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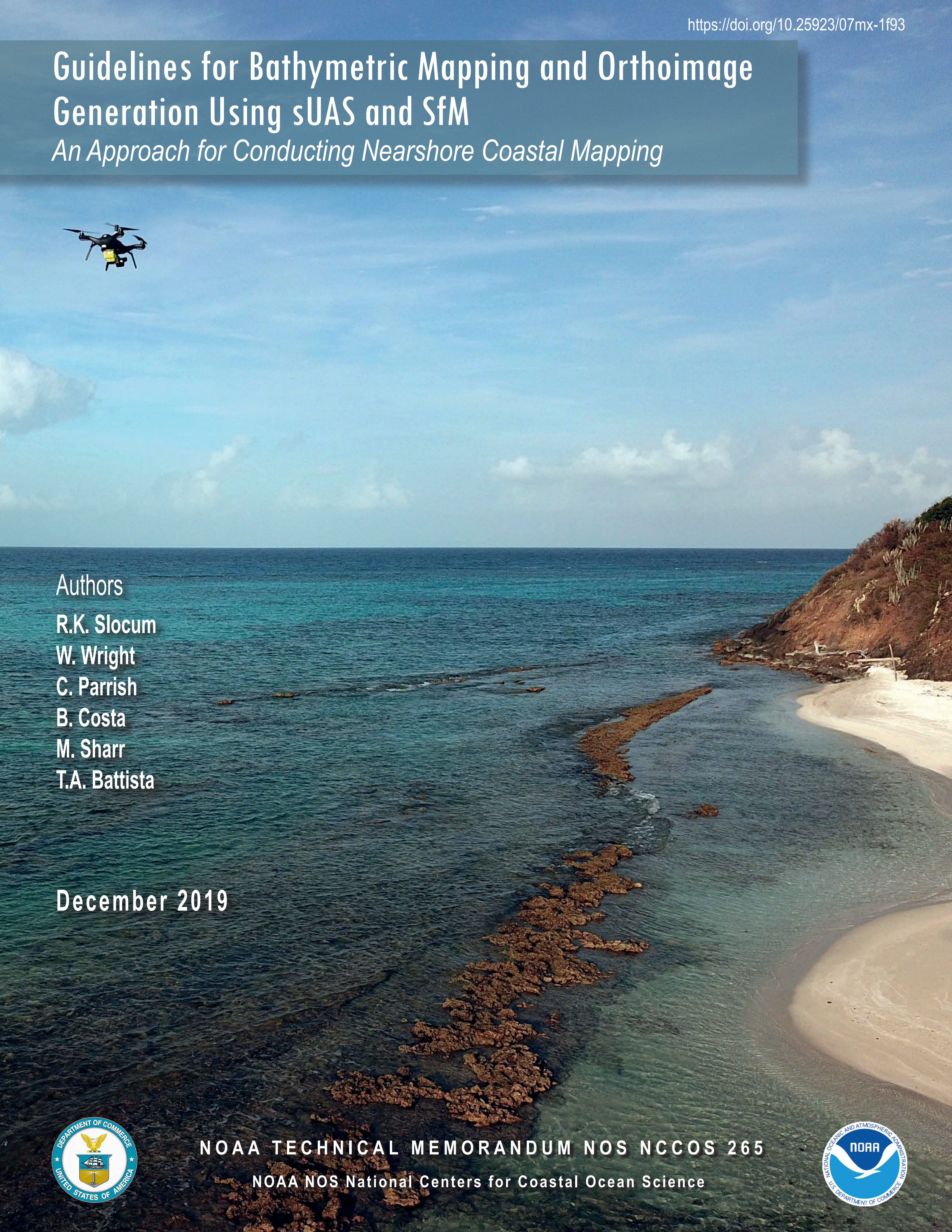
Guidelines for Bathymetric Mapping and Orthoimage Generation Using sUAS and SfM

An Approach for Conducting Nearshore Coastal Mapping



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Images used throughout the report are used in courtesy of Wayne Wright, Oregon State University and NOAA NCCOS.

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DJI Mavic Pro flying east of Buck Island, St. Croix.
Photo Credit: Oregon State University.

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Commonly Used Acronyms

AOI	area of interest
ASV	autonomous surface vehicle
DEM	digital elevation mode
DSM	digital surface model
DTM	digital terrain model
GCP	ground control points
GCS	Ground Control Station
GNSS	global navigation satellite systems
MVS	multi-view stereo
PPK	post-processed kinematic
RGB	red, green, blue channel
RTK	real-time kinematic
SDB	satellite-derived bathymetry
SfM	structure from motion
sUAS	small Unmanned Aircraft Systems
TIN	triangulated irregular network
VTOL	vertical takeoff and landing fixed-wing aircraft

sUAS image looking along shore of Santa Cruz Island, CA.
Photo Credit: Oregon State University.

Executive Summary

The absence of accurate, contemporary, or detailed bathymetric data in nearshore coastal waters impedes coastal research, conservation, disaster response, planning, and management efforts. The use of small Unmanned Aircraft Systems (sUAS) and low cost RGB (red, blue, green) cameras, coupled with advanced photogrammetry methods, structure from motion (SfM), provides a portable, efficient, rapid-response, and cost-effective method to fill nearshore data gaps. The sUAS–SfM approach provides an alternative method to traditional nearshore collection techniques, and is one that can benefit a diverse user community. The digital elevation models (DEMs) and photomosaics that result from the sUAS-SfM approach can provide users access to data of unparalleled resolution, previously unavailable. This methodology works well in environments with clear water, low wave conditions, and distinct visible features on the seafloor. Areas with poor water clarity, high wave conditions, breaking waves, or homogeneous sandy bottoms, are not well suited for this acquisition and processing methodology. Additionally, it is recommended that the sUAS platform selected be capable of acquiring a high accuracy trajectory (e.g., Carrier phase global navigation satellite systems), in order to generate accurate data products. These recommendations, and others introduced in this report are intended to encourage and aide the coastal mapping community in implementation and further advancement of this technique.

sUAS image of kayakers offshore of Buck Island, St. Croix.
Photo Credit: Oregon State University.

Chapter 1 Introduction

1.1 The Unmet Need

NOAA's requirement for high-resolution bathymetry in the nearshore coastal zone (depths 0–20 m) is currently unmet, particularly in remote locations. Vast extents of nearshore coastal areas either remain unmapped, lack sufficient high-resolution coverage, or only have antiquated datasets available. This absence of contemporary bathymetric data impedes NOAA's ability to conduct and provide accurate nautical charts and habitat characterizations, inform management decisions, evaluate regulatory actions, and formulate resource protection and conservation plans in the coastal zone.

Currently, the tools and techniques used to map the nearshore coastal zone include: acoustic sonar (sound navigation and ranging), lidar (light detection and ranging) and satellite-derived bathymetry (SDB; Figure 1.1); described in more detail in Appendix A. However, these techniques have inherent limitations in shallow-waters, minimizing the extent to which high-resolution bathymetry can be obtained in the nearshore coastal zone. Navigational hazards and narrow sonar swath-widths make acquisition of acoustic depth data challenging and inefficient. Airborne bathymetric lidar can be cost-prohibitive to deploy for projects, particularly in remote locations. And while SDB estimation has had variable success, it is limited by cloud cover and satellite spatial resolution.

To address this unmet need, the development of a rapid response, cost-effective solution is necessary for accurately surveying the coastal zone in high detail. The use of small Unmanned Aircraft Systems (sUAS) and low cost cameras, coupled with the imagery processed in structure from motion (SfM) software, has the potential to fill this data and informational need in nearshore coastal zones.

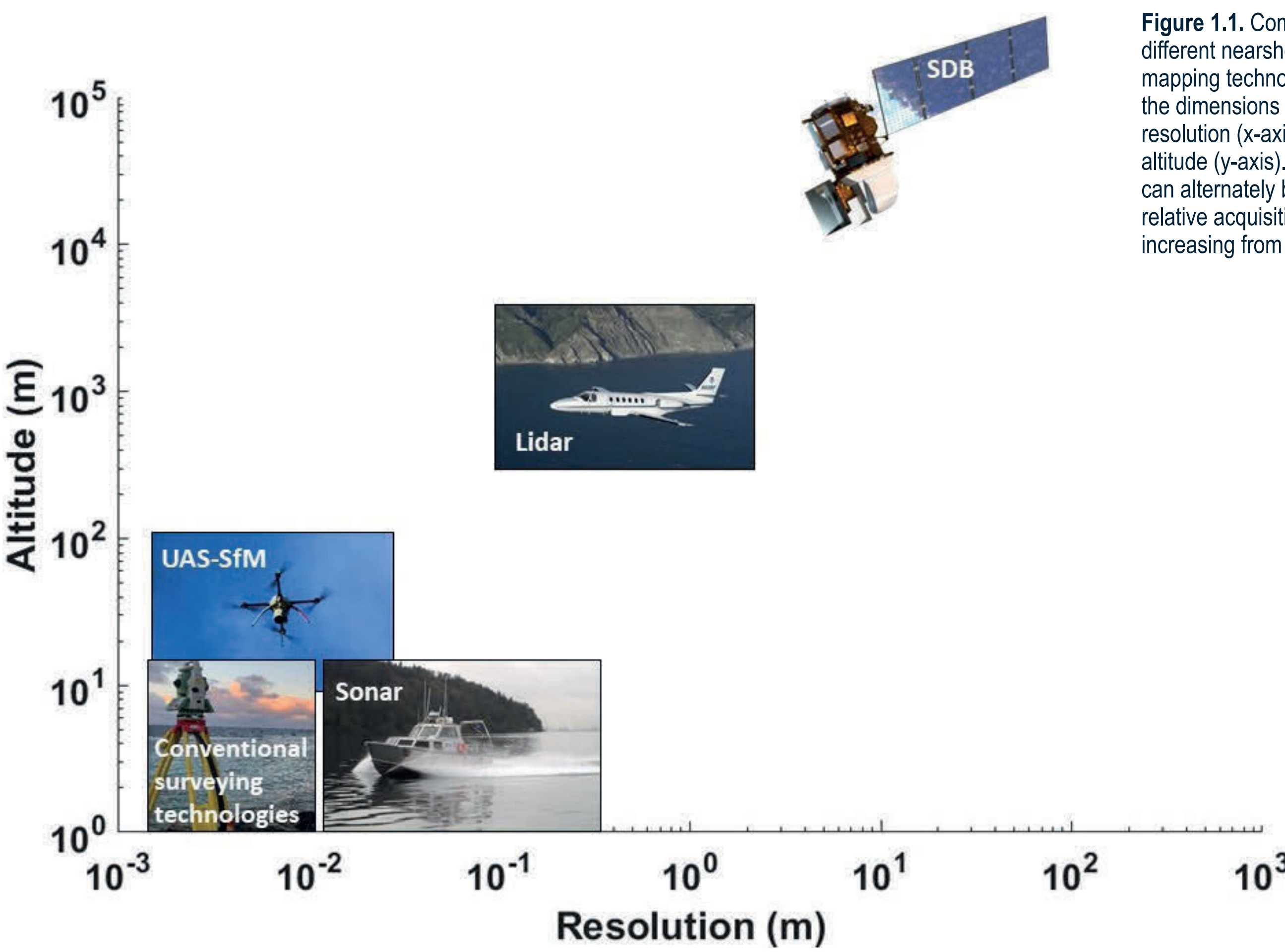


Figure 1.1. Comparison of different nearshore bathymetric mapping technologies along the dimensions of: spatial resolution (x-axis) and altitude (y-axis). The y-axis can alternately be viewed as relative acquisition speed, increasing from bottom to top.

1.2 What is SfM?

Structure from motion (SfM) is a relatively new type of photogrammetry, which leverages advanced computer vision algorithms to enable highly-automated processing and the use of non-mapping-grade cameras, such as those typically installed on commercial sUAS. Like conventional stereo photogrammetry, SfM relies on sets of overlapping images to reconstruct 3D geometry from 2D imagery. However, unlike conventional photogrammetry, which came into maturity well before today's advanced computer hardware and software, SfM overcomes the need for highly-calibrated metric mapping cameras and stable imaging geometry through advanced algorithms. SfM works well with sUAS imagery as it is highly automated, and enables the generation of point clouds (sets of data points in space) with spatial resolutions and accuracies generally comparable to lidar. SfM applications are growing rapidly within geomatics, geosciences, cultural heritage mapping, and other fields (Westoby et al. 2012).

For mapping a site, SfM utilizes overlapping sets of nadir (downward-pointing) imagery as input. "Overlap" is the amount of an image that includes the same area covered by another image along sequential flightlines. "Sidelap" is the amount of overlap between images from adjacent flighlines (Figure 1.2). These values are normally reported as a percentage, and for SfM processing are typically 75% or greater.

The SfM algorithm automatically computes correspondences between points in overlapping images, using algorithms which detect and describe key points such as SIFT (scale-invariant feature transform; Lowe 2004) and SURF (speeded-up robust features; Bay et al. 2008). The correspondences between the key points (also known as tie points) are used to compute the exterior orientation (position and orientation) of each acquired image, the interior orientation of the camera (lens calibration parameters), and the position of each key point in a local coordinate system (sparse point cloud). The coordinate system of the data is often constrained by computing the position of the camera when each image was acquired via global navigation satellite systems (GNSS), and/or using accurately surveyed ground control points (GCPs) and manually selected position of these GCPs in each image. Additionally, the interior orientation of the camera can be pre-calibrated and input into the system in order to help constrain the solution. All of these data are fed into a nonlinear bundle adjustment, which optimizes the camera positions, 3D key point coordinates, and camera interior orientation. Finally, a multi-view stereo (MVS) algorithm leverages the exterior orientation parameters (output by SfM) to create a dense point cloud. Typical outputs from SfM processing are point clouds, orthophotos, and digital elevation models (DEMs). Recommended literature on SfM include: Westoby et al. (2012), Fonstad et al. (2013), Tonkin et al. (2014), and Micheletti et al. (2015).

SfM is well established and used for topographic mapping, but there are significant issues not accounted for in current SfM software packages. The photogrammetric equations used in SfM and MVS processing assume that the to and from points of the light ray travel in straight lines. Imagery acquired from above the water surface (hereby called bathymetric SfM) is distorted as light refracts at the air–water interface, and the perceived position of tie points is too shallow (Figure 1.3). Recently, researchers have developed algorithms to correct the perceived water depth computed through SfM, to a more accurate, deeper depth (Woodget et al. 2015, Dietrich 2017). Additional challenges with bathymetric SfM include surface waves creating varying incident angles, poor water clarity, active wave

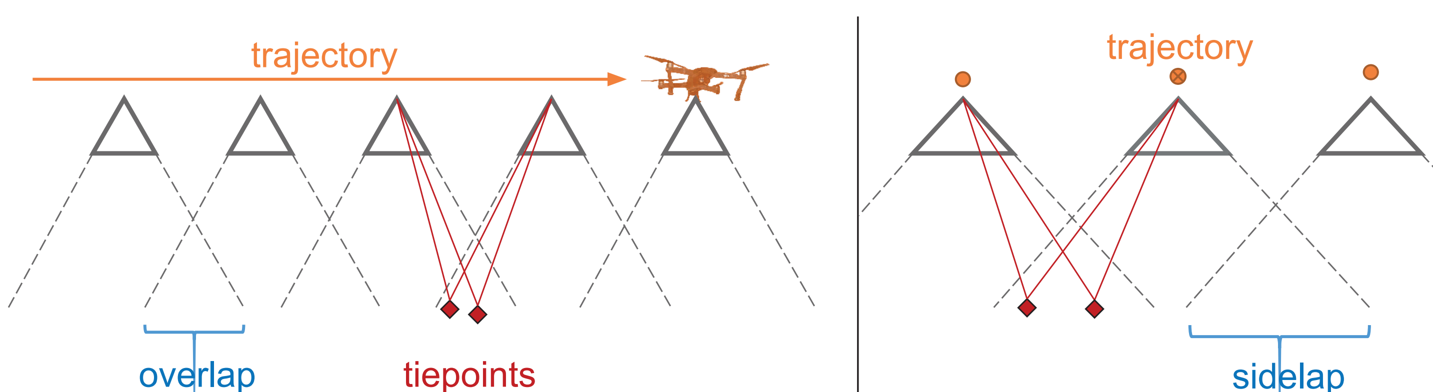


Figure 1.2. Tiepoints computed in images with overlap (left) and sidelap (right) are used in the initial SfM processing to estimate the camera exterior orientations, interior orientation, and sparse pointcloud. Note that the triangles indicate the viewing frustum of an image.

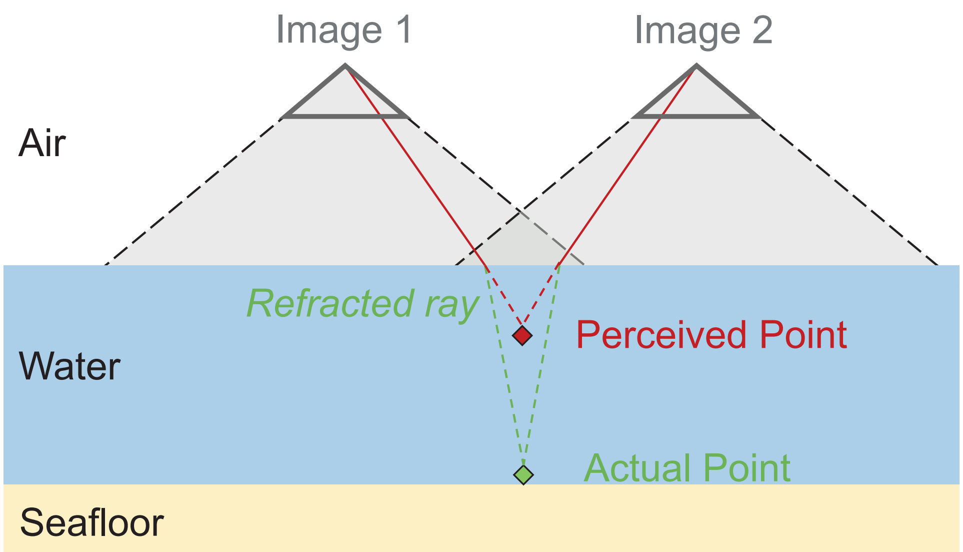


Figure 1.3. The perceived point cloud Z is shallower than the true location due to uncorrected refraction at the air–water interface.

breaking, and the impracticality of placing GCPs underwater. These challenges and the methods to mitigate the errors associated with bathymetric SfM processing are discussed in detail within this report. This discussion is designed to help users understand the advantages and disadvantages of the sUAS and SfM approach, so they can make an informed comparison to other shallow-water mapping techniques (i.e., sonar, bathymetric lidar, SDB, and conventional surveying technologies).

1.3 Project Objectives

In order to better understand the limitations of bathymetric SfM, the project team performed mapping missions on Buck Island, St. Croix, U.S. Virgin Islands (USVI) and on Santa Cruz Island of the Channel Islands, California (Figure 1.4). The lessons learned from the collection and processing of these data are included throughout this report.

From March 30–April 1, 2018, the project team acquired sUAS imagery and ground-truth datasets at multiple sites on St. Croix using three multirotor platforms and traditional surveying equipment. Additionally, bathymetric lidar data was acquired for St. Croix by the U.S. Army Corps of Engineers (USACE)–Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) four months after the sUAS data acquisition, enabling a high density accuracy assessment.

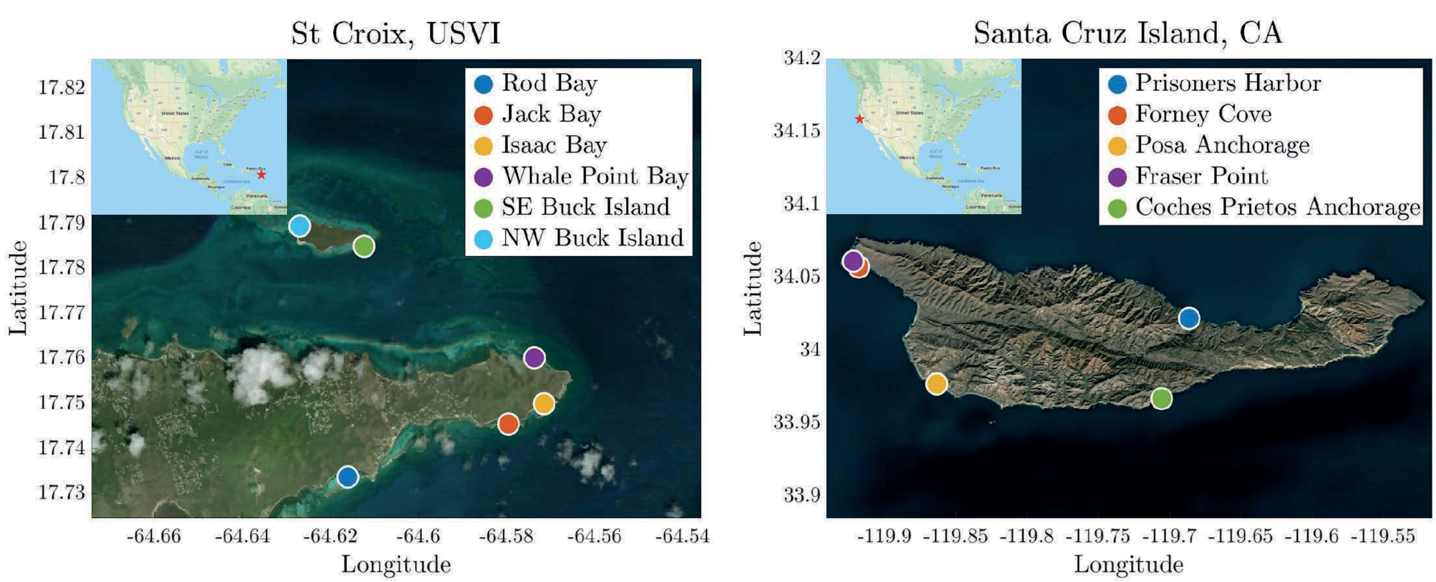


Figure 1.4. Locations of the two mapping missions performed by the project team that are used as case studies for this report. More information on mission locations can be found in Appendix B. Imagery credit: Oregon State University

Three airframes were selected and flown by the project team on St. Croix (Figure 1.5a-c). The smallest, and least expensive sUAS was a stock DJI Mavic Pro™. This system represented one of the least expensive sUAS available at the time, and provided ±2 m positioning for the imagery. The second system was a 3DR Solo Drone™ (3D Robotics, Inc.), with a Ricoh GR-II (Ricoh Imaging Company, Ltd.) digital camera and a custom PPK (post-processed kinematic) GNSS system. The final system was a DJI S900 with a Sony™ A6300 camera and a custom PPK GNSS system. Over 70 flights were performed at six different field sites, varying airframes, time of day, and polarization filter orientations. Additionally, computer generated virtual experiments were performed in simUAS, a simulated sUAS image rendering workflow (Slocum and Parrish 2017), to investigate SfM performance of bathymetry estimation under a number of scenarios.

The project team also performed sUAS flights on Santa Cruz Island, from December 11–18, 2018, using a DJI P4P™ RTK (real-time kinematic) sUAS operated in PPK mode (Figure 1.5d). The flights around Santa Cruz Island built on the previous lessons learned in the USVI, and tested the operational and environmental limitations of this approach for wider use at NOAA. A Seafloor Systems Hydrone™ autonomous surface vehicle (ASV) was also deployed around Santa Cruz Island to collect single beam depth soundings to assess the accuracy of depths derived using SfM (Figure 1.5e). More specifics about the Buck Island, St. Croix and Santa Cruz Island research missions can be found in Appendix B.

1.4 Organization of This Document

The objective of this Technical Memorandum is to document recommended procedures and best practices for using sUAS specifically for coastal/nearshore bathymetric mapping projects. While sUAS rules are discussed in this report, up to date knowledge and details of the most recent regulations are ultimately the responsibility of the vehicle operator. It is assumed that the reader is familiar with and will abide by all applicable rules, regulations and procedures concerning sUAS operations. This document will describe recommended best practices for conducting sUAS bathymetric mapping in nearshore waters, but is not intended to be a guidebook of all steps or procedures regarding planning, operations, or data post-processing methods.

Figure 1.5. sUAS platforms used in St. Croix, USVI: a) DJI Mavic Pro, b) 3DR Solo Drone with PPK, c) DJI S900 with PPK, d) DJI P4P PPK sUAS, and e) Seafloor Systems Hydrone ASV for Santa Cruz Island, CA. Credit: Oregon State University

The document is organized into a series of chapters, briefly described below, which generally define the chronological sequence of steps needed to plan, execute, and complete a sUAS bathymetric mapping mission. The document is intended to benefit a range of readers with pre-existing knowledge and/or intended use of sUAS bathymetric mapping.

Chapter 2: Equipment Selection– Once mission objectives and the operational location have been defined, the principal investigators must consider and evaluate a range of equipment (both hardware and software) that are needed to meet the predefined project requirements. This chapter describes equipment selection considerations for executing sUAS SfM missions.

