshop on the Management of South Pacific Inshore Fisheries. Noumea, New Caledonia. BP* (Vol. 76, No. 2, pp. 677-691).

Lirman, D., Gracias, N., Gintert, B., Gleason, A., Reid, R., Negahdaripour, S., and Kramer, P., 2007. Development and application of a video-mosaic survey technology to document the status of coral reef communities. Environmental Monitoring and Assessment, Vol. 125, 59-73.

MEGIS (2016). UH Manoa Map Library website. http://magis.manoa.Hawai‘i.edu/USGS_Pacific/300dpi%20jpegs/Oahu/1945/IC/Indexmap_IC.jpg (last accessed 11-03-2016).

Moore, L.J., Shoreline Mapping Techniques, 2008. Journal of Coastal Research, 16(1), 111-124.

Mumby, P.J., Skirving, W., Strong, A.E., Hardy, J.T., LeDrew, E.F., Hochberg, E.J., Stumpf, R.P., David, L.T., 2004. Remote Sensing of coral reefs and their physical environment. Marine Pollution Bulletin. Volume, pages

NOAA Earth System Research Lab – Solar Position Calendar, http://www.esrl.noaa.gov/gmd/grad/solcalc/azel.html (last accessed 11-20-2016).

O’Conner, R., 2010. GIS as a tool to review and modify bottomfish restricted fishing areas in the Main Hawai‘ian Islands, Proceedings of the Fourth International Symposium on GIS/Spatial Analysis in Fishery and Aquatic Sciences, International Fishery GIS Society, 329-336.

Precht, William F.; Aronson, Richard B.; Swanson, Dione W., 2001. Improving scientific decision-making in the restoration of ship-grounding sites on coral reefs, Bulletin of Marine Science, Volume 69, Number 2, September 2001, pp. 1001-1012(12).

Rahel, F.J., 2004. Introduction to Geographic Information Systems in Fisheries, Geographic Information Systems in Fisheries, American Fisheries Society, vol 1-12.

Rango, A., Laliberte, A., Herrick, J. E., Winters, C., Havstad, K., Steele, C., & Browning, D. (2009). Unmanned aerial vehicle-based remote sensing for rangeland assessment, monitoring, and management. *Journal of Applied Remote Sensing*, *3*(1), 033542-033542.

Riegl, B. M., & Purkis, S. J. (2005). Detection of shallow subtidal corals from IKONOS satellite and QTC View (50, 200 kHz) single-beam sonar data (Arabian Gulf; Dubai, UAE). *Remote Sensing of Environment*, *95*(1), 96-114.

Rodgers, S.K, and E.F. Cox, (1999). Rate of spread of introduced rhodophytes *Kappaphycus alvarezii, Kappaphycus striatum, and Gracilaria salicornia* and their current distributions in Kane ‘ohe Bay, O‘ahu, Hawai‘i. Pacific Science 53: 232-241.

Roy, K. J. (1970). Change in bathymetric configuration, Kāne‘ohe Bay, O‘ahu, University of Hawai‘i, T882-T969.

Schmidt, V. E., & Rzhanov, Y. (2012, October). Measurement of micro-bathymetry with a

GOPRO underwater stereo camera pair. In 2012 Oceans (pp. 1-6). IEEE.

SFA (Sustainable Fisheries Act) 1996. Report of the Committee on Commerce, Science, and Transportation on S.39: Sustainable Fisheries Act Report 104-276, 104th Congress, Second Session, U.S. Senate 23 May 1996. Washington D.C., U.S. Government Printing Office.

Smith, J. E., Conklin, E.J., Smith, C.M., Hunter, C.L. 2008. “Fighting Algae in Kāne‘ohe Bay” Science, Vol. 319, 157 p.

Smith, M.K., 1993. An ecological perspective on inshore fisheries in the main Hawai‘i an Islands. Mar Fish Rev, Vol. 55, 34-49 p.

SOEST (2016). The UH Manoa School of Ocean and Earth Science and Technology website. http://www.soest.Hawai‘i.edu/coasts/erosion/oahu/flt15.php (last accessed 11-04-2016).

Soriano, M., Marcos, S., Saloma, C., Quibilan, M., & Alino, P. (2001). Image classification of coral reef components from underwater color video. In Oceans, 2001. MTS/IEEE Conference and Exhibition (Vol. 2, pp. 1008-1013). IEEE.

Reddy, K. S., Reddy, K. R. L., (2013). "Enlargement of Image Based Upon Interpolation Techniques". *International Journal of Advanced Research in Computer and Communication Engineering*. **2** (12): 4631.

Star Advertiser 2012. “New 'Super Sucker" unveiled to rid Kāne‘ohe Bay of invasive algae” September 27, 2012. http://www.staradvertiser.com/news/breaking/171673931.html (last accessed 02-21-2014).

State of Hawai‘i 2011. “Ahu o Laka safety zone”, Hawai‘i Administrative Rules, 13-256-73.13.

State of Hawai‘i 2013. Hawai‘i Statewide GIS Program, Office of Planning. http://planning.Hawai‘i .gov/gis/ (last accessed 02-20-2014).

Stevens, T., Connolly, R.M., 2005. Local-scale mapping of benthic habitats to assess representation in a marine protected area. Marine & Freshwater Research, 111-123.

Stimson, J., Larned, S.T., Conklin, E. 2001. Effects of herbivory, nutrient levels, and introduced algae on the distribution and abundance of the invasive macroalgae *Dictyosphaeria cavernosa* in Kāne‘ohe Bay, Hawai‘i, Coral Reefs (2001) 19: 343-357.

Stumpf, R.P., Holderied, K., Sinclair, M., 2003. Determination of water depth with high-resolution satellite imagery over variable bottom types, Limnology and Oceanography, 547-556.

Suka, R., McCoy, F., 2016. Bathymetric Surveys in Shallow Water: SIGMA, A New Portable Survey System. Journal of Coastal Research (in review).

Swain, M. J., & Ballard, D. H. (1991). Color indexing. *International journal of computer vision*, *7*(1), 11-32.

Turk, L., http://nearlab.ece.pdx.edu/echomap/070502_CoralReef_Report.pdf (last accessed 10-27-2016).

Turner, D., Lucieer, A., & Wallace, L. (2014). Direct georeferencing of ultrahigh-resolution UAV imagery. IEEE Transactions on Geoscience and Remote Sensing, 52(5), 2738-2745.

Waddell, J.E. and A.M. Clarke (eds.), 2008. The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2008. NOAA Technical Memorandum NOS NCCOS 73. NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team. Silver Spring, MD. 569 pp.

Walker, B.K., Riegl, B., Dodge, R.E., 2008. Mapping Coral Reef Habitats in Southeast Florida Using a Combined Technique Approach, Journal of Coastal Research, 1138-1150.

Wedding, L. M., Friedlander, A. M., McGranaghan, M., Yost, R. S., & Monaco, M. E. (2008). Using bathymetric LiDAR to define nearshore benthic habitat complexity: Implications for management of reef fish assemblages in Hawai‘i. Remote Sensing of Environment, 112(11), 4159-4165.

Wedding, L., 2006. Coral Reef Mapping For Ecosystem-Based Fisheries Management, Masters Thesis, University of Hawai‘i, UMI Dissertation Publishing.