Chapter 3: Evaluating Mission Feasibility and Logistics – sUAS operations can require extensive pre-planning prior to conducting the mission. This chapter describes several facets that should be considered for mission planning including legal considerations and requirements, logistical challenges, and site environmental considerations.

Chapter 4: Planning and Executing the Mission – The execution of a sUAS mission requires the implementation of a number of steps to ensure its operational success and the output of high quality products. This chapter describes a series of important mission execution concepts including camera calibration, mission planning steps, flight procedures, and data stewardship.

Chapter 5: SfM Processing Workflow – Deriving bathymetric surfaces from SfM requires utilization of a processing workflow. This chapter described a series of sequential steps required including GNSS trajectory, SfM processing, point cloud editing, and refraction corrections.

Chapter 6: SfM Data Dissemination – Dissemination of bathymetric SfM data is often done in multiple file formats. This chapter describes each file type, and the associated quality assurance and quality control that should be performed on each data type with varying levels of ground control.

Chapter 7: Conclusions and Supporting Research – The results and analysis from over a 100 sUAS flights are provided, evaluating the influence of airframes, sensors, environmental conditions, and processing procedures.

Chapter 8: Limitations and Future Work – The results and analysis from over a 100 sUAS flights are provided, evaluating the influence of airframes, sensors, environmental conditions, and processing procedures.

Supplemental information and project documentation such as alternative research methods, mission reports, technical glossary, permits and forms, and regulations are included at the end of the report.

Preparing to deploy Seafloor Systems Hydrone ASV on Santa Cruz Island, CA. Photo Credit: Oregon State University.


DJI S900+PPK flying offshore of St. Croix.
Photo Credit: NOAA NCCOS.

Chapter 2 Equipment Selection

Conducting a bathymetric survey using sUAS, requires considering multiple factors when selecting hardware and software. The considerations described in this report are intended for bathymetric survey missions; however, they may be applicable to missions with a different set of applications (e.g., topographic mapping, benthic habitat classification, aquatic species identification, etc.).

2.1 sUAS Hardware

As of August 2019, there are numerous commercial sUAS platforms available, varying in size, sensors, and capabilities. The authors recognize that the sUAS market is constantly evolving and improving, and have made an effort to make platform and sensor agnostic recommendations and avoid specific platform or sensor recommendations. The airframes and sensors used by the project team are described in Appendix B, and will be referenced to provide examples for consideration. Reference to these commercial sUAS and camera sensors does not constitute an endorsement or recommendation by the authors or federal government.

2.1.1 Airframe

The three types of sUAS currently available include fixed-wing, multirotor, and vertical takeoff and landing (VTOL) fixed-wing (Figure 2.1 and Table 2.1). Fixed-wing aircraft have the longest endurance and range of the three types, but require much larger landing zones and typically subject payloads to greater shock and potential damage (Figure 2.1-left). Multirotor sUAS aircraft provide the most flexibility and fewest limitations for takeoff and landing, but are generally the most limited in endurance and range (Figure 2.1-middle). As of August 2019, VTOL fixed-wing airframes are relatively new to the market, and not yet widely adopted for surveying and mapping (Figure 2.1-right). Multirotors and VTOLs provide the softest, most controlled landings, in the most restrictive landing zones, affording shock-sensitive and easily misaligned optical payloads (cameras, lenses) the most protection during that phase of flight. VTOLs generally address the takeoff and landing deficiencies of fixed-wing aircraft. It is important to note that only multi-rotor sUAS were tested here.

Figure 2.1. The three main types of airframes are fixed-wing (left), multirotor (middle), and vertical takeoff and landing (VTOL; right). Credit: senseFly, Oregon State University, and C.W. Wright

Table 2.1. Comparison of the three sUAS main types of airframes.

Airframe Types	Advantages	Disadvantages
Fixed-wing	• Long endurance • Long range	• Large landing zone requirement • More shock and potential damage to payloads
Multirotor	• Most flexibility for takeoff and landing • Few limitations for takeoff and landing • Soft, controlled landings • High payload protection during takeoff and landings • Can hover for inspection surveying	• Limited endurance • Limited range
Vertical takeoff and landing (VTOL) fixed-wing	• Soft, controlled landings • High payload protection during takeoff and landings	• Takeoff and landings require highest pilot skill level. • Higher incident risk during takeoff and landing in windy conditions. • Lowest payload weight vs max gross takeoff weight.

2.1.1.1 GNSS accuracy

One of the most important considerations when purchasing a sUAS for bathymetric SfM surveying is the ability of the airframe to acquire high accuracy 3D positions of the camera precisely at the time an image is acquired. Large uncertainty (greater than 2 m) in the position of the camera when each image was acquired propagates to large errors (sometimes greater than 5 m) in the resultant data products, further discussed in Section 7.1. This differs from strictly topographic SfM mapping (without water refraction), where it is possible to use high accuracy ground surveyed photo–identifiable control points (i.e., ground control points [GCPs]) to compensate for low accuracy camera positions. When performing bathymetric sUAS missions, it is often impractical or infeasible to deploy and survey GCPs on or under water. In addition, distortion at the air–water interface due to waves and light refraction reduces the clarity of any submerged GCPs. These uncertainties can propagate into lower accuracy of the SfM estimated camera positions, which if left loosely constrained by low quality camera positions, will adversely influence the resultant point cloud.

During this project, the team acquired data with low accuracy camera positions, and noted that any processing with these data resulted in inaccurate depths on the order of meters in the vertical dimension. For this reason, if accurate 3D bathymetry is desired, it is essential that the sUAS have the ability to accurately record camera positions (approximately 0.05 m) and the precise time (approximately 0.001 s) of each image exposure. This is currently accomplished using carrier phase GNSS, commonly PPK or RTK GNSS. While every scenario is different, PPK processing generally yields slightly more accurate results than RTK due to availability of more precise satellite orbits and clocks, and more advanced forward and backwards post-processing that is not possible with RTK. However, unlike PPK, RTK data products are available immediately after the data is acquired, which may be beneficial for processing time-sensitive data. A more detailed discussion about PPK versus RTK is included in Section 5.1.1.

The project team utilized PPK GNSS positioning which yielded horizontal and vertical standard deviations of 3 cm and 5 cm of the sUAS position, respectively. Note that it is essential that sUAS is able to record precise time stamps for image acquisition and carrier phase raw GNSS data which can be used to produce a high accuracy (cm level) trajectory. While most RTK sUAS systems do record raw carrier phase GNSS data, some sUAS on the market are currently advertised as RTK systems, but only enable

Setting up Total Station on St. Croix.
Photo Credit: Oregon State University.

precise navigation of the sUAS rather than the ability to record a high accuracy trajectory and image positions. Such systems should not be used for SfM mapping purposes. Note that these recommendations and accuracy values are based on the current sUAS market and the current positioning hardware. They are also based on the current state of SfM algorithm development. Future photogrammetric processing methods, such as those which directly account for refraction, may lessen the requirement of having high accuracy camera positions for bathymetric SfM processing.

2.1.1.2 Flight duration

The flight duration and speed of a sUAS determines how large of an area can be mapped before a battery change is required. Flight duration may vary depending on the airframe design, airframe type, and weather conditions, but durations are constantly improving due to improvements in battery technology and sUAS efficiencies. A fixed-wing airframe, either VTOL or conventional, can normally fly for a longer duration than a multirotor airframe, due to the ability of the airframe to generate lift and carry the load while only using motors for forward propulsion. A multirotor, on the other hand, is designed such that its motors maintain altitude and forward motion, resulting in considerably larger power consumption from the motors than does forward propulsion alone.

When considering an sUAS platform, it is important to consider the size of the area(s) to be surveyed and to investigate whether the flight time specifications will meet the desired requirements. It is important to note, frequent battery changes can extend the time needed to conduct the mission. This time increase can subject the survey area to changes in sun angle and illumination, therein affecting data accuracy. In addition, current Federal Aviation Administration (FAA) rules require operating the sUAS below 400 ft (Part 107 of FAA regulations [FAA 2019a]) and within line of sight, unless approved for a waiver. The size of many commercially-available sUAS make the aircraft difficult to see beyond 500 m in typical visibility conditions. Combined with these current legal restrictions, the advantage of sUAS with extensive flight duration may be rendered negligible by the restrictive nature of an observer's line of site. Note that wind will greatly reduce the flight duration to a value which is much less than manufacturer specifications.

2.1.1.3 Takeoff/Landing

The takeoff and landing requirements of an sUAS will influence the location and the type of environment where a sUAS can be utilized. A fixed-wing airframe requires a larger, flat area to takeoff and land, and would not be a practical option for small boat or narrow beach takeoffs and landings. However, unlike the fixed-wing, VTOL fixed-wing and multirotor airframes can takeoff and land from very small areas and may be the only viable airframe for some scenarios (Figure 2.2). It should be noted that currently, some VTOLs can be more challenging to operate than multirotors when taking-off and landing in windy conditions where the wing or airframe will generate lift while it is hovering in the wind. It is difficult to generalize the challenges associated with VTOL systems because it is such a new design of sUAS, and the performance of these systems can vary dramatically.

2.1.1.4 Manual flying learning curve

The level of difficulty in flying the airframe is an important consideration when selecting a sUAS platform for a mission. While most commercial mapping platforms can be flown in autonomous mode, the operator should be competent and comfortable flying the airframe manually, in windy conditions, both with and without GNSS enabled. From the experience of the authors and colleagues, multirotor airframes are easier for new pilots to learn to fly, and have greater latitude for error compared to fixed-wing airframes.

2.1.1.5 Airframe size and weight

The airframe size and weight can be limiting factors for surveys in rugged or difficult to access sites where equipment transport and shipping may become a factor. Fixed-wing airframes are traditionally larger than the comparable multirotor airframes, and require a larger carrying case. If the airframe is too large, it can be difficult to ship, fit in rental vehicles, boats, etc., and thereby creating logistical challenges. Larger aircraft are also more inherently dangerous to operate with larger propellers and engines. Additionally, if the sUAS has a takeoff weight of greater than 55 lbs it will be subjected to a different set of FAA regulations.

2.1.1.6 Battery capacity

Battery capacity can be a limiting factor when traveling with a sUAS by plane. In the United States, the FAA currently (as of August 2019) restricts lithium ion batteries to 100 Wh (watt hours) in carry-on baggage. An additional two spare lithium ion batteries, 101–160 Wh per battery, may be allowed on flights upon approval from the airline, as long as they are individually protected and the terminals are properly covered or insulated. Loose lithium batteries are currently not permitted in checked baggage on commercial airlines. sUAS batteries with a larger capacity need to be shipped via certified shipping companies, which can increase cost and complexity of field logistics. For up-to-date restrictions, consult the FAA website: https://www.faa.gov/hazmat/packsafe/.

Figure 2.2. Narrow beaches with a small takeoff and landing area, such as this site on St. Croix, are best suited for VTOL or multirotor airframes. Credit: Oregon State University

2.1.1.7 Wind/Weather resistance

When performing sUAS surveys in regions with strong winds, high humidity, or salt spray, the wind and weather resistance of a sUAS should be considered. A sUAS that is able to withstand and fly in more rugged conditions with fewer mechanical issues can support a variety of missions, without sacrificing safety. Ingress Protection (IP) rating is a metric which defines the level of sealing effectiveness against foreign bodies and moisture, and can be used to evaluate airframes being considered.

2.1.1.8 Ease of data acquisition

The interface and workflow to acquire data varies for each sUAS. In general, there are several capabilities useful to consider when planning a mission. First, ensure the mission planning application (app) is easy to use and interfaces seamlessly with the sUAS. Second, a first-person view (FPV) system on the sUAS is desirable as it gives the pilot a real-time display and a way to confirm data is being acquired. It can also be used by the pilot to improve their situational awareness and visualize or influence the quality of data being obtained. Additionally, a large, bright screen is advised for visibility during sunny conditions. Lastly, the system is much easier to use if the sensor, payload and autopilot functions are integrated together in a tightly coupled system. If the sensor is coupled with the downlink to the controller, the FPV stream can be downloaded directly from the sensor and quality checks can be performed for further confirmation that valid data are being acquired.

2.1.1.9 Organization specific regulations

A final element to consider when deciding on a sUAS platform is whether there are any organization-specific regulations or limitations regarding (1) the purchase or use of different types of drones, (2) IT security restrictions, or (3) drone manufacturer limitations. For more information on NOAA specific requirements, see Section 3.1.

2.1.2 Sensor

A RGB camera (red, green, blue channel Bayer Array) is the most common sensor for performing sUAS-based bathymetric SfM surveys. On commercial systems, the sensor is often mounted on a gimbal and tightly integrated with the sUAS. Occasionally, a custom airframe will have the sensor mounted manually on either a custom gimbal or on a fixed mount with vibration mounts. This section discusses the different considerations when comparing various camera sensors for bathymetric mapping in more detail.

2.1.2.1 Accurate timestamping

Arguably, the most important aspects of an sUAS system designed for bathymetric and topographic SfM surveying is accurate positioning of each image. If this position is not directly recorded by the sUAS, an accurate timestamp for each image is required. Even slight timing offsets will increase uncertainty associated with the camera position, and increase error in the resultant point cloud. For example, a sUAS flying laterally at 10 m/s will experience 1 cm of horizontal positional error for each millisecond of timing error. Some commercial systems have the sensor tightly integrated into the entire system and record timestamps internally. Systems with a sensor that is not as tightly integrated often rely on logging the time of a mid-exposure pulse from the camera. On machine-vision cameras, this pulse is often easy to access via a dedicated connector. With consumer cameras, this is normally achieved using a flash shoe, which is traditionally used to trigger an external flash while the shutter is open.

sUAS image of coral reef offshore St. Croix.
Photo Credit: Oregon State University.

2.1.2.2 Camera sensor size and type

The camera sensor size and resolution influences imaging sensitivity and signal-to-noise ratios (SNRs). The distance between neighboring pixels on a sensor is called pixel pitch. The area of each pixel is the product of the horizontal pitch multiplied by the vertical pitch. Pixel areas are called “wells”. The SNR of each pixel well is adversely affected by smaller pixel areas. Pixels of the same material with larger areas will have better SNRs, and larger dynamic ranges than those with smaller pixels areas. For example, consider two sensors which are the same size (such as 1/2.3 in size or Advanced Photo System type-C [APS-C] size, etc.), but one is a 10 MP (megapixel) camera and the other has 40 MP camera. The 40 MP camera will have a smaller pixel pitch and will capture fewer photons per pixel, resulting in fewer electrons, and therefore a lower SNR for the same exposure settings compared to the 10 MP camera. The 10 MP camera will have lower resolution, but is capable of generating imagery with lower noise at faster shutter speeds. While this is the case for sensors which have the same amplification circuitry, an older sensor of the same size and pixel pitch will likely have an inferior signal-to-noise performance. With these trade-offs in mind, it is difficult to select or provide advice on a “best” sensor. However, it is useful to keep in mind that a camera with a large number of pixels does not necessarily make it the best option. There are other important factors that impact photon to electron conversion efficiency, such as fill factor, front or back illumination, as well as the sensing material and how the data are extracted from each pixel well. The two dominant sensor types used today are CCD (or charged coupled device) and CMOS (or complementary metal–oxide–semiconductor). It is important to select a sensor which maximizes the signal to noise as this can improve the image dynamic range and reduce image noise which may increase the SfM algorithm performance (Mosbrucker et al. 2017).

2.1.2.3 Camera shutters

When performing photogrammetric mapping, a global shutter is important as it ensures that all of the pixels are exposed at the same time. A rolling shutter progressively exposes rows of pixels over time, which can greatly reduce the photogrammetric accuracy of the imagery with the rolling shutter effect. A rolling shutter introduces significant spatial distortion in the image when items in the scene, or camera, are in motion. Correcting for this motion is difficult to account for in post-processing, as it is often non-linear due to accelerations of the airframe. Note that Pix4D (Pix4D S.A.) and others have introduced algorithms to attempt to correct for this, but it is still strongly advised to use a camera with a global shutter and avoid introducing more unknowns into the post-processing. Global shutters can be mechanical devices, or be part of the electronics within the sensor. Mechanical shutters can be used on both CCD and CMOS sensors and do not degrade the sensor efficiency, though they will eventually wear out. Electronic shutters on the other hand do not wear out; however, the required additional electronics (within the sensor pixel well) will degrade the sensor efficiency. Which global shutter you choose depends on how long (how many photos) you expect the camera to capture before replacement. In practice, it is common to research camera reviews and sUAS reviews, which will often include information indicating the expected performance of each sensor.

2.1.2.4 Lens selection

A fixed focal length, or prime lens, is advised for photogrammetric mapping as it has a more stable interior orientation than a variable zoom lens. The mechanical stability of the lens is essential, as it ensures that the relative orientation of the lens optics do not vary between photos, which would change the camera interior orientation. Any horizontal movement or change in the distance from the lens to the sensor will change the principal point and focal length, respectively. Most off-the-shelf camera lenses and cameras are only concerned with individual photo quality, and slight changes in the physical relationship of a few pixels does not adversely affect the consumer target market. Photogrammetric SfM processing, however, is greatly affected by changes to the camera interior orientation and the accuracy is diminished.

The focal distance, which is set by focusing the lens, will also affect the interior orientation of the camera. Therefore, a fully manual lens is preferred as it is possible to mechanically lock down the focus adjustment on the camera body, perform a calibration, and have the calibration be retained from flight to flight. Lenses which enable automatic focusing are electronically controlled by small motors mounted in the lens, which can introduce uncertainty in the focal point of the lens.

2.1.2.5 Camera cycle rate

The cycle rate of a camera, or how fast it can take and store pictures, is important as it dictates how fast the sUAS can fly while reliably acquiring imagery at the required overlap (see Chapter 4, Section 4.4). A camera with a slower sampling rate will require the sUAS to fly slower, resulting in a longer mission, greater battery usage, more takeoff and landings, and more time for environmental parameters to change.

2.1.2.6 RAW imagery acquisition

Some sUAS provide the option to record JPG, RAW, or JPG and RAW. RAW imagery is always preferred, as the imagery is “raw” or “unprocessed”, will suffer no compression loss, and will retain more information in the shadows or bright areas, depending on the sensor pixel resolution (e.g., 8-bit, 10-bit, 14-bit). Each sensor will vary regarding whether which is faster, writing RAW or JPG, but it is never advisable to configure the camera to acquire JPG and RAW imagery at the same time. Concurrently capturing JPG and RAW imagery will reduce the effective cycle rate of the camera. The camera storage medium (flash memory card, etc.) must be rated for sustained writing at the photo rate multiplied by the photo size. For example, if each photo is 16 megabytes, and data are acquired at one image per second, then the storage card must be able to sustain at least 16 megabytes per second write speed.

RAW imagery is normally recorded at greater than 8-bit depth and commonly has a higher dynamic range which can contain more texture in the highlights and shadows and generally higher contrast. This can be beneficial in scenes where there is high variability in signal levels throughout the image scene. For example, a dark coral reef adjacent to a very bright, white sandy beach. In these type of scenes, it is challenging to ensure that the reef is not underexposed, and the beach is not over exposed.

2.1.2.7 Gimbal and vibration damping

A gimbal mounted camera helps maintain the camera fixed at nadir, and can also be adjusted off-nadir inflight to help eliminate or reduce sun glint during a flight. Utilizing a camera stabilized in pitch, roll, and heading yields images with less potential for motion induced blur than fixed mounted cameras and can be operated with slower shutter speeds. While a gimbal mount is beneficial, it is not necessarily a requirement for general near-nadir SfM topography or bathymetry mapping. Additionally, the gimbal does not need to report highly accurate roll, pitch, and yaw values because SfM processing is not highly sensitive to uncertainty in these parameters.

2.2 Software and Hardware for Mission Execution

The selection of hardware and software for mission planning and execution can be a significant factor in determining the ease of use in operating a sUAS. The user-friendly nature of a hardware or software solution is difficult to quantify and can be highly dependent on user preference. Therefore, this section is intended to indicate considerations that should be taken into account when selecting and evaluating various systems. The underlying flight control electronics hardware will determine what software is used for both mission planning and for operational control during flight.

2.2.1 Ground Control Station Hardware

When performing a sUAS survey, the Ground Control Station (GCS) consists of the hardware (i.e., controller and screen) and internal software. There are different types of controllers, ranging from video-game style controllers, to traditional RC style controllers, to custom controllers from the manufacturer (Figure 2.3). The GCS should be intuitive and easy to hold, and the screen should be large and bright enough to clearly visualize the mission status or FPV. If the screen is not attached to the controller, it should be easy to mount or hold without distracting the pilot. Additionally, the overall size and weight of the GCS is important to consider, especially if potential field sites are hard to access by vehicle or require hiking. Finally, the controller and screen ruggedness should be taken into account if the expected survey locations could be in harsh environments.

Figure 2.3. Three common style of sUAS controllers are video-game style controllers (left), traditional RC style controllers (middle), and custom controllers from the sUAS manufacturer(right).

2.2.2 Software

The software used to plan surveys, upload missions, and monitor the real-time acquisition of data from the drone is an important component of the system. An intuitive, easy to use software can enable more reliable, and potentially, safer data collection.

2.2.2.1 Mission planning

When preparing for missions, it is helpful to pre-plan flight lines before deploying into the field. The ease of planning a mission in a controlled office environment with a mouse and larger screen can be beneficial, but is not required. When in the field, it is helpful if new missions can be created and adjusted quickly and accurately using an existing basemap with historic orthoimagery for reference. Additionally, terrain following, or the ability to maintain a constant elevation above ground across varying topography, can be an essential feature if there are large cliffs or varying topography in or near the area of interest. This can help maintain a constant ground sampling distance (GSD) in sloping terrain, and ensure the sUAS does not fly too high or too low above ground level.

A limitation of some sUAS software is that they are reliant on an internet connection either to log in to the system or to download a local basemap. This can be limiting in situations without internet access, and should be considered when evaluating software. Also, it is important to ensure that the software selected is compatible with the operating system on the laptop or tablet selected.

2.2.2.2 Real-time display of mission status

Most sUAS systems have a control software which indicates mission status, battery life, time remaining, and other useful updates while the mission is in progress. These status updates help give the operator confidence during the acquisition and to monitor when the sUAS should return home if the battery power falls below a predefined level. These types of status updates are essential for a sUAS to be used operationally.

Most software packages allow for adjusting the camera acquisition parameters on the fly, which helps to ensure the imagery is being acquired with the appropriate exposure settings to capture the texture in the scene without over or under exposing the imagery. A system which provides this type of feedback during mission acquisition is recommended, as it provides confidence that the data is being acquired correctly and allows for problems to be addressed in the field.

2.3 Structure from Motion Data Processing

2.3.1 SfM Software

There are a number of commercial and open source SfM software packages currently available. These packages all utilize SfM algorithms to compute camera exterior orientations, interior orientation, and a sparse point cloud, then a MVS algorithm to generate a dense point cloud. Most software packages also enable orthophoto and digital surface model (DSM) generation. As of June 2019, none of the commercial software packages currently account for refraction directly in the SfM algorithm, but it is expected that there will be advancements in this area in the near future. A few of the most common commercial software packages are Agisoft Metashape (Agisoft LLC) and Pix4D (Pix4D S.A.), while a few of the open source SfM packages are visualSfM and openSfM. The authors used Agisoft PhotoScan (now Metashape) for this work, but as this is a rapidly advancing field, the authors do not recommend a specific software package. At NOAA, SfM software packages will need to meet NOAA's IT security requirements and be approved for use by NOAA IT staff. For more information, please see NOAA's Information Technology Security Policy webpage (NOAA 2003).

2.3.2 Computing Hardware

While acquisition of imagery for SfM processing can be inexpensive, the processing time after collection and processing hardware can be a significant portion of the cost of a survey. This section is intended to give a high level view of what to consider when purchasing hardware and software for SfM processing.

2.3.2.1 Local computer

A powerful workstation is essential for processing large SfM projects with a significant number of images. Most threshold values are intentionally omitted in this section because this metric is very dependent on rapidly changing image resolutions and computing power. At this point in time (August 2019), the authors deem "a significant number of images" to be 500+, and a powerful central processing unit (CPU) to be have at least eight cores and 64 gigabytes of RAM. It is advisable to choose the desired SfM software package first, then consult the software manufacturer or forums for recommendations on hardware configurations. For example, some software packages are optimized to utilize the graphics processing unit (GPU) more than others.

2.3.2.2 Cloud computing

Cloud computing or network computing can be leveraged in lieu of a workstation to process large projects more quickly or to process large projects that exceed the hardware limitations of workstations. Recommendations for setting up these types of processing workflows are beyond the scope of this document. However, at NOAA, cloud computing services are available (as of August 2019) through IBM, Amazon web services, Google cloud platform, Open Commons Consortium and Microsoft Azure. Please see NOAA's Big Data Project (NOAA 2019b) for the latest information, how to participate and other frequently asked questions.

sUAS image looking east along the shoreline of Buck Island, St. Croix.
Photo Credit: Oregon State University.

Chapter 3 Evaluating Mission Feasibility and Logistics

Every potential sUAS mission must be evaluated to ensure that it is safe, legal, and feasible, and uses the appropriate equipment to complete the mission safely and successfully. This chapter specifically explains the process, and some of the main logistical, legal and environmental considerations necessary for determining if bathymetric mapping using sUAS and SfM will have a high probability of success. Travel considerations unique to sUAS based missions are also described.

3.1 Legal Considerations and Requirements

3.1.1 Pilot Certification and Airspace Legality

For operations within the United States or its territories, sUAS operators must currently receive a Part 107 Remote Pilot Certification from the FAA or operate under a Certificate of Waiver or Authorization (COA) for airframes, including the payload, less than 55 pounds. This certification requires completing an application, online training and written exam (FAA 2019b). Operating rules for sUAS are set forth in Title 14, Part 107 of FAA regulations (FAA 2019a). The most current Part 107 rules may be found here: https://www.faa.gov/uas/commercial_operators/. Waivers may be requested from the FAA to deviate from certain operating rules, if the operations can be performed safely. Permitted rule deviations and waivers requests are available from here: https://www.faa.gov/uas/commercial_operators/part_107_waivers/. Operations in Class B, C, D and E airspace are allowed with the required waiver and Air Traffic Control (ATC) permission. Operations in Class G airspace are allowed without ATC permission. Airspace maps (Figure 3.1) are available from here: https://faa.maps.arcgis.com/apps/webappviewer/index. html?id=9c2e4406710048e19806ebf6a06754ad.

3.1.2 NOAA Privacy and Personally Identifying Information (PII) Requirements

Proposed sUAS operations for bathymetric mapping must address the NOAA sUAS Privacy Policy. This privacy policy was created on February 15, 2015, and it outlines how Federal sUAS Programs are required to handle personal identifying information (PII). NOAA is committed to ensuring that collection of PII from sUAS, and the subsequent use, retention, or dissemination of that information about individuals comply with the Constitution, and Federal law, regulations, and policies. The types of PII that sUAS may potentially acquire include, but are not limited to, residential

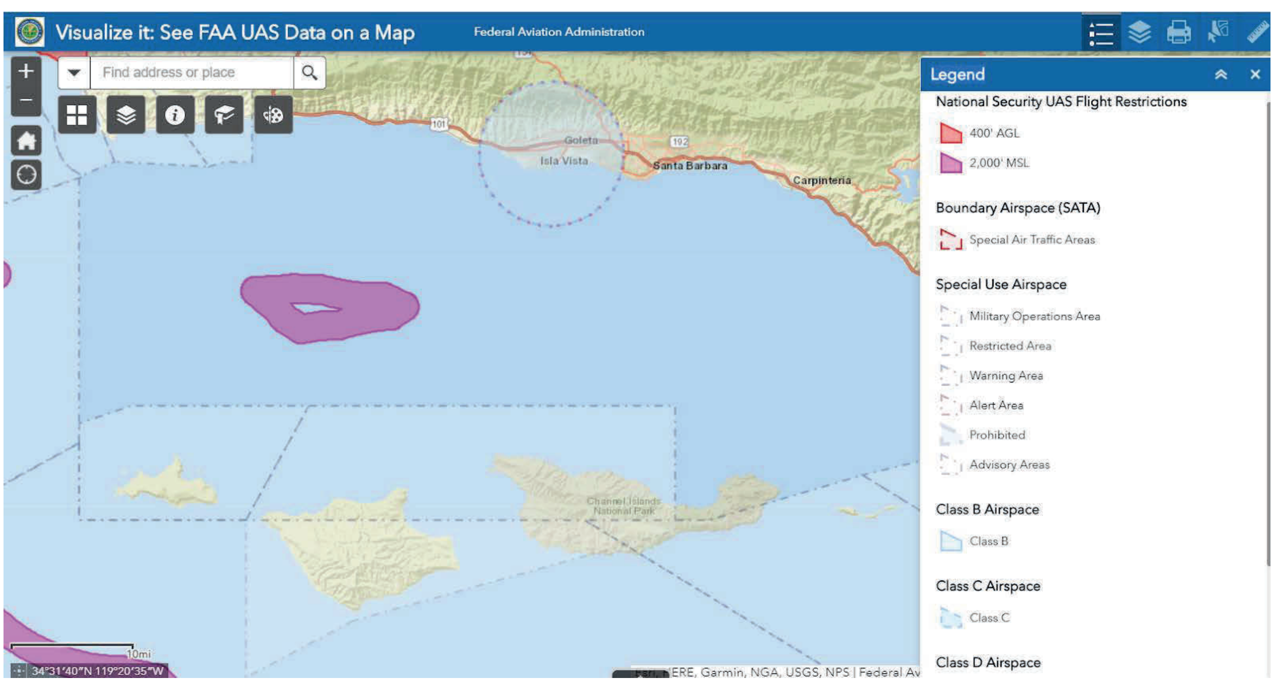


Figure 3.1. Map showing FAA flight restrictions for sUAS operations around Santa Cruz Island, CA. Operations on western Santa Cruz Island were in Class G airspace, but required permission by The Nature Conservancy and permits from NOAA's Channel Islands National Marine Sanctuary.

address locations, video or photographic images identifying individuals, vessel identification numbers, and images of residential locations and current tenancy. This policy applies to all NOAA activities that include the operation of sUAS, whether conducted by NOAA, a grantee, or a contractor. For more information about NOAA's sUAS privacy policy, please see https://www.cio.noaa.gov/itmanagement/pdfs/Signed_UAS_PrivacyPolicy.pdf.

3.1.3 NOAA Cyber Security and Information Technology Requirements

Proposed sUAS operations for bathymetric mapping must also address Federal Cyber Security and Information Technology Policies. This includes, but is not limited to Sec. 205 of the Cyber Security Information Sharing Act of 2015, OMB Circular A-130, NIST SP 800-37, and NAO 212-13 NOAA Information Technology Security Policy. For more information, please see NOAA's Cyber Security's Policies, Regulations and Laws webpage: https://www.csp.noaa.gov/policies/

3.1.4 Permitting and NOAA Environmental Compliance

Proposed sUAS operations for bathymetric mapping must also undergo all necessary environmental compliance reviews, consultations, and permitting requirements, including, but not limited to, the National Environmental Policy Act (NEPA), 42 U.S.C. §4321 et. seq; NOAA Administrative Order 216-6A; Endangered Species Act, 16 U.S.C. § 1531 et seq., and Marine Mammal Protection Act, 16 U.S.C. § 1361 et seq. If applicable, the statement of work should address any required mitigation measures, best management practices, monitoring, terms and conditions, or other environmental compliance requirements. More information, training, and advice about NOAA's compliance with NEPA requirements is available from here: https://www.nepa.noaa.gov/

3.1.5 Other NOAA Specific Requirements

For any sUAS flight, it is also necessary to abide by any organization specific requirements that may exist. Organizational requirements for NOAA are established by the Office of Marine and Aviation Operations (OMAO) Unmanned Aircraft Systems (UAS) Program (NOAA 2019c) and Aircraft Operations Center (AOC) (NOAA 2019a). The authors recognize that these organization specific requirements are likely to change as technology evolves. The latest NOAA specific requirements are outlined in NOAA AOC's Policy 220-1-5 and NOAA's UAS Handbook, which are available from here:

NOAA AOC Policy 220-1-5:
https://www.omao.noaa.gov/sites/default/files/documents/220-1-5%20AOC%20UAS%20Policy.pdf

NOAA UAS Handbook:
https://www.omao.noaa.gov/sites/default/files/documents/NOAA%20UAS%20Handbook.pdf

3.2 Logistical Considerations

This section discusses key factors that should be considered when evaluating sites for sUAS bathymetric operations. These considerations include, but are not limited to travel logistics, flight logistics and site accessibility and environmental conditions. Local knowledge of potential project locations is extremely helpful when conducting this evaluation. Collaborating closely with local partners is strongly recommended for developing sUAS bathymetric operations. In St. Croix and Santa Cruz Island, the expertise, connections and logistical support from local partners was essential for identifying appropriate sites before deployment (Figure 3.2) and critical to the overall success of both sUAS bathymetric operations. This report focuses on UAS operations in the United States, but local regulations should be followed if operating in other countries/territories.

3.2.1 Travel Logistics

Travel logistics associated with sUAS operations will depend on the size of the sUAS and capacity of the sUAS batteries. Some sUAS platforms may be carried on commercial airlines, while others may need to be shipped to the field site. Most commercial airlines restrict baggage weights to <70 lbs, with bags >70 and <100 lbs subject to oversize charges. Baggage with total outer dimensions (length + width + height) measuring more than 115 inches (292 cm) are not currently accepted on passenger airlines, checked or otherwise. sUAS platforms heavier and larger than these maximum weights and dimensions will need to be shipped via a commercial shipping company. Battery sizes and quantities will also be an important consideration when choosing to transport sUAS platforms (refer to Chapter 2, Section 2.1.1.6 for additional battery requirements). sUAS pilots should check with the FAA (https://www.faa.gov/hazmat/packsafe) and their individual airline for specific restrictions and requirements before traveling.

3.2.2 Flight Logistics

Several flight logistics should be considered when planning sUAS missions. Suitable project locations and potential takeoff and landing areas should be identified beforehand

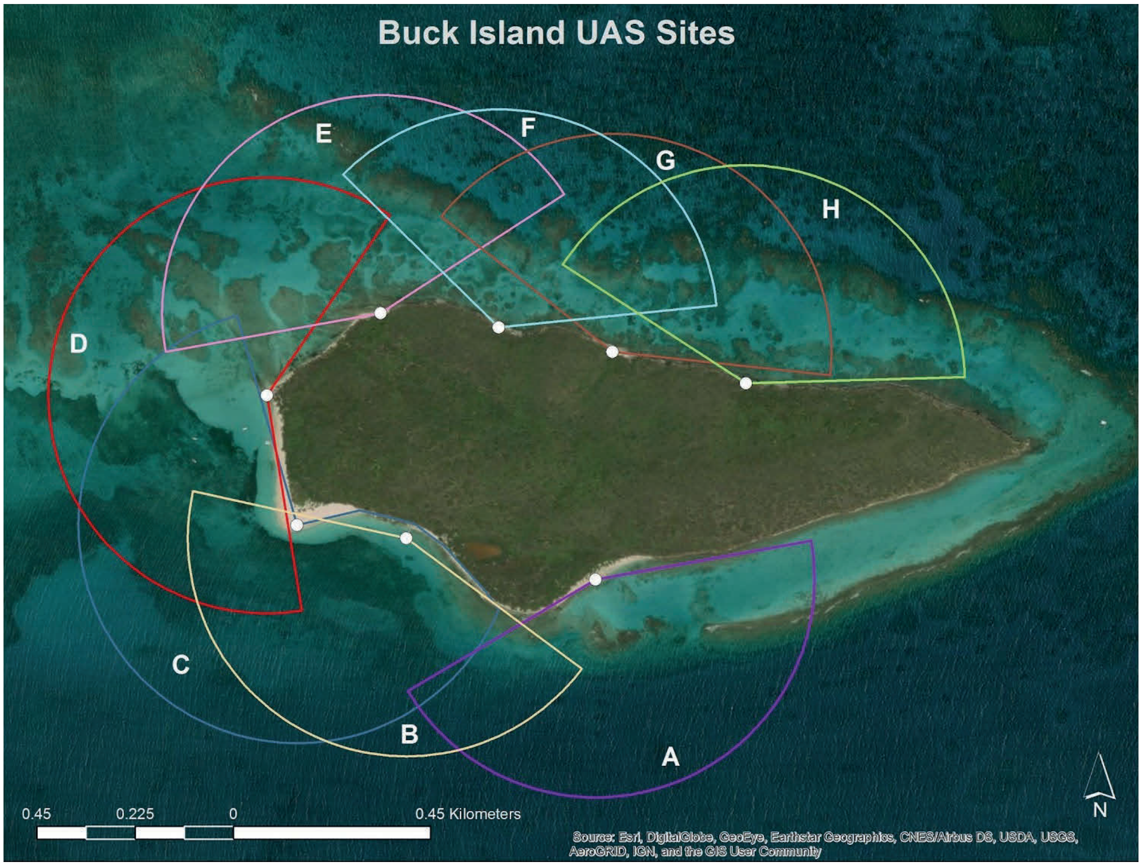


Figure 3.2. Map showing pre-planned project areas, and takeoff and landing locations around Buck Island, St. Croix. These potentially suitable sites were selected before going into the field. While in the field, this map was used to choose operational areas each day, depending on a variety of factors and conditions.

(refer to Chapter 2, Section 2.1.1 for more discussion on these factors). Primary considerations should include: (1) site safety and accessibility, and (2) weight and volume of gear. The ease of access to a field site will be determined by the mode of transportation to and from the site, and the weight and volume of equipment needed for the mission. Equipment should include enough batteries (and spare batteries) to complete the mission or provide a reliable method to recharge batteries while in the field (e.g., generator, solar panels or inverter for car or boat). Several other environmental conditions will also influence the choice of project locations, the timing of the field work and the selection of flight parameters (e.g., flying altitude). Figure 3.2 depicts a preliminary site plan performed for Buck Island, St. Croix. Each shape is an estimate for the expected line of sight at each location. These environmental considerations are discussed in detail in the next section.

3.3 Environmental Considerations

A range of environmental conditions may impact sUAS operations, including the sUAS's ability to safely fly the mission and to acquire imagery that meets specifications for SfM bathymetric mapping. Key environmental conditions and their potential impact are listed and discussed below. This list provides guidelines and is not exhaustive. Before flying, any unique environmental conditions or operational constraints should be considered on a site-specific basis.

3.3.1 Water Clarity

Water clarity will have a major impact on the quality of imagery that a sUAS platform acquires, and subsequently, the quality of the bathymetric products created using SfM. Water clarity affects how deep you can see into the water. If the seafloor is not clearly visible in the imagery, bathymetric SfM will not succeed for that area. The clarity of water is influenced by the amount of organic (e.g., algae) and dissolved inorganic (e.g., silt) matter that is present in the water column. The amount of suspended organic and inorganic matter affects the maximum depths that can be mapped using sUAS and SfM. When planning a sUAS mission, sUAS imagery acquisitions should be timed, to the extent possible, to coincide with optimal water clarity conditions. This planning includes flying before rain events, after rain events once water clarity improves, seasonally when turbidity is low, and seasonally when winds are calm and sea states are low.

For this project, sUAS flights were timed to coincide with the best water clarity conditions in each project area. In St. Croix, sUAS flights took place in March/April, before the hurricane season began. In Santa Cruz Island, sUAS flights were conducted in December, before the rainy season and when kelp canopy cover was at its minimum. These two sites were chosen because they had very different water clarity conditions. The SfM products from these sites were compared to better understand the impacts of varying water clarity on bathymetric mapping using sUAS and SfM, and to identify thresholds where turbidity causes SfM to fail to derive depths. Figure 3.3 is an aerial image captured by the team over Santa Cruz Island which exhibited poor water clarity within the inner surf zone. These regions were unable to be mapped using SfM, and produced a gap in the data products.

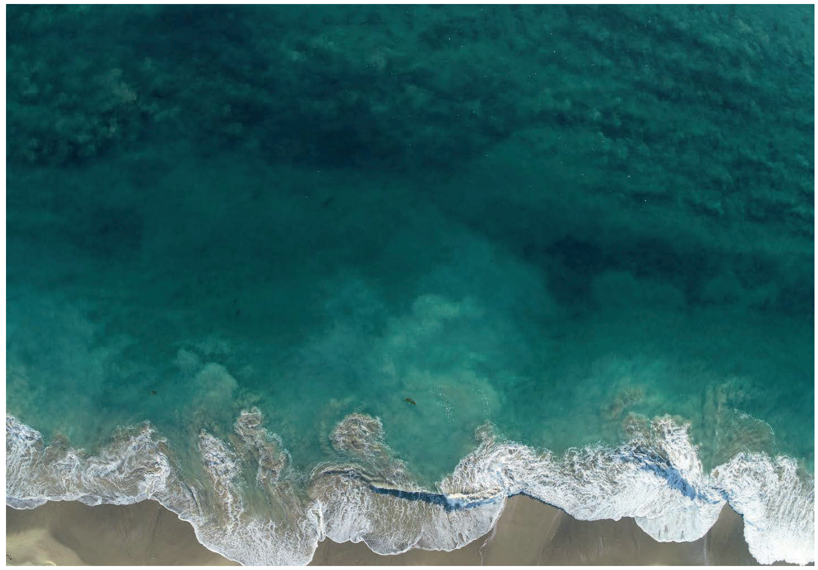


Figure 3.3. Suspended sediment and high water turbidity hinder visibility of the seafloor texture, resulting in greatly degraded, and sometimes spurious, SfM results. This image from Santa Cruz Island, demonstrates how plumes of sediment near the active breaking waves at the bottom of the image propagate offshore and significantly degrade water clarity.

3.3.2 Bottom texture

Bottom texture affects the ability of SfM to match and align overlapping images taken by the sUAS. Figure 3.4 shows examples of an image from St. Croix, which exhibits a region of high texture over the coral reef and low texture on the sandy bottom. SfM is most successful in locations with high bottom texture, and fixed non-moving bottom features. SfM will fail to derive a depth solution in areas with low bottom texture, in areas that lack discrete bottom features (e.g., bare sand or mud), or in areas where waves cause the biological cover (e.g., seagrass or macroalgae) on the seafloor to move. In these situations, SfM is unable to match and correctly align overlapping images, and subsequently solve for the relative structure and absolute depth of the seafloor. When planning a sUAS mission, the amount of imagery acquired over featureless seafloor areas should be minimized (to the extent possible). Methods to improve depth estimation in these regions is an area of active research, and are discussed in detail in Chapter 7.

Figure 3.4. Example of benthic features with high bottom texture (upper-left of the photo) and low bottom texture (bottom-right of the photo) in St. Croix. Higher amounts of bottom texture are critical for SfM to match and align images, and map seafloor depths. SfM will create inaccurate depths over geographic locations that are featureless and have low bottom texture.

3.3.3 Wave Conditions

Wave conditions will also have a major impact on the quality of imagery that a sUAS platform acquires, and therefore, the quality of the bathymetric products created using SfM. The quality of the images is degraded by waves because they alter the optical path of light in a manner which is unknown without precise knowledge of the 3D sea-surface, which is currently unattainable. The waves also refract and refocus sunlight through waves, causing visible light patterns on the seafloor to change (Figure 3.5; Casella et al. 2017). These changing patterns are known as caustics. Caustics can be removed through different image processing approaches (e.g., Chirayath and Earle 2016, Dietrich 2017), but it is preferred to avoid caustics during flight to the extent possible. When planning missions, sUAS imagery acquisitions should be conducted during the calmest conditions possible. This planning includes flying when waves are the smallest seasonally. Impacts from waves can also be mitigated by choosing protected and unprotected project locations, so that sites can be prioritized, and the calmest sites flown based on real-time weather and wave conditions. Predicting the calmness of a site involves consulting predicted weather forecasts, and observing how different wind angles affect the fetch for each location.

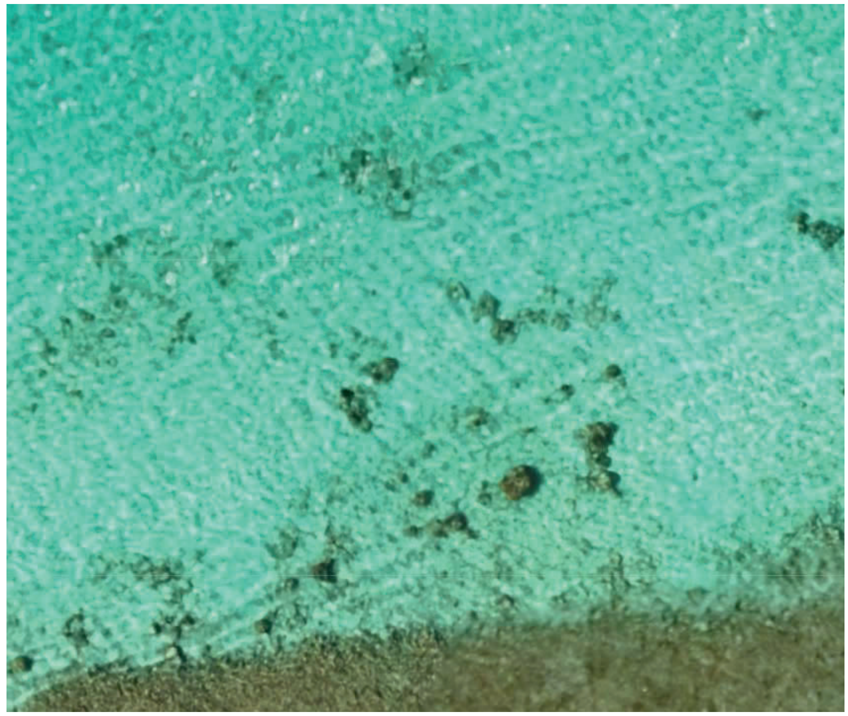


Figure 3.5. Example of caustic patterns on the seafloor offshore of St. Croix. Changing light patterns on the seafloor (as seen above) can reduce the ability of SfM to match and align sequentially acquired images and accurately map depths.

3.3.4 Regions of Active Wave Breaking

In addition to caustics, regions where waves are actively breaking will also have a major impact on the quality of imagery acquired by a sUAS platform, and therefore, the quality of the bathymetric products created using SfM. The quality of the images is degraded for two reasons. First, the white water and foam caused by breaking waves obscures features on the seafloor. Second, the location of the foam patterns in the white water moves, causing areas on the seafloor to be visible in some images, but not in others. Figure 3.6 shows examples of breaking waves offshore of Santa Cruz Island and St. Croix. These two issues cause SfM to fail to efficiently match and align images properly and therefore, map seafloor depths. As mentioned above, when planning a sUAS mission, imagery acquisitions should be conducted (to the extent possible) during the calmest conditions possible. This planning includes flying when waves are the smallest seasonally, and adjusting flying locations based on real time weather and wave conditions.

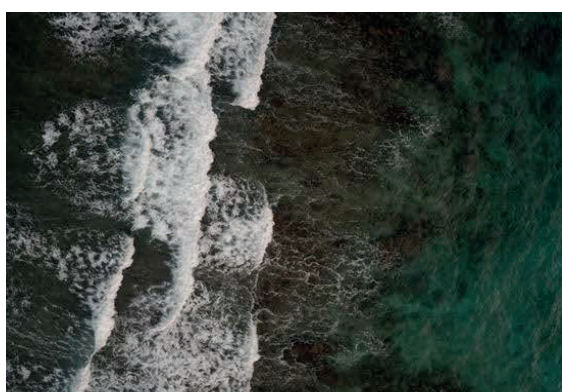


Figure 3.6. Example of whitewater in Santa Cruz Island (top) and St. Croix (bottom). Breaking waves and whitewater (as seen in these images) obscure the seafloor, reducing the ability of SfM to match and align images and accurately map depths.

3.3.5 Tidal Dependent Features

Water level changes from tides should be considered when performing sUAS bathymetric operations, especially in regions with large tidal ranges. Figure 3.7 shows tidally emergent coral reefs offshore of St. Croix. Tidal measurements should be considered to enable vertical correction of SfM derived depths, and thereby maximize the utility of the imagery acquired. For example, acquiring sUAS imagery when tides and water levels are at their maximum is preferred for delineating shorelines. However for nautical charting, the optimal tidal window is when water height is at its lowest level to identify least depths and dangers to navigation. A large tidal range could be beneficial if a portion of the area of interest (AOI) can be surveyed when it is above the waterline, and refraction and wave induced errors are non-existent. Other environmental (e.g., weather, solar elevation) and/or logistical (e.g., time, funding) considerations may take precedence when planning sUAS imagery acquisitions.

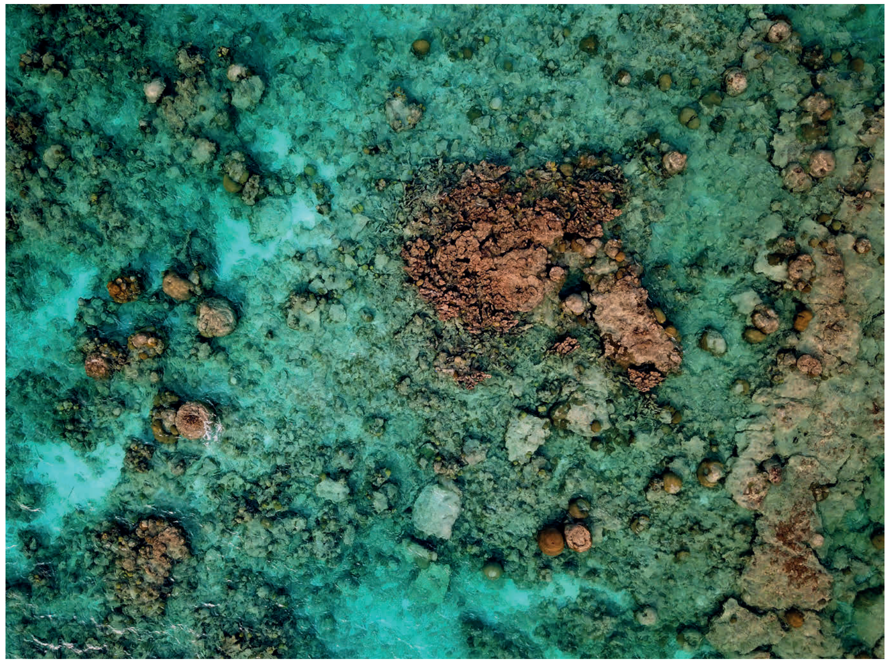


Figure 3.7. Example of tidally emergent features offshore of St. Croix. Tides should be considered during planning to maximize the utility of the sUAS imagery acquired for SfM bathymetric processing.

3.3.6 Wind Conditions

Wind conditions will have a major impact on sUAS operations. These impacts include affecting the quality of the sUAS imagery, the quality of the bathymetric products created using SfM, and the sUAS pilot's ability to safely fly the mission. Wind conditions in particular may have the largest impact on sUAS missions, including both prevailing wind speed and direction. Some small sUAS cannot operate in wind speeds greater than 20 knots. Larger sUAS may be able to operate in these conditions, but their battery life and flight times may be reduced (Joyce et al. 2019). Wind direction is important to consider because some sites may be protected on certain days or certain seasons, but exposed during other days or seasons.

Wind conditions will also have a major impact on image quality. Wind conditions affect sUAS image quality because wind driven waves obscure the seafloor and refract and refocus sunlight. Poor image quality will reduce the ability of SfM to efficiently match and align images properly, affecting the quality of the SfM bathymetric surface. When planning a sUAS mission, sUAS imagery acquisitions should be conducted, to the extent possible, during the calmest conditions, both daily and seasonally. Ideally, wind speed should be less than 10 knots (Joyce et al. 2019). Impacts can also be mitigated by choosing protected and unprotected project locations, so that the calmest sites can be flown based on real-time weather and wind conditions. In St. Croix, sUAS operations were conducted outside of hurricane season (June-September) and when wind speeds were at their lowest out of the East (Figure 3.8). Sites on the east side of St. Croix and Buck Island, which were more exposed to these easterly winds, were flown opportunistically based on daily forecasts.

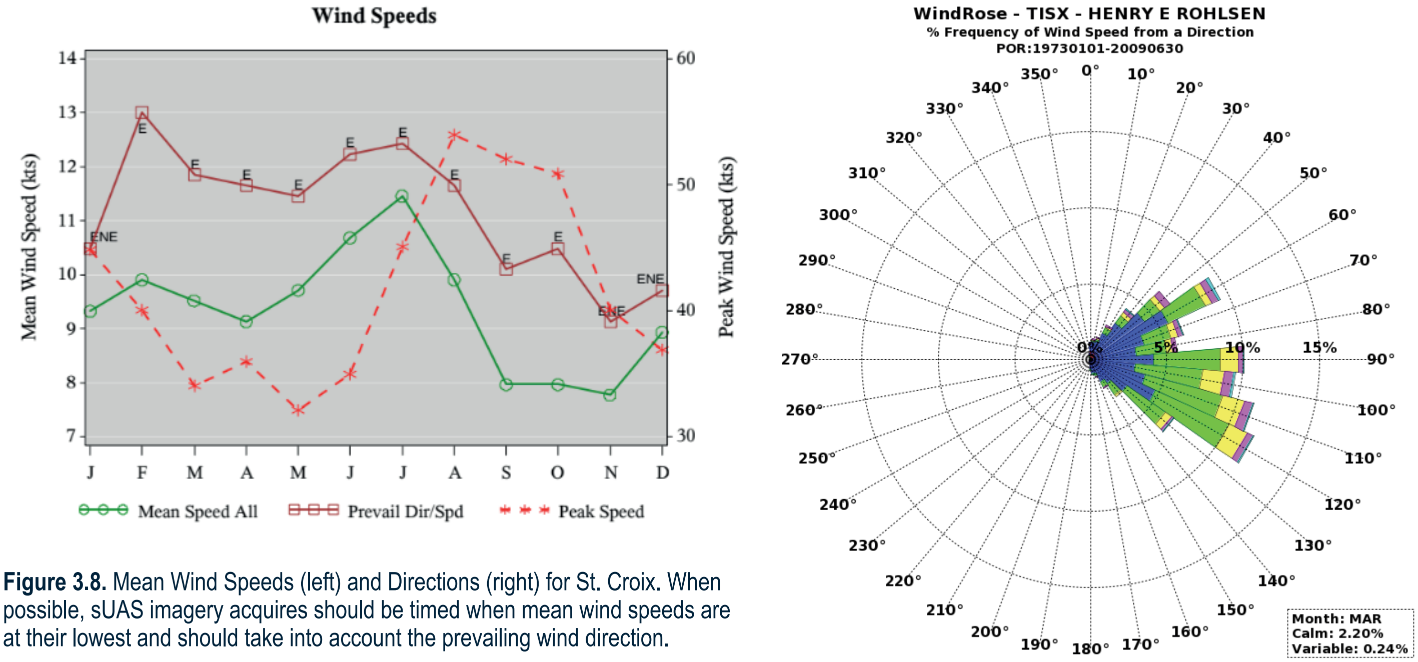
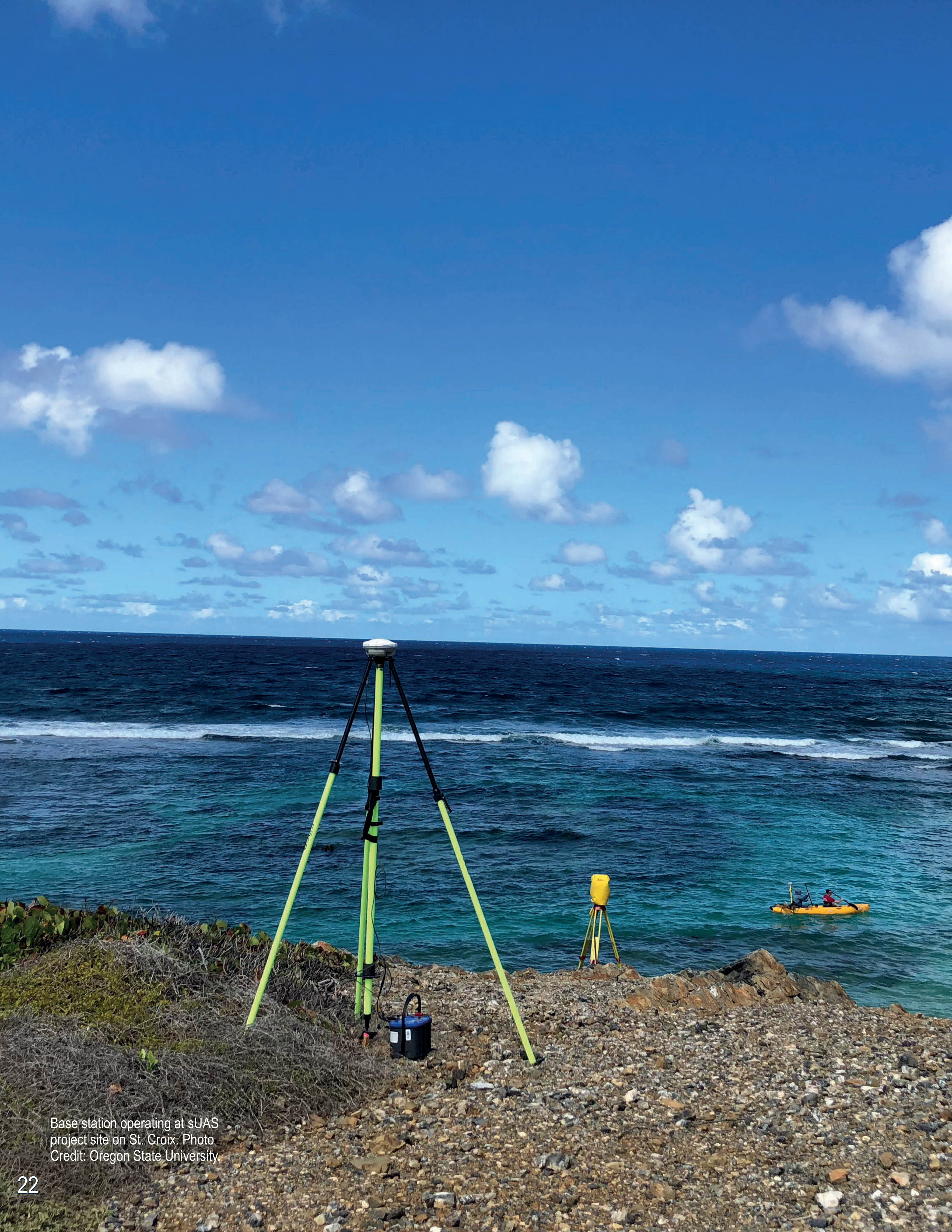


Figure 3.8. Mean Wind Speeds (left) and Directions (right) for St. Croix. When possible, sUAS imagery acquires should be timed when mean wind speeds are at their lowest and should take into account the prevailing wind direction.

3.3.7 Terrestrial and Marine Animal Disturbance

sUAS flights have the potential to disturb terrestrial and marine animals, most notably marine birds. Studies indicate that flying sUAS at higher altitudes tends to reduce disruptive effects for marine birds (McEvoy et al. 2016, Rummler et al. 2015, Johnston 2019). The sUAS platform design may also be important. Particular sUAS designs (e.g., delta-wing sUAS) have been documented to elicit stronger reactions from marine birds than others (McEvoy et al. 2016). For other terrestrial and marine animals, their response to sUASs are largely influenced by flight altitude and life history, with breeding colonies most affected by sUAS presence (Pomeroy et al. 2015). When planning a sUAS mission, the site-specific permitting process often requires outlining strategies to mitigate potential disturbances of marine and terrestrial animals. These strategies can include, but are not limited to, carefully selecting suitable takeoff and landing locations, altering flight times during the day and/or time of year and changing flight altitudes to minimize potential interactions with terrestrial and marine animals (Junda et al. 2015, Mulero-Pázmány et al. 2017; Figure 3.9). There are tools to help with this planning, including U.S. Fish and Wildlife Service Information for Planning and Consultation (IPaC) website: https://ecos.fws.gov/ipac/location/index. This website provides information about what animals may be present in the sUAS operational area, and therefore what mitigation strategies may be considered and needed.

Figure 3.9. sUAS image of sea turtle offshore of St. Croix. sUAS flights have the potential to disturb terrestrial or marine animals, but there are strategies to mitigate potential interactions.



Base station operating at sUAS project site on St. Croix. Photo Credit: Oregon State University.

Chapter 4 Planning and Executing the Mission

This chapter aims to highlight the considerations and decisions that need to be made when planning and executing sUAS flights for a bathymetric SfM mapping. These considerations and decisions include calibrating the camera, defining the AOI, selecting appropriate takeoff and landing sites, choosing flight line overlap, selecting flight altitudes, minimizing water surface reflections, setting up base stations, occupying ground control points and accounting for instantaneous water levels, adjusting to real-time conditions and stewarding data.

4.1 Camera Pre-calibration

Topographic SfM processing is often performed with an unknown interior orientation, which is computed using a self-calibration (i.e., using image tie points, camera positions, and GCPs to solve the interior orientation). Studies have shown that for a non-metric camera, this self-calibration can be the most accurate method of processing SfM data (Griffiths and Burningham 2019). However, when performing bathymetric SfM, the results from this project suggest that performing a self-calibration over a stable topographic site, saving the self-calibration results, and using that calibration is more accurate and reliable than performing a self-calibration over the bathymetric survey site. This is likely due to the large uncertainty in image tie point positions that is induced by refraction and waves at the air water interface causing propagation of error into the camera calibration computation. If possible, it is recommended to perform this pre-calibration, but it should be noted that the authors were still able to achieve accurate results using a camera self-calibration when GCPs on land were used, and there were significant overlapping images of features on land.

4.2 Area of Interest Size/Level of Effort

When selecting an AOI, characteristics such as the size and shape of the AOI, and obstruction within it must be considered to ensure line of sight between the sUAS and the pilot. sUAS coastal mapping operations may often be conducted in estuaries, bays, and along coastlines where cliffs, outcroppings, or bends in the shoreline limit line of site operations. See also Section 4.3.

SfM-derived topography generally has larger errors along the outer edges of the acquired imagery (Slocum and Parrish 2017). It is therefore recommended to increase the AOI size to minimize edge effects, wherein there are one or two flight lines beyond the edge of the region where accurate data is desired. Once an AOI has been selected it is important to consider how many batteries are needed in order to map the entire site. This is often estimated by the mission planning app for the sUAS, though the expected number of batteries required may be underestimated by the app. Prior experience using the drone in varying wind conditions should be taken into account when estimating the actual number of batteries required.

An additional consideration for each AOI, is whether or not the AOI is in airspace that is legal based on sUAS regulations, and enabled via the sUAS software. Some sUAS are designed to restrict or forbid operation within the lateral bounds of certain airspace and require digital, internet-based authorization from the sUAS vendor in order to operate at all.

4.3 Takeoff/Landing Location

Takeoff and landing zones for the sUAS need to be both safe, and in a location that retains the line of sight to the sUAS. A safe landing zone will vary based on the requirements of each sUAS (Chapter 2, Section 2.1.1), but generally provide a large, flat landing area free from obstructions. Line of sight between the sUAS and the pilot is important to maintain as it ensures a high quality data link between the sUAS and the pilot for control. Visible obstructions between the pilot and the aircraft will quickly degrade the control link to the aircraft unless special provisions have been made for non-line of sight operations (e.g., via satellite or cellular data link communications).

A survey of a large AOI may benefit from multiple takeoff/landing sites in order to maximize line of sight to the sUAS, while also reducing the amount of battery required to map an area by minimizing the distance the sUAS needs to travel while not mapping. For example, a takeoff and landing zone which is centrally located for each mission will be more battery efficient than a takeoff location that is 500 meters away. When selecting a takeoff and landing size, consider that propwash from the sUAS may kick up sand or other debris, so a stable landing platform or tarp may be necessary.

When considering potential takeoff and landing sites, one should consider the substrate or platform that the sUAS is capable of landing on. For example, a sandy beach may kick up significant sand when a multirotor is landing, which could damage the camera or the sUAS hardware. In cases like this, a stable landing platform should be used to minimize the effect of propwash on unstable terrain. Another potential takeoff/landing site could be from a ship, which add additional challenges and may not be possible for specific sUAS. Aircraft that use electronic magnetic compasses may be adversely affected, and refuse to fly, if near metallic structures on the deck of a ship. Some aircraft are unable to calibrate their onboard flight inertial measurement unit (IMU) when onboard a ship, which is not stable in pitch, roll, heading, and heave. If utilizing a ship as the takeoff/landing area, consider positioning the ship to minimize sUAS transit time to and from flight lines, thereby increasing battery and data acquisition efficiency. However, most sUAS have a "return-to-home" feature, which automatically navigates the sUAS back to the takeoff/landing site, and attempts to land the sUAS automatically. If a ship is used, and is moved from the takeoff and landing location, the sUAS could potentially "return-to-home", and land in the water. The "return-to-home" feature can often be disabled in software, if this could be an issue.

4.4 Flight Line Overlap/Sidelap

When performing SfM surveys, overlap and sidelap refers to how much each sequential image overlaps the previous image, and the image on an adjacent flight line. Results from the project team suggest that data acquired with 66% or lower overlap/sidelap yields poor and inconsistent results when computing elevations. Therefore, the authors recommend using at least 75% overlap and sidelap when performing bathymetric SfM surveys. This amount of overlap and sidelap ensures that each point on the seafloor is imaged from a variety of look angles. Note that all of the sUAS flights were performed using parallel flight lines, with no perpendicular flight lines. Perpendicular flightlines may strengthen the photogrammetric network and reduce the amount of overlap required. Additionally, if the desired data product is only an orthophoto without associated elevation values, a lower sidelap/overlap may be feasible, though the horizontal error in the orthophoto will likely be increased.

4.5 Altitude

The flight altitude of the sUAS dictates the ground sampling distance (GSD) and SfM derived point density, and directly impacts the number of batteries and flight time required to complete a mission over an AOI. In traditional SfM over varying topography, a lower flying altitude will generate a higher resolution point cloud that is capable of resolving smaller features with an increased accuracy, when compared to higher altitude flights. With bathymetric SfM, however, it is recommended that the flying height should be set higher, often at the maximum altitude. This higher flying height reduces the effect of wave induced refraction, and increases the probability that there will be some texture visible in the image frame.

For example, consider a case where the AOI contains high texture submerged aquatic vegetation and coral reef, separated by a 30 m wide channel with a sandy, textureless bottom. Imagery from a low flying sUAS will capture multiple images with only the featureless channel, which preclude and SfM solution (Figure 4.1, right). The imagery from either side of the channel will have no correspondences linking the two regions, which will result in poor processing results, and sometimes errors in the SfM model. In this case, a higher flying sUAS will be able to image both sides of the channel at once, creating correspondences between images on either side of the channel (Figure 4.1, left). While

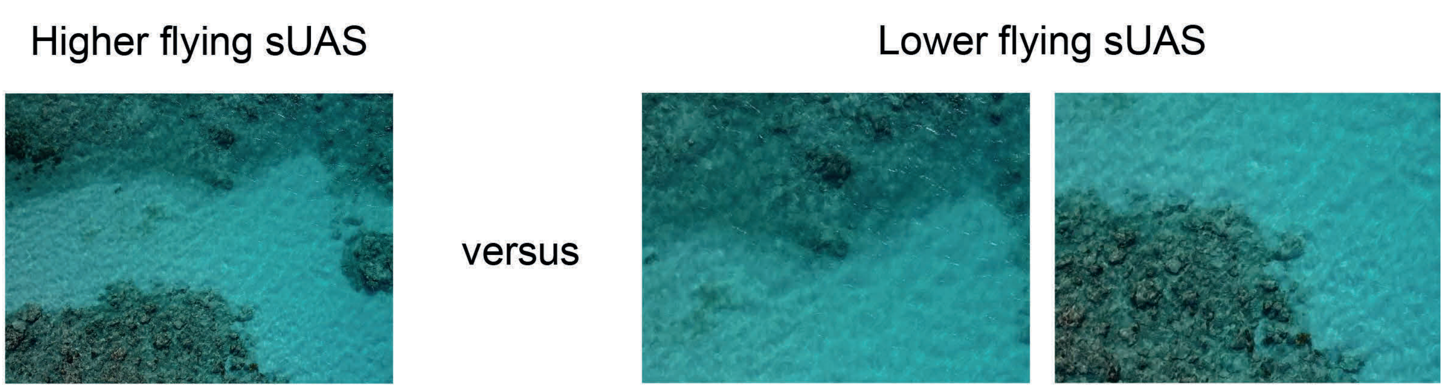


Figure 4.1. Comparison of low flying sUAS (left) over the same area as a high flying sUAS (right).

this example is a very extreme case, consider that this can happen on a smaller scale, with small patches of sand or other featureless regions. These areas will greatly reduce the photogrammetric network geometry, and quality of the resultant data products.

4.6 Water Surface Reflections

Imaging the seafloor is often hindered by reflections of light off of the surface of the water. Light that is reflected directly from the sun, often called specular solar reflections or glint, is very bright and often yields patches of oversaturated imagery. Light from the rest of the sky and clouds is not as bright, though it can still mask the texture of the seafloor and negatively affect SfM processing. Each of these two types of reflected light and methods to reduce their affect are described in this section.

4.6.1 Specular Reflections

Specular reflections, or reflections directly from the sun, overexpose the image and hinder observation of seafloor texture by oversaturating the image sensor, as shown in Figure 4.2. If the seafloor is not visible in the imagery, the SfM algorithms will be unable to map these areas.

To minimize specular reflection, one method is to fly when the solar elevation is low enough to not induce glare in the camera field of view. The time of day when specular solar reflections will be an issue is a simple computation as a function of the field of view of the camera and the solar elevation. Specular solar reflections can also be minimized by conducting flights earlier or later in the day, when the solar elevation is lower on the horizon. However, while early morning or late evening flights will minimize specular reflections in the imagery, the solar illumination may be so low at those times as to drastically reduce image quality. Additionally, depending on the structure of the scene being imaged, the shadows will change rapidly which can also reduce the quality of the SfM processing. The optimal data collection window of time will vary depending on the latitude of the field site, time of year, and weather. Test flights of the AOI during various times of day and evaluation of the resulting imagery are recommended, if possible, to determine how to best balance minimizing solar elevation, maximizing solar illumination, and minimizing other weather or sea-state patterns which can vary based on time of day. In practice, however, this can induce a great limitation on when sUAS imagery can be acquired, which may conflict with other site considerations.

In order to maximize the amount of time when glare is not an issue, the camera should be oriented in a manner such that the wider portion of the image is facing away from the sun. Most sUAS camera sensors have a wider horizontal field of view than vertical field of view, and are mounted such that narrower, vertical field of view is oriented in the same way as the direction of travel. When flying sUAS missions with this camera configuration, it is recommended that flight lines be flown into and away from the sun. The importance of this is shown in Figure 4.3, where incorrectly oriented flight lines are hindered by specular reflections at the edge of the imagery. These specular reflections are avoided when the vertical field of view is oriented correctly. In practice, it may not be possible or ideal to always orient the flight lines into and away from the sun due to other site specific considerations (e.g., diamond shaped AOI, line of sight issues, etc.); however, orienting the sUAS in this manner will provide a longer time window in which to operate and acquire good, glare free imagery.

Figure 4.2. Specular reflections off of the water surface reduce the ability to image the seafloor, which in turn causes SfM to produce poor results. This image from St. Croix, depicts severe specular solar reflections on the left side of the image by the beach. Note how the submerged reef is unrecognizable due to specular reflections.

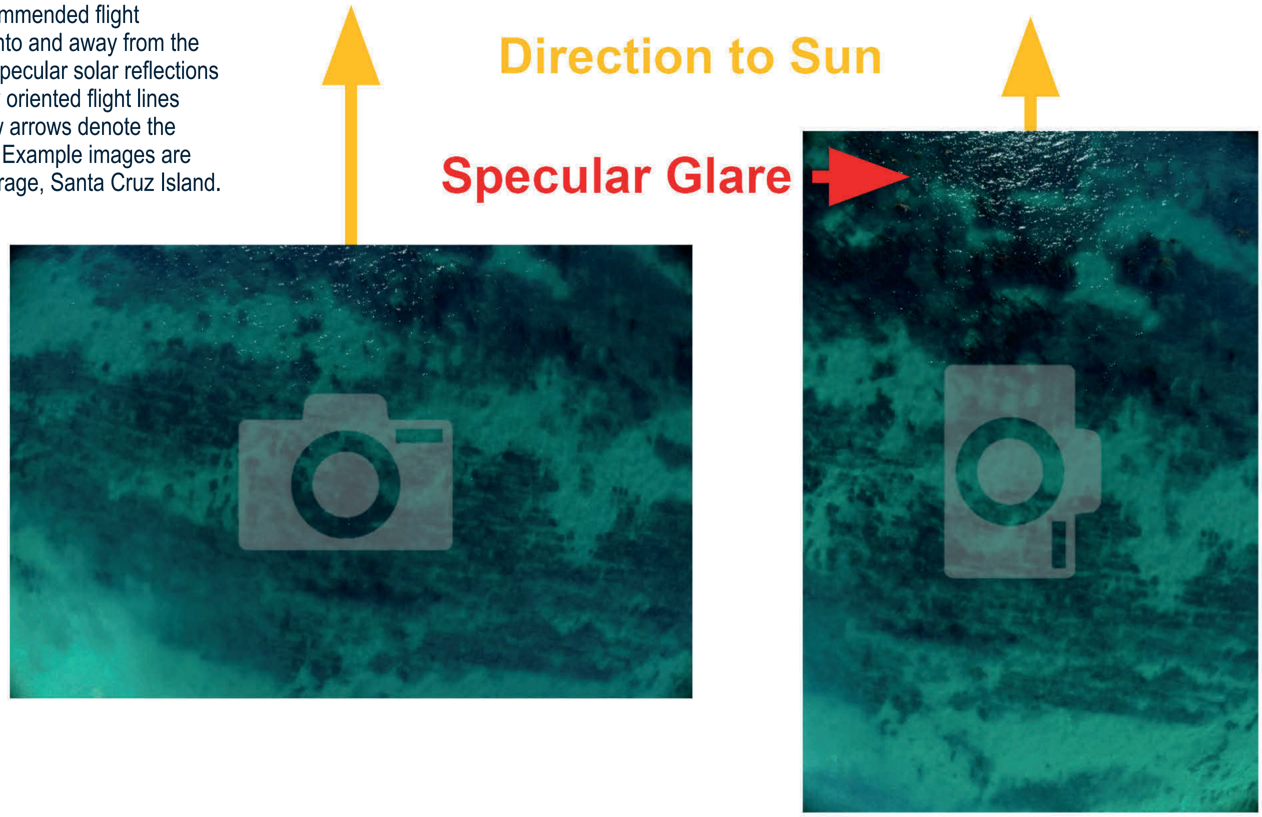


Figure 4.3. Recommended flight orientation (left) into and away from the sun to minimize specular solar reflections versus incorrectly oriented flight lines (right). The yellow arrows denote the direction of flight. Example images are from Pozo Anchorage, Santa Cruz Island.

A final method to reduce specular solar reflections is to tilt the camera off-nadir, and away from the sun. The flight lines and sUAS azimuth will then need to be oriented such that the camera is always pointed away from the reflections from the sun. While this method will reduce specular solar reflections, it should be used with caution as the effect of non-nadir imagery on SfM derived bathymetric data has not been studied thoroughly, and could potentially reduce the quality of the SfM results. Additionally, if the camera is pointed at a non-nadir angle that is too large, the reflection of light from the seafloor will be non-existent due to total internal reflection of the light rays. For water, this angle is approximately 49 degrees off nadir, and therefore a camera with a 40 degree field of view should never be tilted by more than 29 degrees.

4.6.2 Polarized Water Surface Reflections

Light reflected off of the water surface from the sky and clouds is partially, linearly polarized parallel to the water surface, and can be reduced by using a linear polarizing filter oriented perpendicular to the polarization of the light. Most digital camera manufacturers recommend using a circular polarizing filter (CPL), which is just a linear polarizing filter followed by a quarter wave plate. This recommendation by camera manufacturers is to ensure that the autofocus mechanism of the camera works correctly. The linear polarizing filter will reduce the amount of light into the sensor, and can cause unwanted effects in the images (e.g., higher noise if the ISO is increased, lower depth of field if the aperture is opened up, more motion blur if the shutter speed is decreased). However, when used in the correct orientation, the polarizing filter will work to reduce surface reflections, causing the water to appear more transparent in the image (Figure 4.4). This will increase the signal to noise level, therefore increasing the accuracy of the SfM data products.

However, the optimal orientation of a polarizing filter for nadir imagery is a function of the sUAS azimuth, the solar azimuth, the solar elevation, and potentially the cloud cover. The ambient light from the sky will be polarized with different angles and degrees of polarization, depending on where the sun is in the sky. Additionally, the percentage of reflected light from the water surface that is polarized is a function of the incident angle of the reflected light ray. A reflected light ray which is in the center of a nadir image, will not be polarized at all, due to it's small incident angle. If a polarizing filter is oriented vertically, the reflected light rays from the top and bottom of the image will be reduced, but the light rays from the sides will not be reduced. However, in some situations, due to either cloud cover or solar azimuth, the light rays

Figure 4.4 Correctly oriented circular polarizing filter (left) and no circular polarizing filter (right). Example from Santa Cruz Island.

reflected to the sides of the image may be polarized from the sky in a manner which already reduces the amount of reflected light from the water surface (e.g., vertically polarized light from the sky can not become horizontally polarized at the water surface). Hence, it is difficult to provide simple rule-of-thumb practices, which will apply in all conditions, as to when to use a polarizing filter on the sUAS's camera and how to orient the filter. The project team used a polarizing filter for some flights, and oriented it in an empirical manner, whereby the pilot oriented the polarizing filter by manually spinning the filter until it appeared to best reduce the sea surface reflections. However, if the reflection off of the water surface does not appear to be an issue, it is recommended that a polarizing filter not be used, as it can serve to decrease the signal to noise or induce image blur as the camera compensates for the reduction of photons to the sensor.

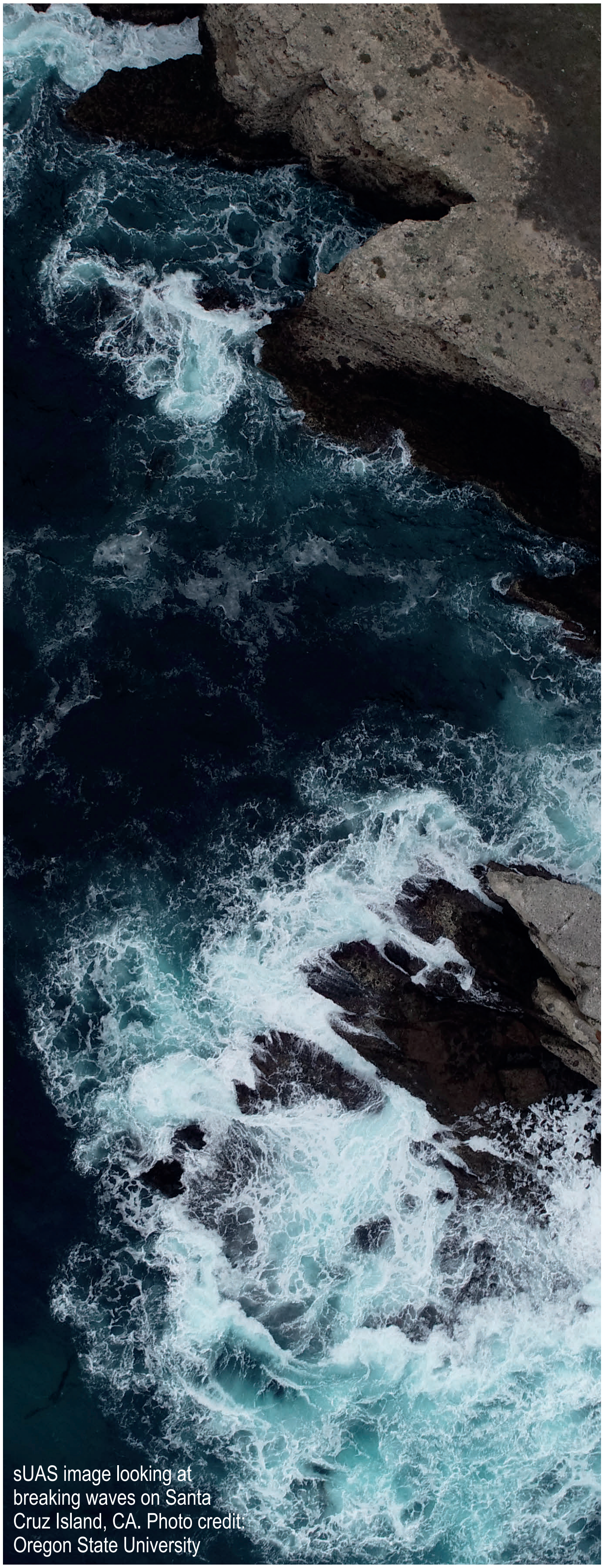
4.7 Base Stations

Accurate GNSS positioning using PPK or RTK positioning methods is reliant on a local base or cross-origin resource sharing (CORS) station to provide differential corrections to the sUAS (Wright and Battista 2018). Note that other methods may not need a base station, such as RTN/ virtual reference station services, PPP, PPP-RTK, total station-based positioning, or other future methods. If a base station is needed to support the mission, it is important to identify an appropriate location which provides unobstructed sky visibility to ensure a quality GNSS solution. In the Northern hemisphere, the visibility of the southern portion of the sky should be prioritized to maximize GNSS data quality.

4.8 Ground Control Point/Checkpoint Locations (Optional)

PPK and RTK sUAS systems are increasingly used to reduce the need for manually placed GCPs, thereby increasing productivity and survey efficiency. While these are optional, the use of control points will increase the accuracy of the data and can be used as validation checkpoints to assess SfM accuracy. If GCPs are used, their locations should be planned ahead of time and a survey plan developed to ensure accurate measurements in the field. One useful technique that can be leveraged is to deploy a GCP as the takeoff and landing location for the sUAS, which can be surveyed using the sUAS trajectory and used as a GCP without any additional hardware. A version of this technique is shown in Figure 4.5, where the 3DR Solo was centered on an elevated target as a takeoff platform. It is

Figure 4.5. If a GCP is used as the takeoff/landing site, it can be surveyed using the sUAS GNSS and utilized as a GCP without the need for additional survey hardware. Here, a 3DR Solo with PPK demonstrates this technique on St. Croix.


sUAS image looking at breaking waves on Santa Cruz Island, CA. Photo credit: Oregon State University

recommended that at least one GCP on land be used for bathymetric SfM processing. It should be noted that at best, SfM absolute accuracy can only be as accurate as your control, whether it be PPK onboard or control based on GCP targets on the ground. GCPs floating on the water surface, whether on a buoy or a vessel, that move during the sUAS image acquisition cannot be used in most current commercial SfM software.

4.9 Instantaneous Water Level

The current algorithms used for correcting bathymetric SfM data for refraction are dependent on an accurate measurement of the instantaneous water surface elevation in the same datum as the trajectory. This water surface elevation, or mesh, is used to determine how far underwater each point is, and therefore how refraction induced error is predicted. Prior to initializing a field survey, a method for determining the instantaneous water surface elevation should be selected. Possible methods include: 1) measuring the instantaneous water level with multiple GNSS measurements as the best estimate of the water line; 2) using a local tide gauge which has been referenced to a vertical datum; or 3) using the SfM point cloud to interpolate the water level height at the land-water interface. The method used to measure water level heights should provide sufficient temporal frequency to accurate interpolate instantaneous heights, particularity in regions with large tidal ranges or large sUAS operational areas.

4.10 Adjusting to Real-Time Conditions

When planning a mission, it is important to attempt to prepare contingency plans and make an effort to foresee and plan for a changing environment. While each field site will present unique challenges, a few potential issues are provided to serve as examples. When performing the field work for this project, the project team discussed potential issues like those outlined below before operating the airframe, so that all relevant parties were aware of their responsibilities should one of these situations occur. Additionally, the project team policy was that if any member had any concerns, the sUAS should be immediately landed so that those concerns could be discussed more thoroughly. Changing weather is a common consideration that should be monitored closely to ensure that the drone can still operate safely. Changing wind and incoming storms should be monitored closely, and agreed upon safety thresholds should not be exceeded.

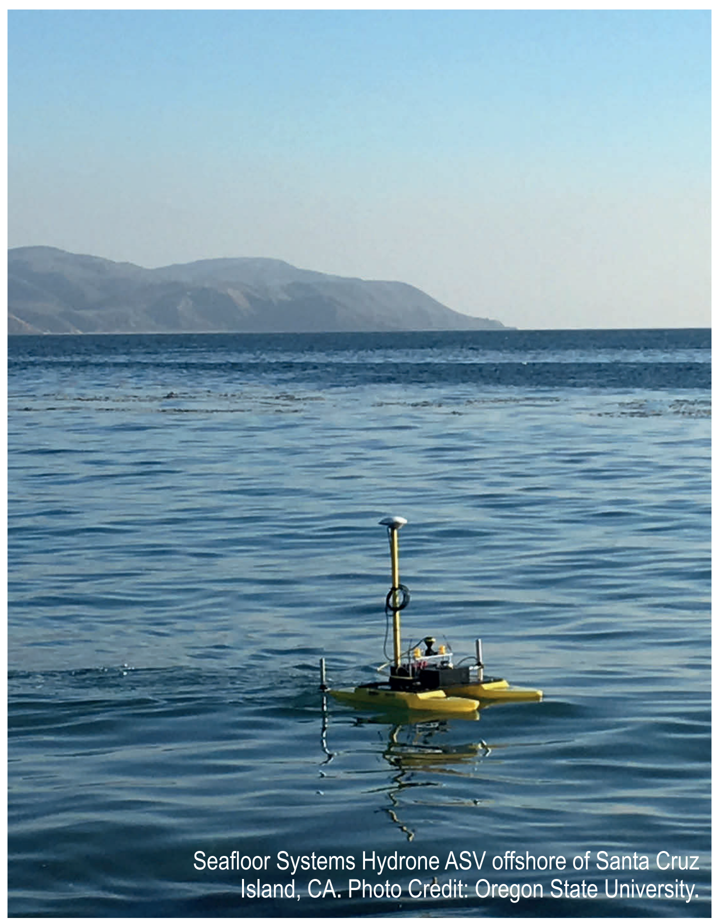
Non-participants near an AOI should always be considered to ensure safety and to mitigate potential PII concerns. Wildlife such as birds or other marine life that may be present within the AOI should be monitored closely to ensure the disturbance of wildlife is minimized. Birds should be monitored closely to ensure there are no collisions with the sUAS, potentially injuring a bird and/or destroying the sUAS. sUAS pilots should also be ready to adjust their flight plans in real-time if birds fly through the project area or other marine animals appear to be disturbed by the presence of the sUAS. Mitigation measures for wildlife may be outlined in the operating permits.

The pilot and any visual observers should always be cognizant of low-flying manned aircraft, and prepared to immediately take action to ensure the safety of all participants.

4.11 Data Stewardship and Organization

Documenting notes from the field, and organizing and backing-up data as it is acquired is an important piece of data stewardship that should not be overlooked. A procedure should be in place to back up data in a redundant, organized structure at the end of each day and minimize the potential for data to be lost (Appendix C). Additionally, a field book which is used to record informal data about the survey is useful for recording environmental conditions or any issues that arise during data acquisition. These notes can be essential when troubleshooting datasets in the office, which can be months/years later.

sUAS image of Buck Island, St. Croix, shoreline. Photo Credit: Oregon State University.



Seafloor Systems Hydrone ASV offshore of Santa Cruz Island, CA. Photo Credit: Oregon State University.

sUAS image showing Chase Simpson (Oregon State University) and
Tim Battista (NOAA NCCOS) collecting GCPs on Buck Island, St. Croix.
Photo Credit: Oregon State University.

Chapter 5 SfM Processing Workflow

This chapter describes the workflow for processing bathymetric SfM by accounting for refraction after using commercial software packages. Currently commercial software packages do not directly account for refraction at the air–water interface. Below are the high-level steps required:

1. Process the sUAS trajectory and compute the position of the nodal point of the camera for each image by interpolating the trajectory and applying lever arms.
2. Use SfM software to compute camera positions and orientations, camera interior calibration, sparse point cloud, dense point cloud, DSM, and orthophoto (note: the elevation values of these products are not corrected for refraction).
3. Filter the dense point cloud to remove points outliers.
4. Apply a refraction correction to elevation data of the dense point cloud and DSM to account for refraction at the air water interface.
5. Note that the workflow used by the project team was developed using Agisoft Metashape (v1.5.2) and a MATLAB-based refraction correction script, and may become outdated as new algorithms and methods are developed.

5.1 sUAS Trajectory

The trajectory of an sUAS refers to the time series of positions, and sometimes orientations, of the sUAS as a mission was flown. Using this information, the position of the nodal point of a camera when an image was acquired can be estimated, and is an essential part of photogrammetry and SfM processing. The orientation of the camera (e.g., roll, pitch, yaw) is less important in SfM processing, as the SfM algorithm and key point matching is effective at solving these parameters very accurately. This section describes the double difference PPK processing of a raw sUAS rinex file and the associated lever arms and interpolation required to compute the exterior orientation of each camera. There are many methods to estimate a trajectory, and the discussion and details are beyond the scope of this report. Readers interested in more detail on this subject can investigate: PPP GNSS processing, PPP-RTK processing (Pazlewski et al. 2018), and tightly/loosely coupled GNSS-INS Kalman filtered processing (Falco et al. 2017). Note that regardless of the method for computing the trajectory, it is essential that the datum, coordinate system,and realization of the trajectory is well documented and understood to reduce errors or confusion when working with the data products.

5.1.1 Trajectory processing

When using a GNSS system for positioning, the basic course/acquisition (C/A) code, augmented with WAAS, ranging accuracy will provide greater than 2 m uncertainty (95% CI) in positions. Note that some sUAS may use an extended kalman filter and incorporate the barometric and INS data with the code-ranging GNSS to achieve more accurate positioning. Higher accuracy systems will record the carrier phase measurements, and can leverage corrections and differencing methods to produce positions with less than 5 cm in positional accuracy. This can be done in real-time, via RTK systems, wherein a nearby GNSS base station sends corrections to the sUAS as the sUAS is flying. These corrections can be via a base station that is set up for the purpose of the survey, or it can be a permanent station maintained by another entity, such as a CORS station. Corrections from CORS stations are often provided via a state government, such as Oregon's (ORGN) or Florida's (FPRN) network. Note that these network corrections may perform poorly at some coastal sites due to the CORS network geometry, and the feasibility of each field site should be investigated prior to field operations. For most photogrammetric processing, an accurate trajectory is not required in real-time, so PPK processing algorithms can be utilized. PPK algorithms apply the corrections to the sUAS carrier phase measurements in a similar manner to RTK, but with increased accuracy due to: 1) the ability to process the trajectory data forward and backward, and 2) the availability of precise satellite positions and clock errors. If the carrier phase measurements are recorded while logging RTK data, the data can be post-processed with PPK algorithms in the same manner as would be possible if RTK corrections were not being performed. The main benefit of RTK is the confidence that data is being acquired with high accuracy in the field, and the high accuracy trajectory is available immediately in case quick processing is required immediately after a flight.

5.1.2 Camera Interpolation

Camera images are acquired at either a fixed time interval, or fixed spacing interval, and tagged with the time that the image was acquired. However, the image time may not exactly match the time that exists in the sUAS trajectory. In order to compute the position of the sUAS when the image was acquired, the position must be interpolated. The position of the sUAS is the most important, but the orientation and positional uncertainties are often also interpolated and input into the SfM software. For this project, the interpolation and computation of positions for each image was performed using custom MATLAB and python scripts, but it is expected that future commercial sUAS with PPK/RTK systems will have a more streamlined process.

The predicted uncertainty of the sUAS position is often computed for each point along the trajectory, which is useful when setting the stochastic model in SfM processing. Currently, GNSS PPK/RTK processing tends to overestimate the accuracy of a system. For example, the predicted uncertainty of an RTK position may be 3 mm, however prior experience may suggest the expected accuracy to be approximately 3 cm. In this instance, applying a scale factor of 10 to the uncertainties will yield better results in the SfM processing. In traditional least squares, the computed reference variance can be tested using the chi squared test to assess the validity of the stochastic model. Depending on the SfM software used, this may or may not be included as a check.

Once the position of the sUAS has been interpolated for each image, it is important to apply lever arms and any rotation offsets to compute the position of the camera nodal point. This process may already be integrated into the sUAS, or may need to be measured. It is recommended that users consult the manual for the specific sUAS that is being used. The project team computed/measured lever arms for each sUAS, and applied them using custom scripts to compute the position of the camera for each airframe.

5.2 SfM Processing

There are many SfM software packages, which all vary slightly in the user interfaces and algorithmic approaches, that can perform topographic and bathymetric mapping. While each algorithm is slightly different, the steps and workflow associated with SfM processing remains very similar. Previous studies have investigated the accuracy of some of the more popular commercial software packages (Schwind and Starek 2017). However, this section will not attempt to compare accuracies between different commercial products since these software packages are constantly improving and changing. In order to describe and demonstrate the general steps in the software, this section will include examples from Agisoft Metashape (previously Agisoft PhotoScan) as this is the software that was used by the research team for this project. Note that reference to this software does not imply an endorsement or recommendation by the authors, NOAA or the U.S. Federal government.

5.2.1 Image Input

The first step is to assess the quality of the imagery acquired, and remove any blurry or poorly exposed images. Additionally, if desired, the user can post-process the RGB imagery to adjust brightness, saturation, and white balance in a separate software. This step will likely only increase the aesthetic quality of the SfM data products, such as the orthophoto. Once the images are color corrected, with poor quality images removed, they are input into the SfM software with the estimated camera positions and uncertainties, if available. In Agisoft Metashape, by right clicking on all of the images and selecting “Estimate Image Quality”, an algorithm populates a column which provides a score for the quality

sUAS image showing coral reefs and seagrass beds offshore of St. Croix.
Photo Credit: Oregon State University.

of an image. A user should review each of the lower image quality results and manually remove any remaining blurry imagery.

The estimated position of the camera for each image is input to constrain the SfM processing and establish a world coordinate system. Note that the estimated position must be input in the correct datum so that any curvature and distortion of a projected coordinate system can be accounted for in the software. Most photogrammetric and SfM processing software will convert projected coordinates into a Cartesian, geocentric coordinate system where errors due to the earth's curvature do not need to be accounted for. Once the coordinates for the images are input, it is important to ensure that the stochastic model reflects the estimated accuracy of each position. Results from this work indicate that a stochastic model that is overly pessimistic (e.g., uncertainty of 10 m when the true uncertainty is 10 cm) introduces significant error into the resultant point cloud. In Agisoft Metashape, the stochastic model is located under "Settings–Measurement Accuracy".

5.2.2 Mask Images

Imagery that contains large amounts of moving features, such as whitewater foam, should be masked so as to avoid the algorithm attempting to match spurious features. This process can be tedious if performed manually where a user must click points to define a polygon which encompasses the whitewater. Advances in algorithm development may enable a more automated approach in the future. For example, note how the seafloor texture in Figure 5.1 is obscured by the whitewater from breaking waves on the left half of the image, but is visible on the right side of the image. In this case, the whitewater regions would be selected as a mask, so that the SfM algorithm would not utilize those features.

5.2.3 Initiate SfM Algorithm

Once the imagery is input, the SfM algorithm is run to align the photos. The SfM algorithm first detects keypoints in each image, then finds corresponding keypoints between images. In order to accelerate processing, SfM software often has a "quality" setting, which will downsample the image prior to keypoint selection. The SfM algorithm will compute relative orientations between each of the cameras, as well as initial estimates for the key points in real world coordinates. These values are input into a bundle adjustment, which then performs the non-linear least squares adjustment to compute the initial sparse point cloud and camera exterior orientations. Optionally, if the camera calibration is not pre-computed, the camera interior orientation can be computed using a self-calibration within this step. In Agisoft Metashape, this is performed with the 'Align Photos' button.

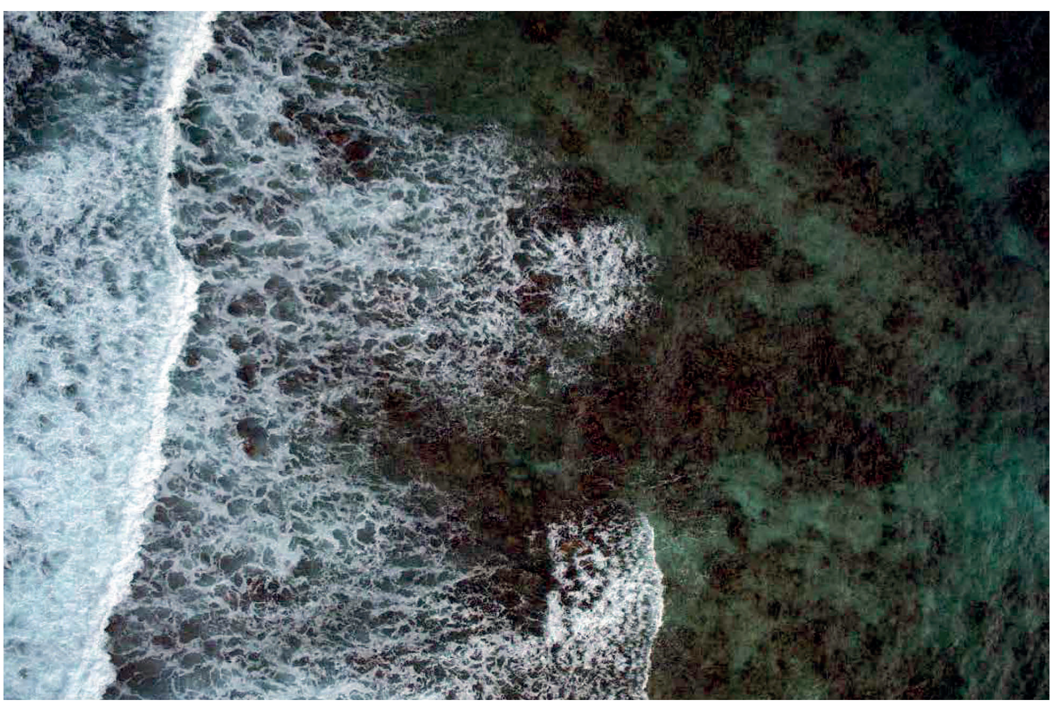


Figure 5.1. Using masks to constrict SfM processing to omit portions of imagery where the seafloor is obscured by whitewater (left of the image) and include portions of the imagery where the seafloor texture is visible (right of the image).

5.2.4 Sparse Point Cloud

The output from the initial SfM algorithm is a sparse, RGB point cloud. Each point in the point cloud is computed as a point in 2D image space, and matched as a corresponding point between multiple images. A point cloud is a large array of points (often in the tens- to hundreds-of millions) with x,y,z coordinates and sometimes associated red, green, blue color attributes for each point. This output point cloud is called the “sparse”point cloud, because the density of points is much less than the “dense” point cloud, output from the Multi-View Stereo processing described in Section 5.2.7. An example dense point cloud is shown in Figure 5.2, as a sparse point cloud is difficult to depict in a figure. Point clouds are often used for change detection, and more advanced analysis where access to the raw data is advantageous. A common, open source format for point cloud data is the LAS file format (ASPRS 2013).

5.2.5 Click GCPs

If GCPs are used at the field site, the world coordinates of these points are input to the software, and the targets are typically manually selected by the user in each image. An example iron cross target which was used as a GCP, shown in Figure 5.3. GCP selection occurs in image space within the SfM software and can theoretically happen before aligning the photos. However, this step is often performed after the initial image alignment as each GCP can typically be roughly identified in each image, thereby streamlining the process by limiting the amount of manual searching through each image for GCPs. Theoretically, with a carrier-phase based (PPK/RTK) sUAS trajectory, the importance of GCPs will be greatly reduced when compared to lower quality trajectories. The project team recommends at least one GCP, as it helps to constrain the focal length of the system. The project team investigated the use of placing GCPs underwater, but found that the surveying and placement

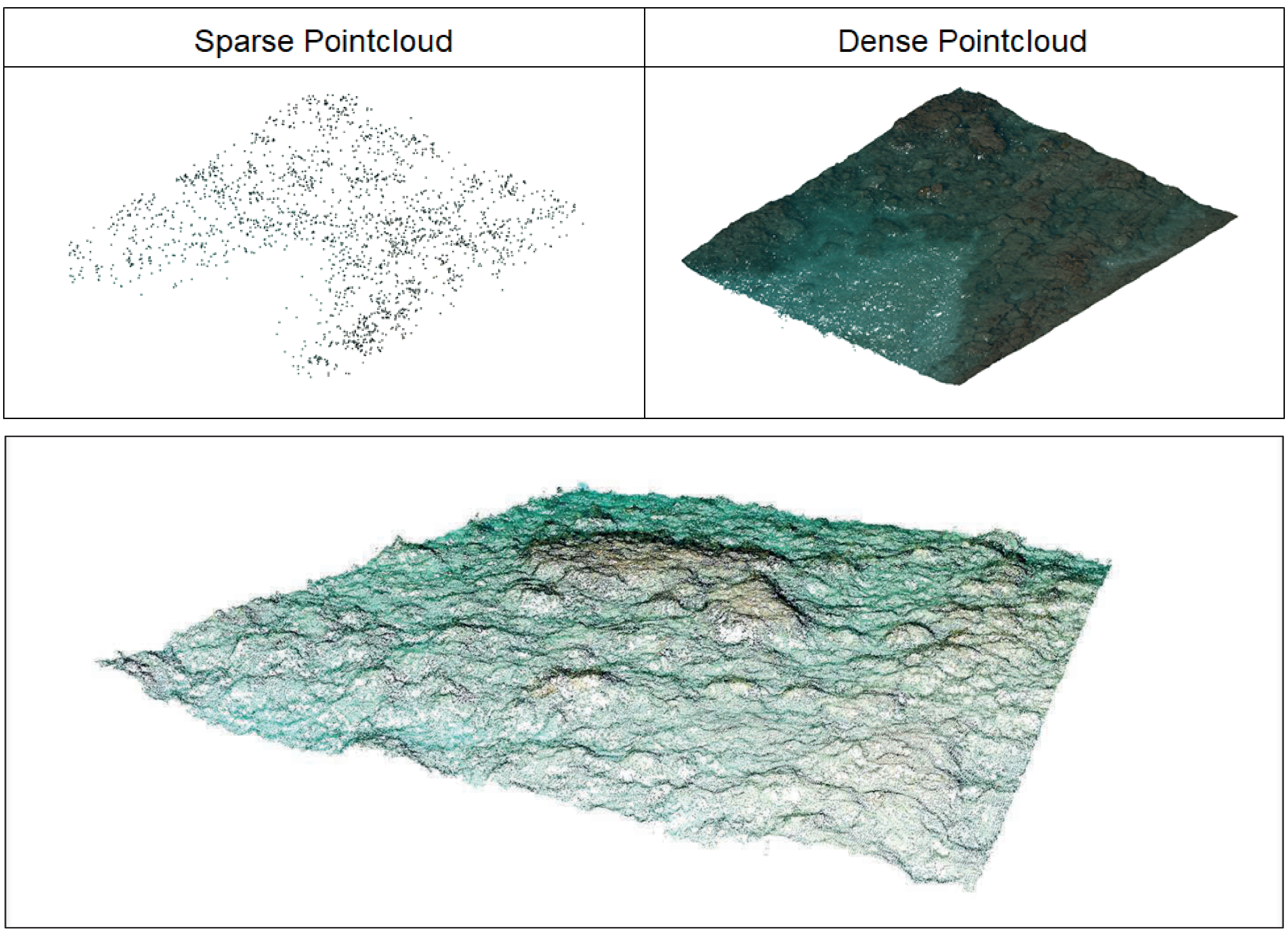


Figure 5.2. Top panel: a sparse point cloud (left) and dense point cloud (right) generated for a portion of submerged coral offshore of St. Croix. Bottom panel: a section of a dense pointcloud from NW Buck Island. These were generated using Agisoft Metashape with imagery from the S900 sUAS.

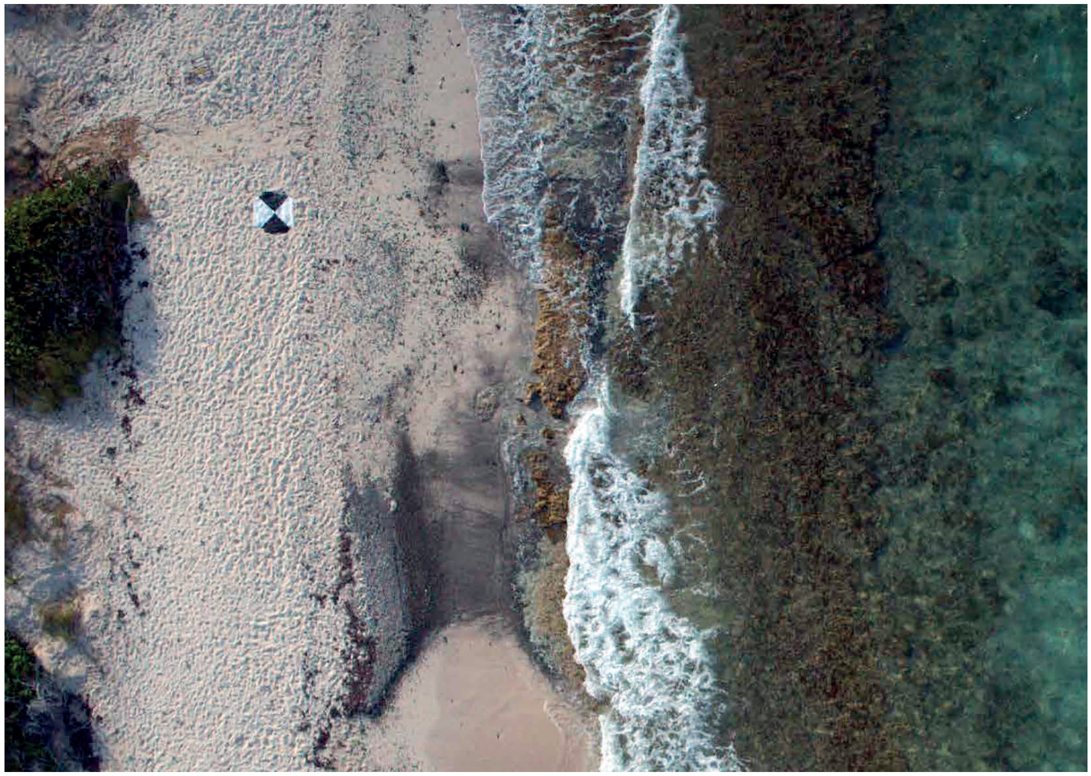


Figure 5.3. Example iron cross GCP target, used on St Croix.

of these points was time intensive and unreliable, as the targets occasionally moved or were covered by sand. Note that it is important to recompute the bundle adjustment after clicking the GCPs.

5.2.6 SfM Tiepoint Filtering

After the initial SfM algorithm, there may be inaccurate outliers in the sparse point cloud which reduce the accuracy of the dataset. These points should be removed either via manual selection or a semi-automatic selection tool. Obvious outliers which are too high, or too low, can easily be selected manually and removed. Inaccurate points which are not as obvious can sometimes be removed via a semi-automatic tool. This method is performed in Agisoft Metashape using the semi-automatic tool, “gradual selection”. The gradual selection tool allows the user to select the points based on a series of scalar values which are computed for each point, and can be used as a proxy for accuracy. After inaccurate tie points have been removed, it is important to recompute the bundle adjustment to ensure that the changes are applied. In Agisoft Metashape, this is performed using the “optimization” tool.

5.2.7 Multi-view Stereo

The second part of most commercial SfM software is the dense reconstruction, or multi-view stereo. This is a generic term for a family of algorithms which are different than the SfM algorithm in that it does not rely on keypoints and global matching. It is important to note that this algorithm relies on the camera exterior and interior orientations computed by the SfM algorithm, but do not use the sparse point cloud or interpolate the sparse point cloud in any way. The algorithm uses the camera interior orientation and exterior orientations, as computed from the bundle adjustment, and computes a more dense point cloud by leveraging epipolar constraints. The performance of the MVS algorithm is often sped up by downsampling the imagery, prior to computation. This downsampling is referred to as “quality” in Agisoft Metashape. The details of this family of algorithms are beyond the scope of this report, but further details can be found here (Furukawa and Hernandez 2015). The result of the MVS dense reconstruction is a much denser point cloud (Figure 5.2). For comparison, the dense point cloud often contains greater than 100 times the number of points as the sparse point cloud, and is often used for analysis and DEM generation.

5.2.8 Orthomosaic and Mesh Computation

After a dense point cloud has been generated, the next step is often to create a DEM or triangulated mesh, and rendering an orthophoto based on these models. These data products are often ingested into geospatial software for further analysis.

5.2.8.1 Digital Elevation Model/Digital Surface Model

A digital elevation model (DEM), digital terrain model (DTM), and a digital surface model (DSM) are gridded surfaces commonly derived from the dense point cloud, although the sparse point cloud or other photogrammetric methods may be used. Each of these consists of a gridded surface made up of evenly spaced cells, where each X,Y cell is represented by only one Z elevation. There is a distinction between these types, which is sometimes debated. As defined in Li et al. (2004), a DEM has grid cells that represent heights relative to a specific datum which normally represent the ground surface, a DSM represents tops of trees, buildings, etc, rather than the ground surface, and the DTM is a more generic term where each cell can represent any terrain property and is not limited to elevation data. A DSM is one of the most common output products from SfM processing, as volumetric analysis and change detection are very easy to implement using the gridded data. An example DSM is shown in Figure 5.4, where the elevation of each cell is depicted by a colorbar, red is shallower, blue is deeper.

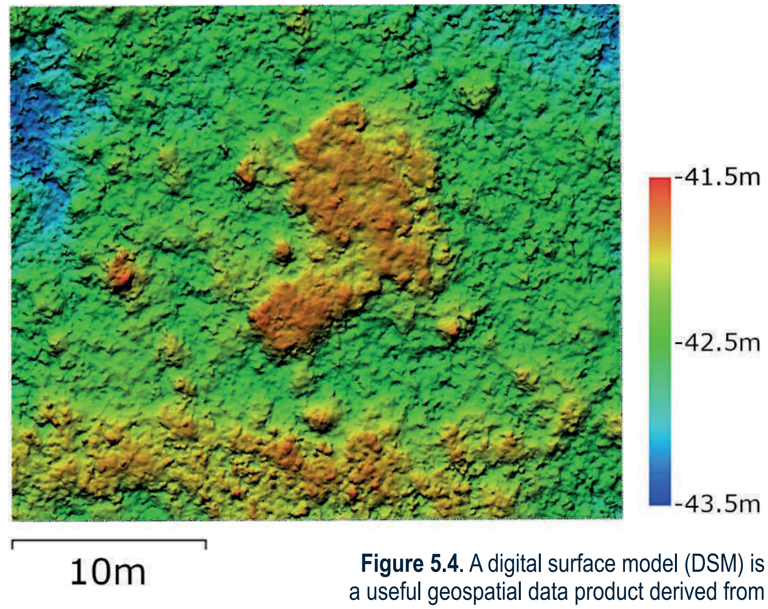
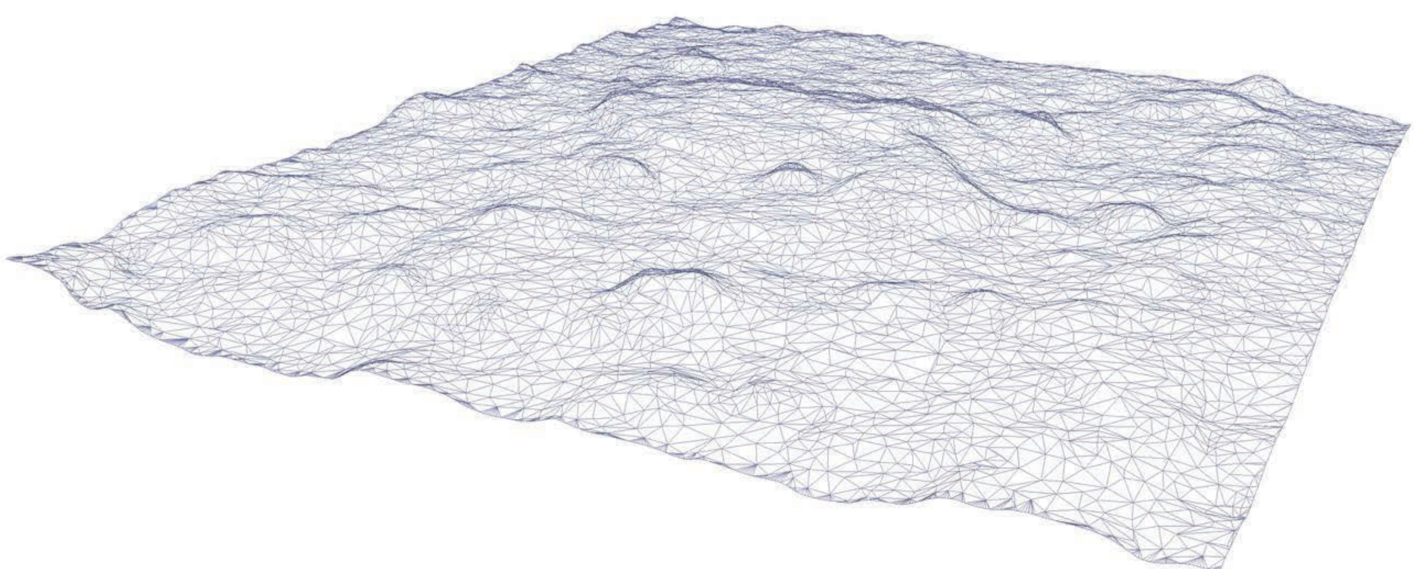


Figure 5.4. A digital surface model (DSM) is a useful geospatial data product derived from SfM-MVS processing.

5.2.8.2 Mesh surface

An alternative surface to a DEM (Behrendt 2012) is a mesh surface, which does not contain evenly spaced cells. A mesh surface, such a Delaunay Triangulation, is derived from either the sparse or dense point cloud, and is comprised of a triangulated irregular network, or TIN. This method enables variable density and resolution, wherein specific regions with high gradients and variability can be represented by many triangles, whereas regions with low curvature and variability can be represented by few triangles without a loss of original resolution. An example triangulated mesh is shown in Figure 5.5.



5.2.8.3 Orthomosaic

An orthomosaic is a georeferenced image which is generated by projecting the original imagery onto the DEM or mesh surface, and assigning a RGB color value for each cell in an array. As multiple camera locations often image the same cell, various algorithms have been developed to either determine which image to use, or to average the values and come up with a mean RGB value. An example orthomosaic is shown in Figure 5.6. Orthomosaics are useful when searching for specific features of interest which may not be visible in the DSM or 3D model. Orthomosaic data products are also useful for basemaps and to provide a more intuitive context for the project area. Orthophoto generation is commonly performed in all SfM software packages, and the most common output file type for geospatial work with orthomosaics is the geotiff. It is a valued GIS product as it removes the relief/tilt distortion and provides an image map with uniform scale, which is different than an image mosaic, or non-orthorectified stitched image.

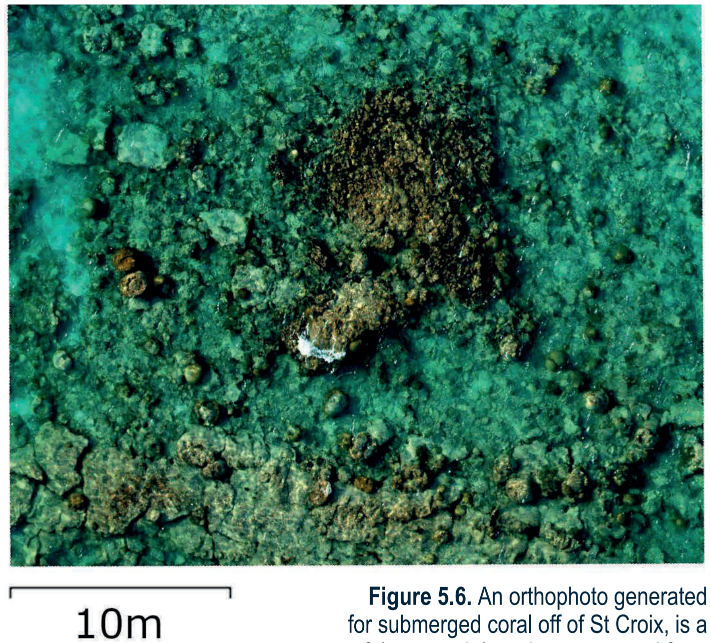


Figure 5.6. An orthophoto generated for submerged coral off of St Croix, is a useful geospatial product generated from SfM-MVS processing.

5.2.8.4 Textured mesh

A textured mesh, is similar to an orthophoto in that RGB values are projected onto a surface, but it maintains the TIN of the original mesh, rather than evenly spaced grid cells. This textured surface is much less common than the orthophoto, but it can be useful for visualization of data or data interpretation. An example textured mesh is shown in Figure 5.7.

5.3 Point cloud Classification

Point cloud data that has been generated via SfM processing methods often benefit from point cloud classification, wherein each point is assigned to a specific class such as: ground, noise, water surface, vegetation, etc. This classification enables users of the data to more easily analyze a point cloud, by omitting undesired features. Classification can be performed either manually, or via an automatic algorithm. Manual editing is more common for small field sites, as it is currently more reliable and robust. Automatic algorithm based editing can be performed on large datasets, using a number of commercially available software packages.

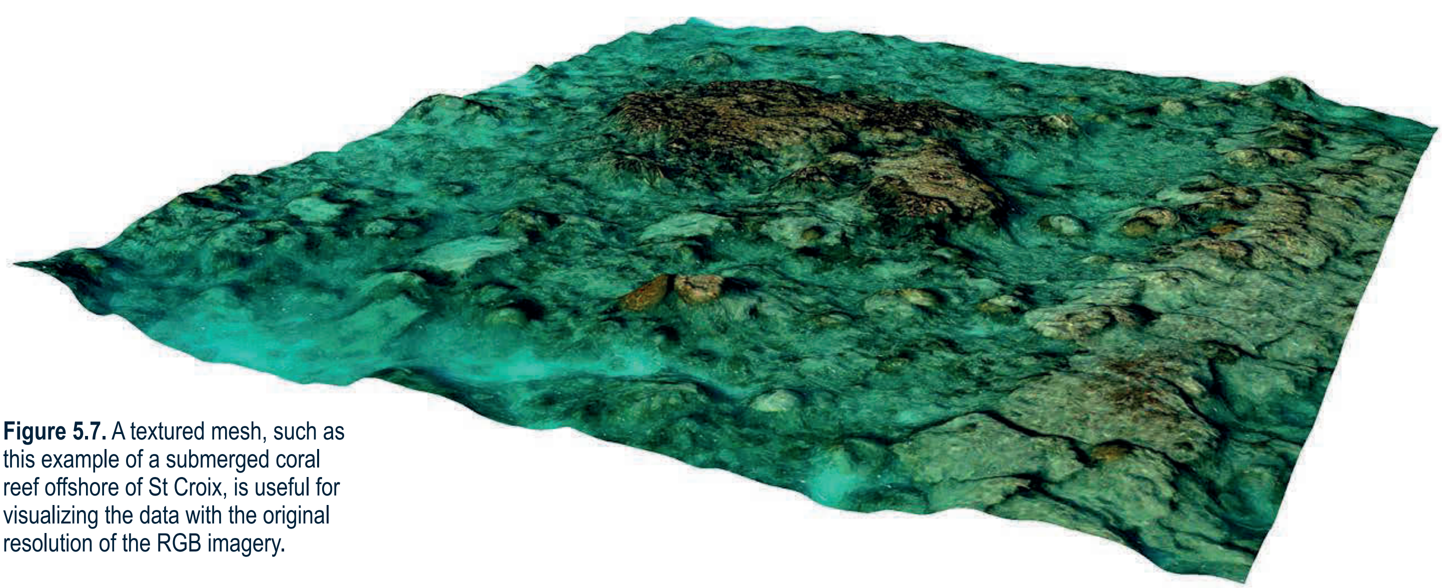


Figure 5.7. A textured mesh, such as this example of a submerged coral reef offshore of St Croix, is useful for visualizing the data with the original resolution of the RGB imagery.

5.4 Refraction Correction

The current method for processing bathymetric SfM data relies on commercial software which does not take into account refraction at the air–water interface. Therefore, the resultant point cloud is biased too shallow (red line in Figure 5.8 bottom). In order to correct this final dataset, the points below the water surface are corrected using either a constant scalar value for the entire dataset or using a more advanced algorithm which computes a correction for each point based on the viewing geometry of cameras which image that point. In order to know which points are below the water surface, a constant water level, or optionally a mesh surface of the water surface, is used to compute the depth of each point within the point cloud. At the time of writing this report, the Dietrich Algorithm (Dietrich 2017) is the most robust method for refraction correction, though it is anticipated that a more advanced algorithm which accounts for refraction within the SfM processing will be developed. An algorithm which accounts for refraction directly within the SfM processing will likely be more accurate, and remove the need for this refraction correction (blue line in Figure 5.8 bottom).

5.4.1 Constant Scalar Correction

The simplest method for correcting water depths is to multiple all of the depths by a constant scalar factor. This constant scalar factor can be based on the index of refraction, the results of previous studies, or computed directly by using existing or acquired ground truth data within the AOI. This method is computationally efficient, and can produce good results if the correct scalar value is used.

5.4.2 Dietrich Algorithm

The Dietrich algorithm computes a scalar correction for each point below the water surface based on the viewing geometry of the cameras which see each point and the index of refraction of the water. The advantage of this method is that it does not rely on acquiring additional bathymetric reference data or results from previous studies with the specific camera. Additionally, the Dietrich algorithm proves advantageous towards the edges on an AOI where the viewing geometry varies and the true depth correction varies more drastically from an average scale factor. The details of the algorithm are not included in this report, but are described in detail in Dietrich (2017). The algorithm is available as python code from GitHub (https://github.com/geojames/pyBathySfM).

5.4.3 Which Method to Use

The type of refraction correction to use was one of the primary factors investigated in the research underlying this report. The three refraction correction methods tested

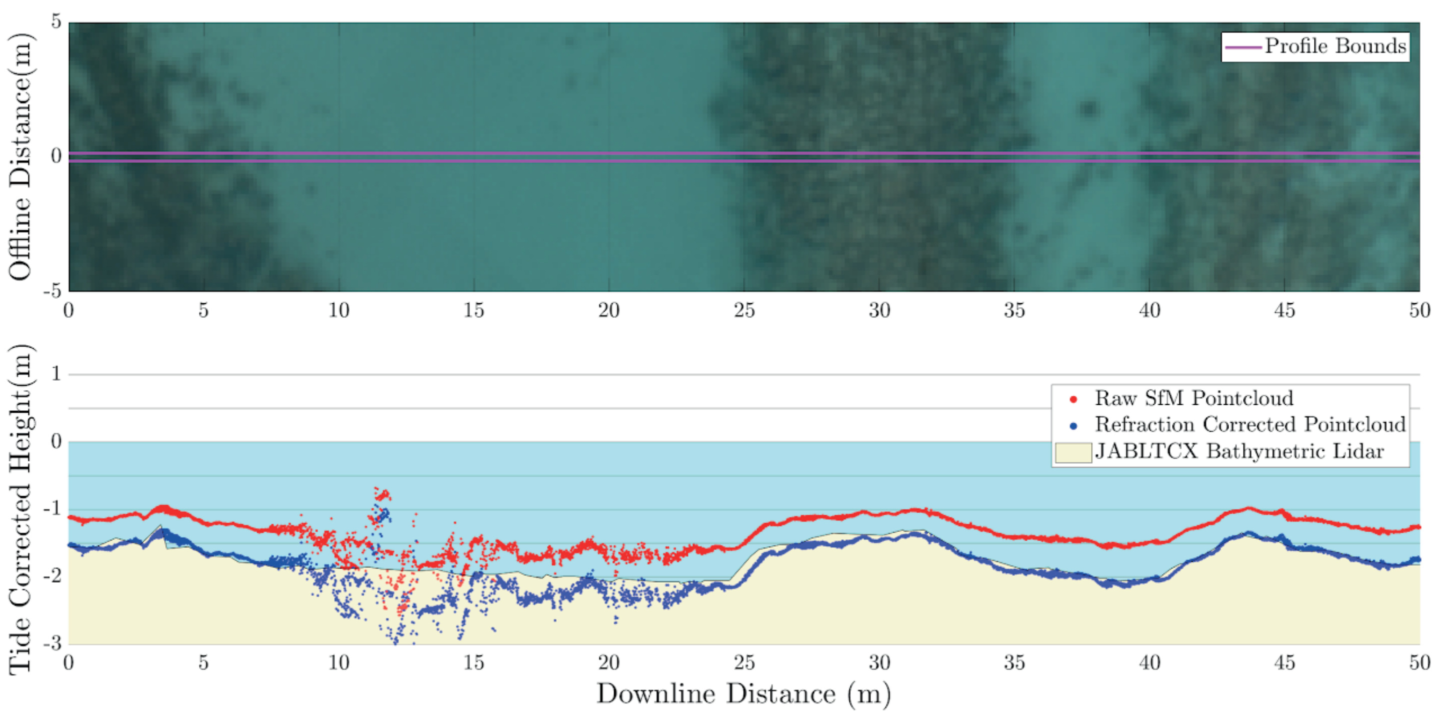


Figure 5.8. An extracted profile demonstrates the vertical error of both the raw, uncorrected point cloud and the refraction corrected point cloud when compared to JALBTCX bathymetric lidar. The top image is a section of imagery collected via sUAS. The bottom graph is a height profile of the raw (red) and refraction corrected (blue) SfM pointcloud compared to reference bathymetric lidar (tan). Note how the accuracy of the point cloud is significantly degraded in the sandy region with no seafloor texture.

were: (1) constant scalar correction obtained from known groundtruth data (e.g. Sonar soundings, total station transects, etc), (2) constant scalar correction based on previous studies, and (3) Dietrich method. Based on a detailed analysis of the results from sUAS data acquired with predominantly nadir imagery at both the USVI and Channel Islands project sites, our primary findings and conclusions are that the constant scalar correction computed from the ground-truth should be used if reference bathymetry data is available, otherwise the Dietrich method should be used. The use of a constant scale factor computed for another location was found to be generally inadvisable, as it was observed that the computed scale factor between flights and datasets varied, which yielded less accurate results.

The Dietrich method computes a spatially variable scale factor based on the position and viewing angles of each camera that capture a point within the field of view, while the constant scale factor uses one scale factor for the entire dataset. The results of this work indicate that the vertical errors after using the Dietrich method were comparable to the errors after using a constant scale factor. This is counterintuitive, as the more advanced correction method employed in the Dietrich method should theoretically produce more accurate results. The cause of this is likely that the constant scale factor method also corrects for errors not associated with refraction, such as the SfM-MVS computed pointcloud elevations and the estimated water surface elevation.

(Clockwise) sUAS flying offshore of Buck Island, St. Croix. Underwater ground control target in project area offshore of St. Croix. Total station set up in project area on St. Croix. Photo Credits: Oregon State University and NOAA NCCOS.

sUAS image showing bedrock shoreline of Buck Island, St. Croix.
Photo Credit: Oregon State University.

Chapter 6 SfM Data Dissemination

After SfM processing, the data should be reviewed to ensure that it is valid, without outliers or artifacts. This chapter describes some methods to check the quality of the data, and describes some potential applications for sUAS remote sensing data products.

6.1 Data QA/QC

Each of the output products described in Section 5.2 should undergo some level of quality assurance and quality control (QA/QC) to ensure the data results meet the desired accuracy standards. The level of and methods of QA/QC that can be performed is dependent on the amount of and quality of the reference data available. This section describes metrics which can be utilized to estimate the accuracy and quality of the data output from SfM processing.

6.1.1 Processing With Reference Data

Ideally, there will be some reference data in the AOI which can be utilized to assess the accuracy of the products. Examples of reference data are surveyed photo identifiable targets, such as iron cross aerial targets or unique rocks, hydrographic sonar data, aerial lidar data (ideally bathymetric lidar), or walking topographic survey data. These data can be used to independently assess the 3D accuracy of the point cloud, DSM, or mesh products. Reference data for the bathymetry is very useful, as bathymetry data are prone to anomalies when processing through COTS software. A comparison of SfM derived depths and reference depths can also be used as a proxy to infer the expected uncertainty throughout the dataset.

One useful method of acquiring a reference dataset is to utilize a small vessel with sonar and a survey grade GNSS to acquire reference depths along discrete transects (Figure 6.1). In this manner, a short survey with an ASV can be used to assess the accuracy of a portion of the SfM dataset. The reference data used for this project was collected in St. Croix using a single-beam sonar mounted on a kayak (and later with a JABLTCX bathymetric lidar dataset), and in Santa Cruz Island using a single-beam sonar mounted on a Seafloor Systems HyDrone.

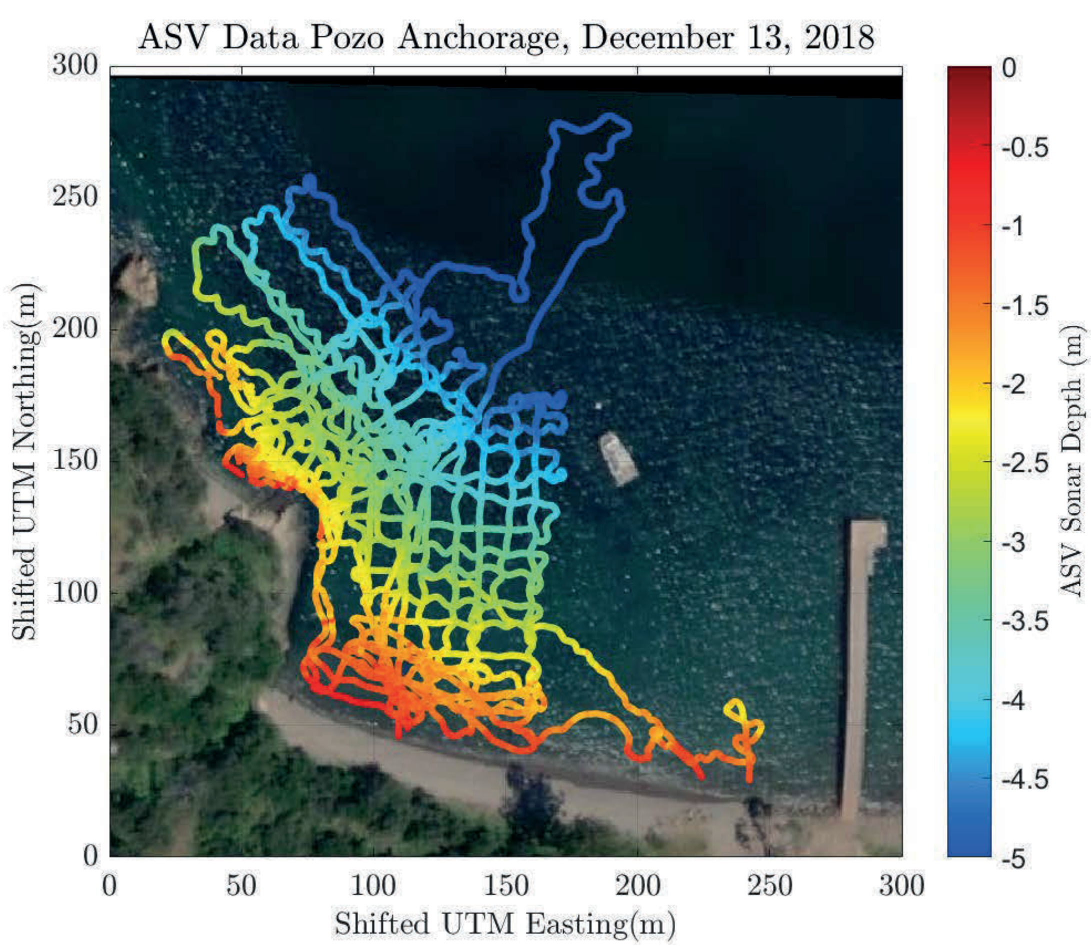


Figure 6.1. The researchers collected thousands of water depth soundings using an autonomous surface vehicle (ASV), represented the figure as depth color track lines and location. This information was used to validate the depths derived from the sUAS imagery.

6.1.2 Processing Without Reference Data

In the absence of reference data, there are a number of useful metrics that can be computed during the SfM processing to assess the accuracy and quality of SfM derived products. One of the most direct methods, only recently becoming available in commercial software, is to use the covariance of each tie point in the sparse point cloud. A covariance matrix is the result of performing total propagated uncertainty, wherein the estimated uncertainty in each of the input data sources is propagated through the least squares bundle adjustment to compute an estimated uncertainty of each point. Computing a covariance for each point in the dense point cloud is currently less common as error propagation through MVS algorithms is not as straightforward, though it has been recently introduced in the literature (Rodarmel et al. 2019). The values from a covariance matrix can be used to estimate the uncertainty of each point, though a chi-squared test should be performed to ensure that the covariance is appropriately scaled (Ghilani 2017).

In *lieu* of a covariance matrix for each point, there are other SfM metrics which can be assessed to infer relative accuracies in the resultant point cloud. While the availability and name of these metrics vary in commercial software packages, they can be used to assist with outlier detection and removal. These metrics in Agisoft Metashape include the reprojection error, image count, reconstruction uncertainty, and projection accuracy. Additionally, there are pseudo metrics which can be used to infer accuracies, such as distance to keypoints, brightness, darkness, and others described in Javadnejad (2017).

While the above approaches could be used to improve data quality, it is often effective to manually QA/QC and edit point clouds directly. Regions with changing texture, such as regions with active wave breaking or wave runup at the shore, often have large amounts of noise which can be manually removed in a point cloud editing software. A common method for manual point cloud editing is to edit small transects of data at a time, so that the data can be viewed from the side as a profile and be easier to edit.

6.2 Data Applications

Several organizations, including NOAA, need photographs, elevation and depth data to inform management decisions in the coastal zone. This project has shown that sUAS, combined with standard cameras and SfM software, are capable of producing centimeter-scale photo-mosaics, elevation and depth data for near-shore environments (Figure 6.2). This research is a first step towards better understanding how sUAS can be used to accurately map coastal regions safely and efficiently. While the primary

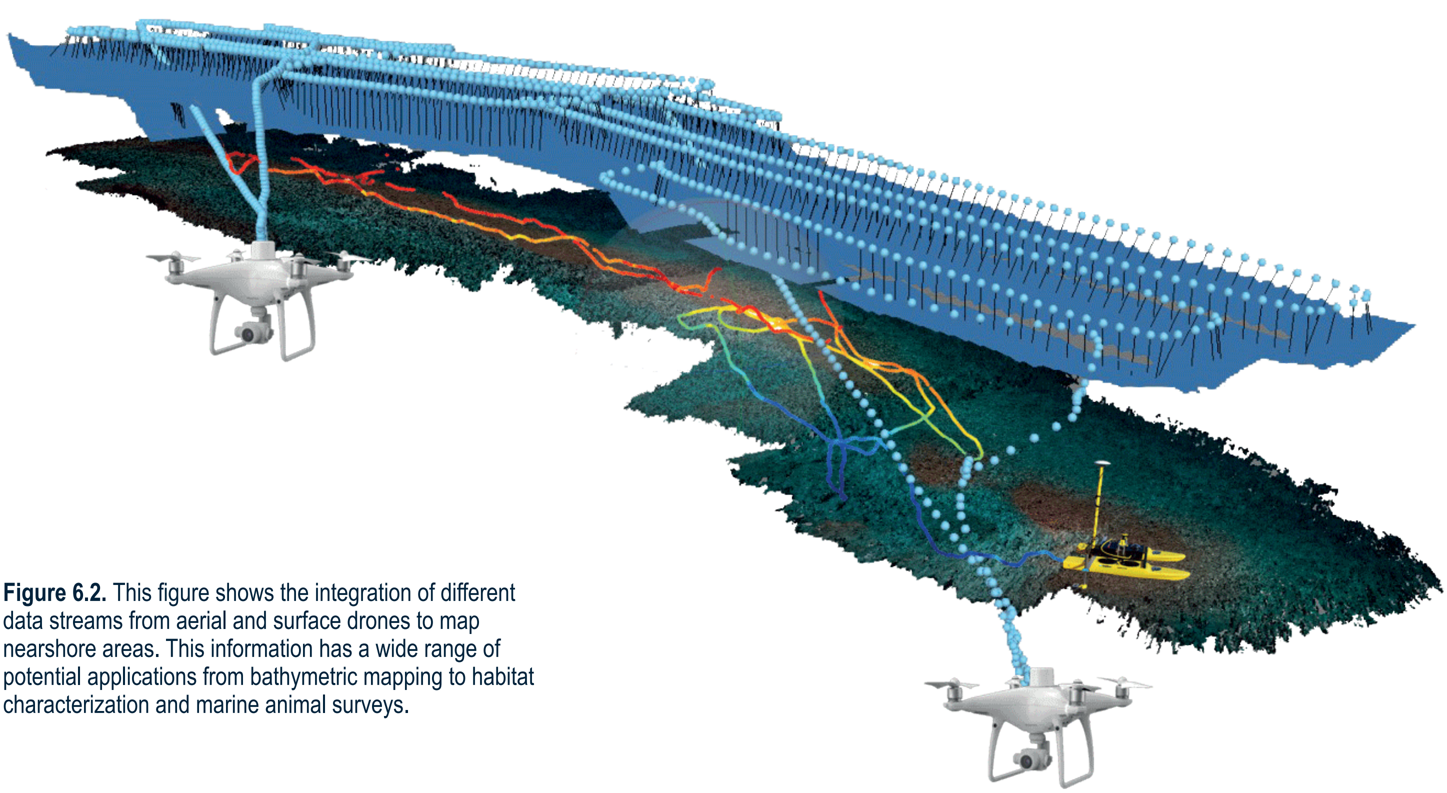


Figure 6.2. This figure shows the integration of different data streams from aerial and surface drones to map nearshore areas. This information has a wide range of potential applications from bathymetric mapping to habitat characterization and marine animal surveys.

focus here was mapping coastal depths and elevations to inform nautical charting, sUAS imagery and associated products are currently being used for a variety of other management applications. Many of these different applications rely on the same suite of SfM products (i.e., orthomosaic, DSM and point clouds). This next section describes in detail, current applications for this suite of SfM products, as well as other potential applications of sUAS technology for coastal and marine managers.

6.2.1 Applications Using Standard RGB Cameras

Most marine applications of sUAS collect and use imagery from standard RGB cameras. These cameras collect high resolution (<3 cm) georeferenced photographs, which are incredibly valuable information for marine managers in coastal environments. While this overlapping imagery can be used to support nautical charting (as was evaluated here), this imagery and derived elevation and depth information has also been used for a wide range of other research and management uses in coastal environments. Notably, these applications have included studying coastal geology, including mapping and verifying shorelines (Sharr and Wisotzkey 2018, Lowe et al. 2019), as well as quantifying beach erosion and deposition over time (Seymour et al. 2017b). sUAS imagery and SfM products are also being used for ecological applications, including monitoring coral health and mapping coral bleaching events (Levy et al. 2018), as well as characterizing benthic habitats, such as seagrass beds (Merrill et al. 2013), coral reefs (Casella et al. 2016, Collin et al. 2018; Figure 6.3), salt marshes and oyster reefs (Kalacska et al. 2017, Ridge et al. 2017).

This technology is also being used to study marine animals, including assessing their health (Pirotta et al. 2017), behavior (Gallagher et al. 2018) and morphometrics (Durban et al. 2015; Figure 6.4). sUAS imagery is also being used to estimate the abundance and density marine animals, including seabirds (Hodgson et al. 2016), pinnipeds

Figure 6.3. sUAS imagery showing coastal vegetation, beaches and coral reef habitats north of St. Croix. Repeated sUAS flights over this area could be used to quantify changes in coastal areas and benthic habitats over time.

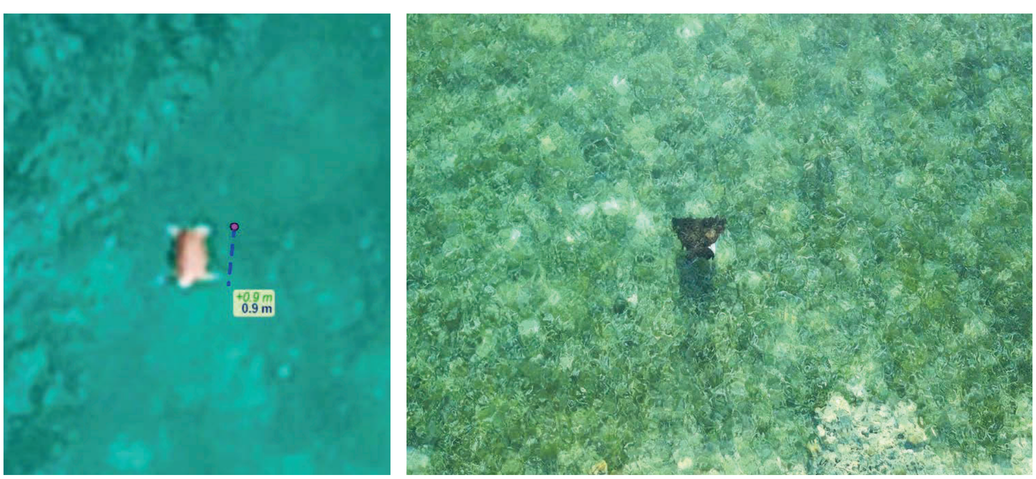


Figure 6.4. sUAS imagery showing a green sea turtle (*Chelonia mydas*; left) and a spotted eagle ray (*Aetobatus narinari*; right). These images were captured in April 2018 offshore of St. Croix.

(Sweeney et al. 2016), dugongs (Hodgson et al. 2013), sea turtles (Sykora-Bodie et al. 2017), and sharks and rays (Kiszka et al. 2016). Some studies have shown that these sUAS surveys are as accurate, if not more so, than animal surveys conducted using traditional methods from manned aircraft (Johnston et al. 2017, Ferguson et al. 2018, Hodgson et al. 2018). This information is particularly relevant to NOAA, as it conducts routine animal surveys and population assessments using manned flights.

In addition to bathymetric and marine animal assessments, unmanned aerial systems are also used for coastal (King et al. 2017) and offshore energy (Wen et al. 2018) infrastructure investigations, and are being tested for maritime surveillance and response. In the case of surveillance, large UAS (e.g., Predators and Pumas) have been tested in remote marine protected areas (like in the northwestern Hawaiians Islands; Brooke et al. 2015). While battery life prevents using sUAS (as tested here) in such remote locations, sUAS have been used in less remote areas to detect and identify fishing vessels (Miller et al. 2013), and count anglers (Kopaska 2014; Figure 6.5). In both applications, the UAS imagery and associated SfM products provided a potentially accurate and cost-effective way to achieve these very different project objectives.

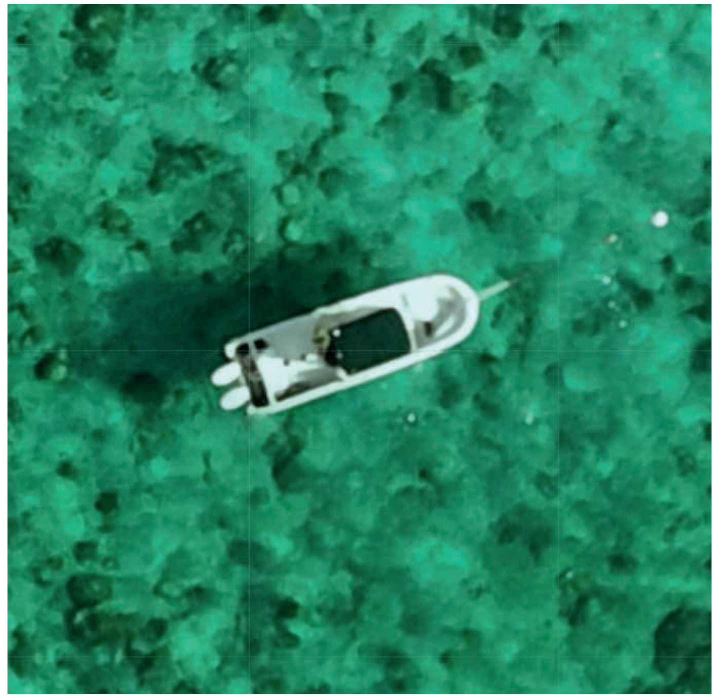


Figure 6.5. sUAS imagery showing a vessel moored offshore of St. Croix. Local law enforcement on St. Croix were interested in using sUAS to monitor vessel activities. Note: this vessel was operated by the project team, and all onboard were willing participants.

6.2.2 Applications Using Other sUAS Payloads

While sUAS are often outfitted with RGB cameras, sUAS are also capable of carrying other payloads, including hyperspectral cameras, thermal cameras, and lidar sensors (Johnston et al. 2019). Hyperspectral cameras sample a broad range of electromagnetic energy in very narrow bands, and can be used for a number of applications including mapping and monitoring harmful algal blooms (HABs; Lyu et al. 2017, Kislik et al. 2018, Becker et al. 2019, Wu et al. 2019). Thermal cameras detect heat signatures, and have been used to detect and count marine mammals at night or when they are obscured by coastal vegetation (Gooday et al. 2018, Seymour et al. 2017a). Lidar sensors are capable of producing 3D point clouds, and advances are being made to miniaturize these systems for sUAS (Lin et al. 2011). There are currently a handful of commercial sUAS lidar systems available (Johnston et al. 2019), with more likely in development. sUAS are also being adapted to collect air, water and sediment samples in marine environment to measure salinity, temperature, algae and contaminants (Di Stefano et al. 2018, Terada et al. 2018, Xu et al. 2018). These examples provide a snapshot of current, civilian sUAS applications. Additional types of applications will likely emerge as this technology matures and advances. The next section (Chapter 7) discusses some of these potential advancements in sUAS technology and likely areas for future research.

DJI S900 sUAS before take off on north side of St. Croix. Buck Island can be seen in the background. Photo Credit: NOAA NCCOS.

(Right) Chris Parrish (OSU) pilots the DJI Phantom 4 Pro RTK sUAS on Santa Cruz Island, CA. The Seafloor Systems HyDrone ASV is seen in the foreground. (Middle) Project team plans and adjusts mission based on real time weather conditions north of St. Croix. (Right) Tim Battista (NOAA NCCOS) deploys GCP target in shallow water offshore of Buck Island, St. Croix. Photo Credits: Oregon State University and NOAA NCCOS.

Oblique image of shoreline of Santa Cruz Island, CA.
Photo credit: Oregon State University.

Chapter 7 Conclusions and Supporting Research

The project team acquired and processed data from over 100 sUAS bathymetric mapping flights, and tested a variety of airframes, sensors, environmental conditions, and processing procedures. This chapter includes a summary of the recommendations and conclusions resulting from these experiments. All plots depicting the vertical error of the SfM pointcloud are computed by generating a DEM for each dataset and comparing it to a DEM generated from a bathymetric lidar dataset. The difference between these two DEMs is the vertical error of the SfM-MVS results.

7.1 sUAS Trajectory Accuracy

For topographic SfM, a low accuracy trajectory can be used to create reasonable results when paired with accurate GCPs. However, this is not the case for bathymetric SfM. When the research team used a low cost DJI Mavic Pro, the low accuracy trajectory yielded poor results and the use of GCPs was not practical in coastal waters. Additionally, refraction and distortion of the air-water interface introduced uncertainty in the key image matching points, causing the relative poses between images to have more uncertainty. This uncertainty quickly propagated to point cloud error. Figure 7.1 demonstrates that the low accuracy GNSS trajectories (i.e., L1 only code-ranging) yield worse results when compared with results from high accuracy GNSS trajectories (i.e., PPK). This selection of data is representative of the broader datasets.

Additionally, it is important to process data with the correct uncertainties input into the software. If the stochastic model is set incorrectly (e.g., 10 m uncertainty instead of 0.05 m), the resultant point cloud will be less accurate. Figure 7.2 depicts a dataset from the S900, processed with both the correct (camera 3D position uncertainty = 0.05 m) and incorrect stochastic model (camera 3D position uncertainty = 10 m). Knowing the uncertainty of your trajectory, and inputting it into the software correctly is crucial to produce the best results.

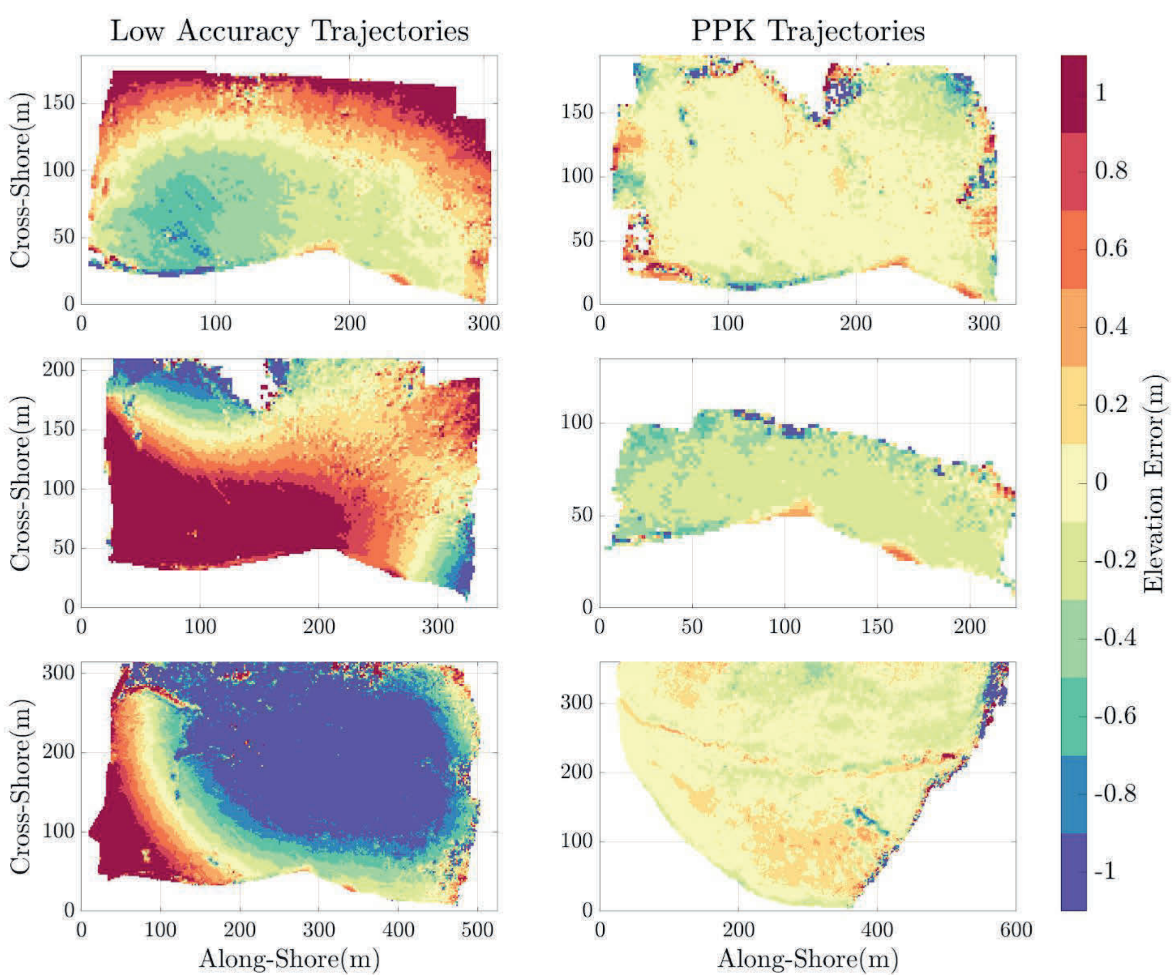


Figure 7.1. The data produced from a sUAS with a low accuracy trajectory is significantly worse than the data produced with a high accuracy trajectory. All locations are from NW Buck Island, except bottom right from Rod Bay, St. Croix.

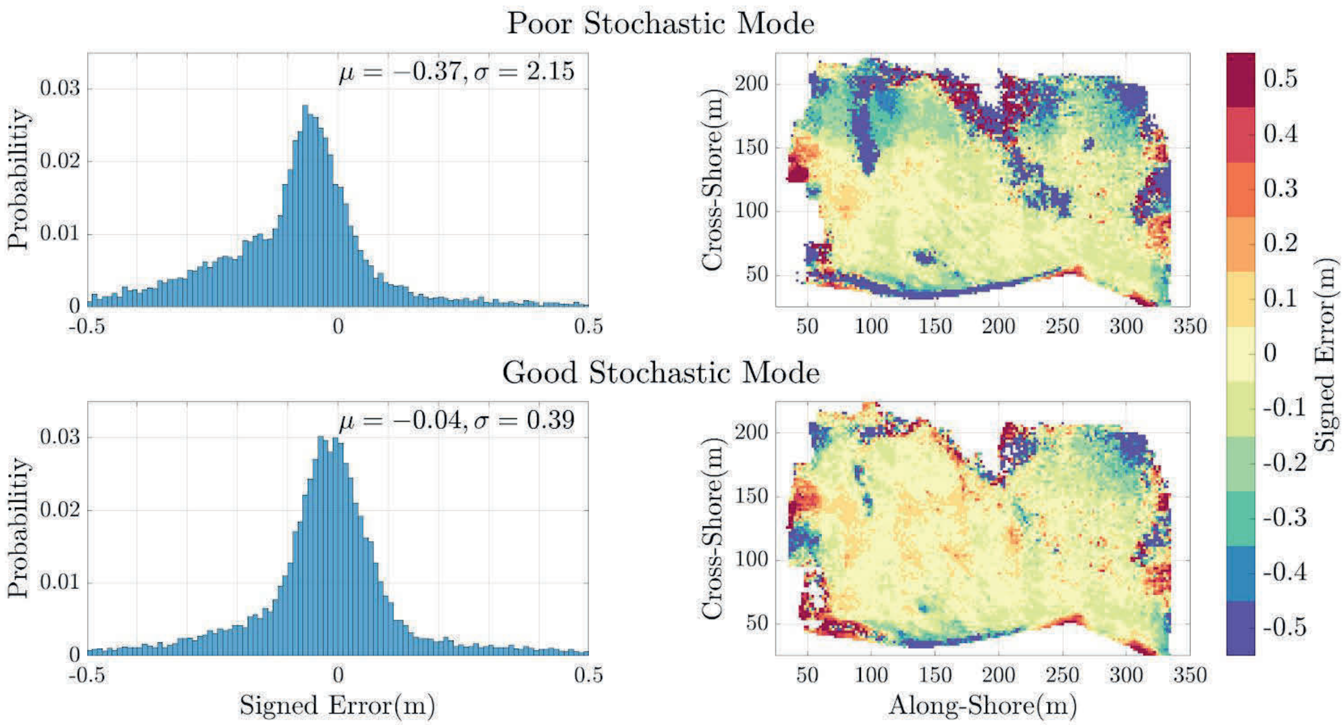


Figure 7.2. SfM data needs to be processed with the correct stochastic model for the trajectory, otherwise the results will exhibit more error. The uncertainty in the camera pose was set to 10m (top) and 0.05m (bottom).

7.2 Seafloor Surface Texture is Essential

One of the more important aspects of SfM mapping is texture. SfM software relies on texture to match features between images, and will produce limited data in areas with low texture. In bathymetric SfM processing, regions which have a seafloor with low texture, like sandy bottoms, will have either poor accuracy data or no data at all. Figure 7.3 highlights depths that were unable to be mapped in the image using SfM processing. These areas produced a data gap, as the texture was not adequate for SfM processing. This area is shown again in Figure 7.4, where the transect shows that SfM was unable to generate depths over the large sandy area. Note the data gap shown in the lower image on the left of Figure 7.4 was due to wave runup, and changing textures on the beach causing issues with the keypoint matching. When performing SfM mapping, it is important to be cognizant about the limitations of SfM and know that it will not produce valid results over textureless areas.

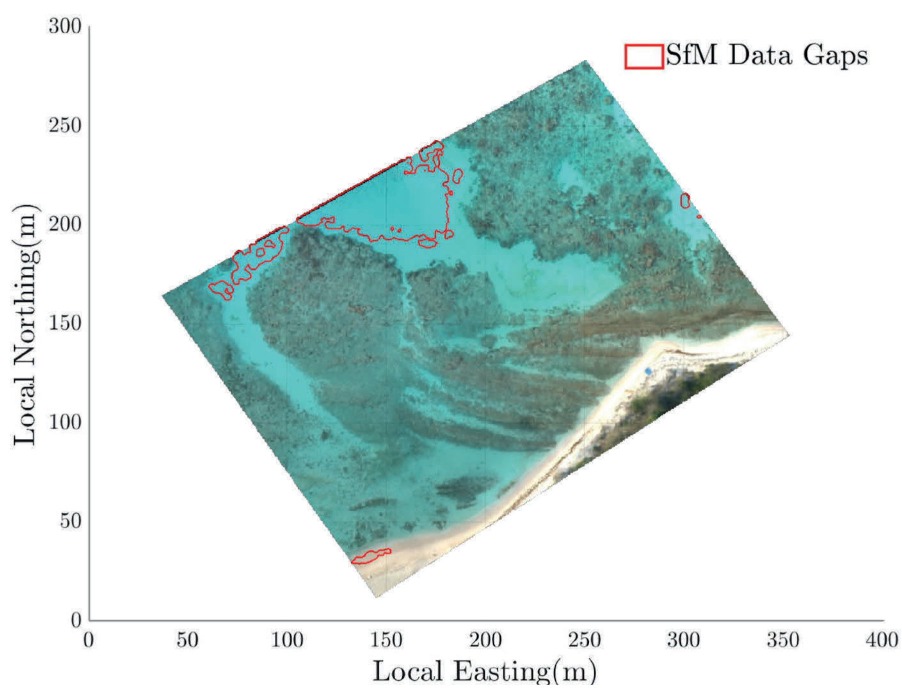


Figure 7.3. Areas surrounded by red indicate where SfM produced data gaps due to low seafloor texture.

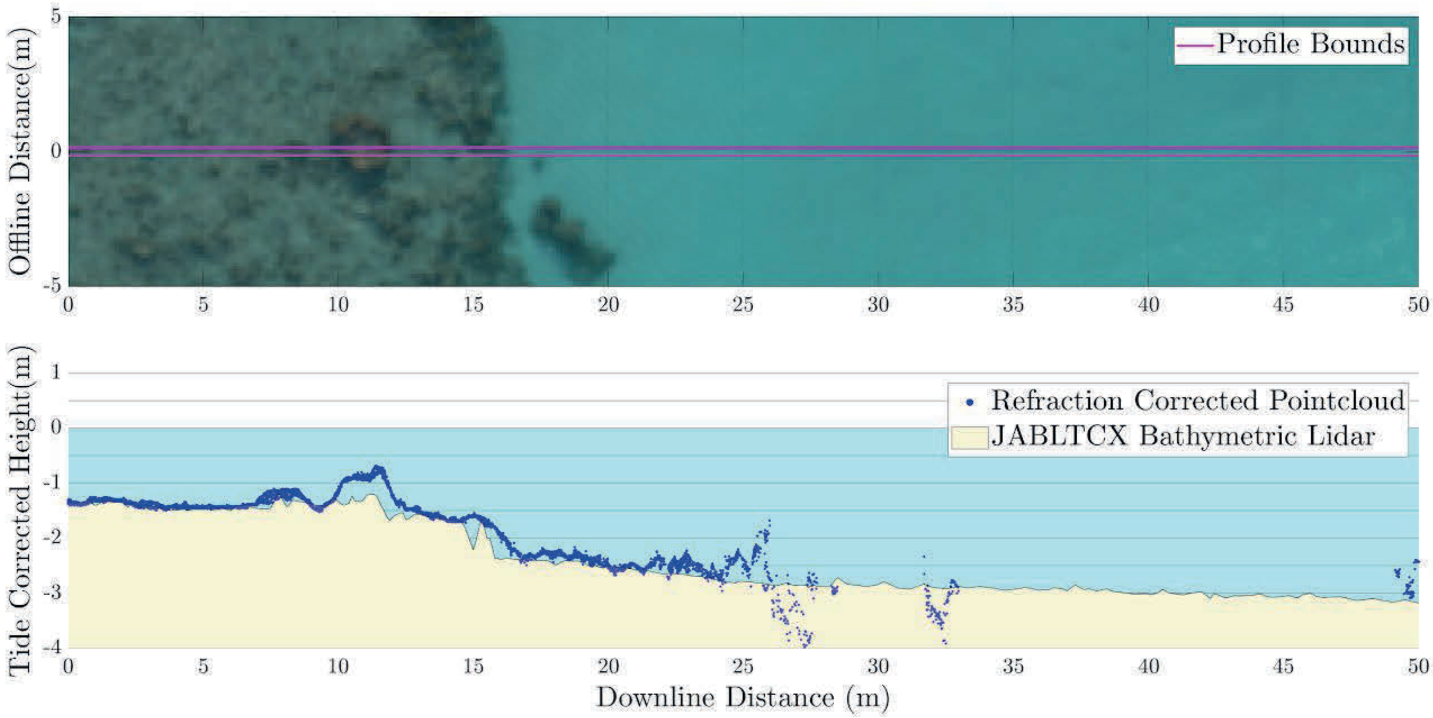


Figure 7.4. A profile showing a submerged coral reef and extending into a sandy seafloor off of St. Croix . This profile demonstrates that SfM will not yield valid results in the featureless areas of a scene. Note: at approximately 11m in the downline distance, the SfM data (bottom image) appears to resolve a coral head that was unmapped by the bathymetric lidar, highlighting the higher resolution of the SfM point cloud.

7.3 Mapping Overlap/Sidelap Should be ≥75%

During the field experiments, the project team processed data with varying overlap/sidelap percentages. The team chose to vary overlap and sidelap by the number of images which would see a point throughout the scene, rather than increment linearly by percentage space, as shown in Table 7.1. The reason for this was that any percentage value in between these numbers will create a non-uniform sampling density, where some parts of an image will be seen by (n) images, and other parts will be seen by (n-1) images. The effect of a overlap/sidelap percentage on the accuracy of the resultant point cloud is unknown, and the results from this experiment were inconclusive. However, it was noted that imagery acquired with an overlap/sidelap of 66% yielded large data gaps more commonly than those with a greater overlap percentage. This is likely due to the refraction and distortions at the air-water interface creating fewer matching features, which when combined with fewer point images (n), increases the chance of multiple images not aligning. For this reason, it is recommended that for bathymetric SfM mapping, an overlap of 75% or greater is selected.

Table 7.1. The number of images which see a point in the overlap dimension, and their corresponding overlap/sidelap percentages. It is recommended that 75% (in gray) or higher is used for bathymetric mapping.

Number of Images (n)	Overlap/Sidelap Percentage 100*(1-1/n)
2	50.0%
3	66.7%
4	75.0%
5	80.0%
6	83.3%
7	85.7%
8	87.5%

7.4 Active Wave Breaking Yields Low Accuracy Data

The project team flew a few sites with active wave breaking and whitewater. In all regions with active wave breaking, the bathymetry beneath the breaking waves and foam was either not resolved in the SfM processing, or highly inaccurate. sUAS imagery over regions with significant active wave breaking are shown in Figure 7.5. Note that for Figure 7.5a, the depths were unable to be resolved at this site with SfM processing. The erroneous SfM data from the field site corresponding to Figure 7.5b is shown in Figure 7.6.

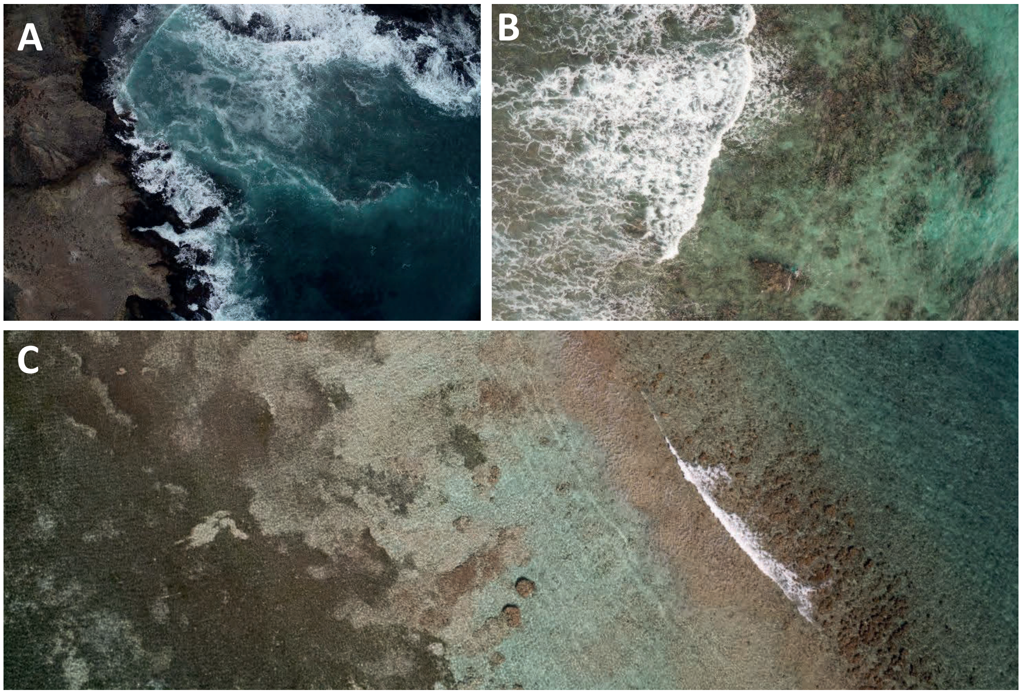


Figure 7.5. Locations of field sites with active wave breaking, whitewater, and foam, adversely affect SfM processing results. A) Extensive wave breaking off the shoreline in Santa Cruz Island yielded no bathymetry. B) Wave breaking off the shoreline in St. Croix yielded very inaccurate data. C) Slight wave breaking on a reef off of St. Croix yielded slight errors in the data.

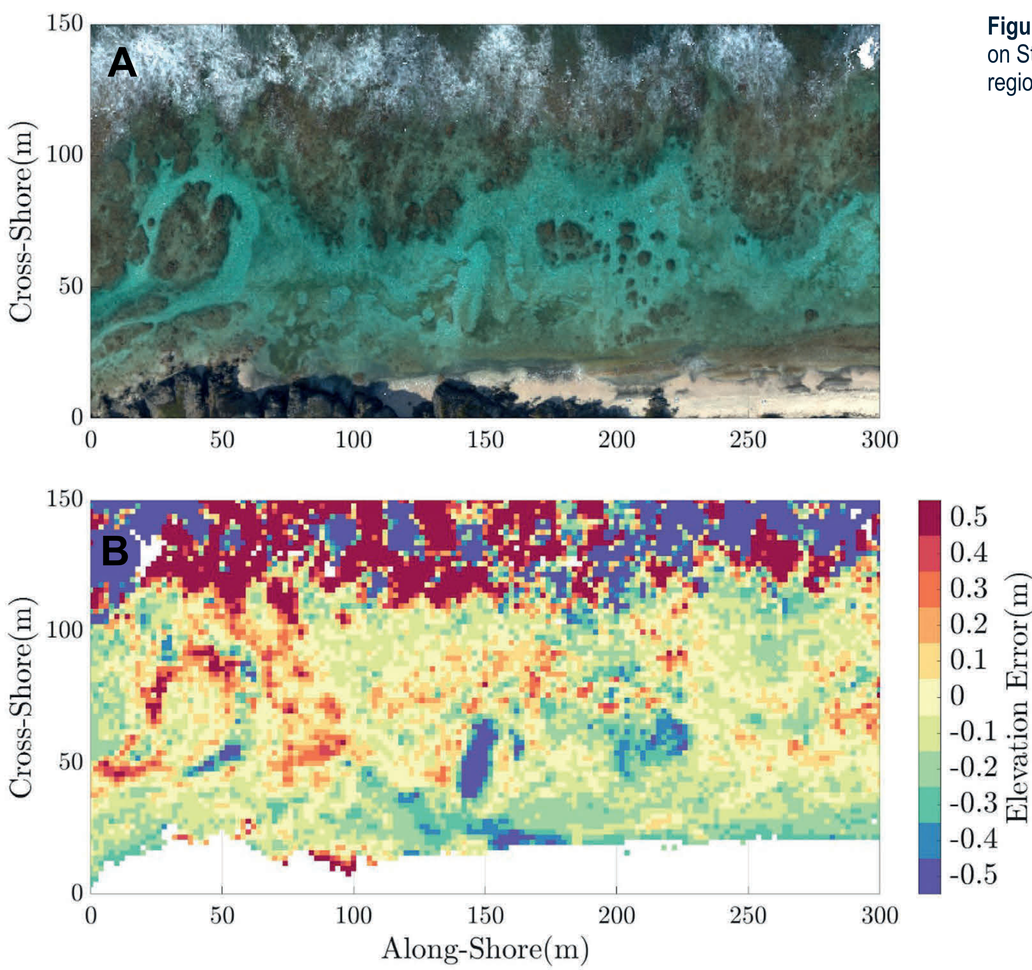


Figure 7.6. Active wave breaking off Whale Point on St. Croix (A) yielded very inaccurate data in regions where whitewater was present (B).

Observe the valid data where no waves were actively breaking, but the data degrades in location where waves were actively breaking. Lastly, the data corresponding to the image in Figure 7.5c, is shown in Figure 7.7. At this field site, the region of breaking was minimal, yet still yielded an error in the resultant point cloud, as highlighted by the magenta polygon.

It is recommended that users not expect valid bathymetric mapping in locations where active wave breaking is occurring. The tidal range, wave conditions, and wind conditions should all be monitored when attempting to map an area when minimal to no wave breaking is occurring.

7.5 Maximum Depth Depends on Water Clarity

Water clarity will be the limiting factor when determining the maximum depth that can be mapped with bathymetric SfM. Depths greater than 4 m were unresolved off of Santa Cruz Island due to water clarity prohibiting imaging of the seafloor texture in deeper depths (Figure 7.8a), while depths greater than 4 m were accurately measured off of Buck Island in St. Croix (Figure 7.8b). Maximum depth derived in St. Croix was 7 m at NW Buck Island, and 10 m on the south coast oc Buck Island. Water clarity is often measured with a Secchi depth, which is the point at which a 12-in diameter black and white Secchi disk lowered into the water is no longer visible. This Secchi depth represents the maximum possible depth that SfM will work for bathymetry, and can be useful for mission planning and setting expectations for a specific field site.

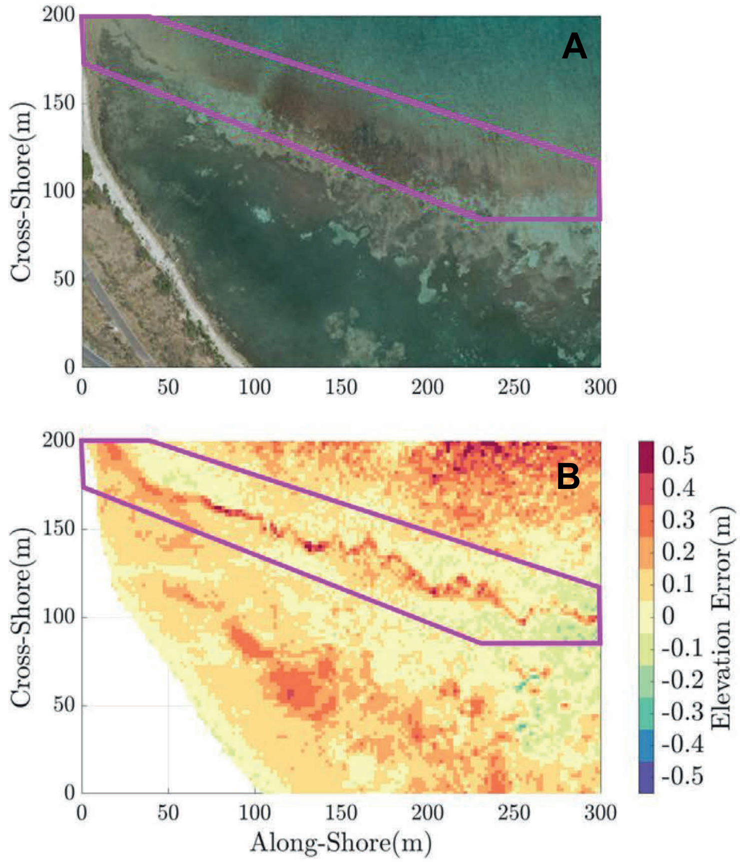


Figure 7.7. Slight amounts of wave breaking on a reef at Rod Bay on St. Croix (A) yielded noticeable errors in the data, which aligns with the wave breaking (B), outlined in magenta.

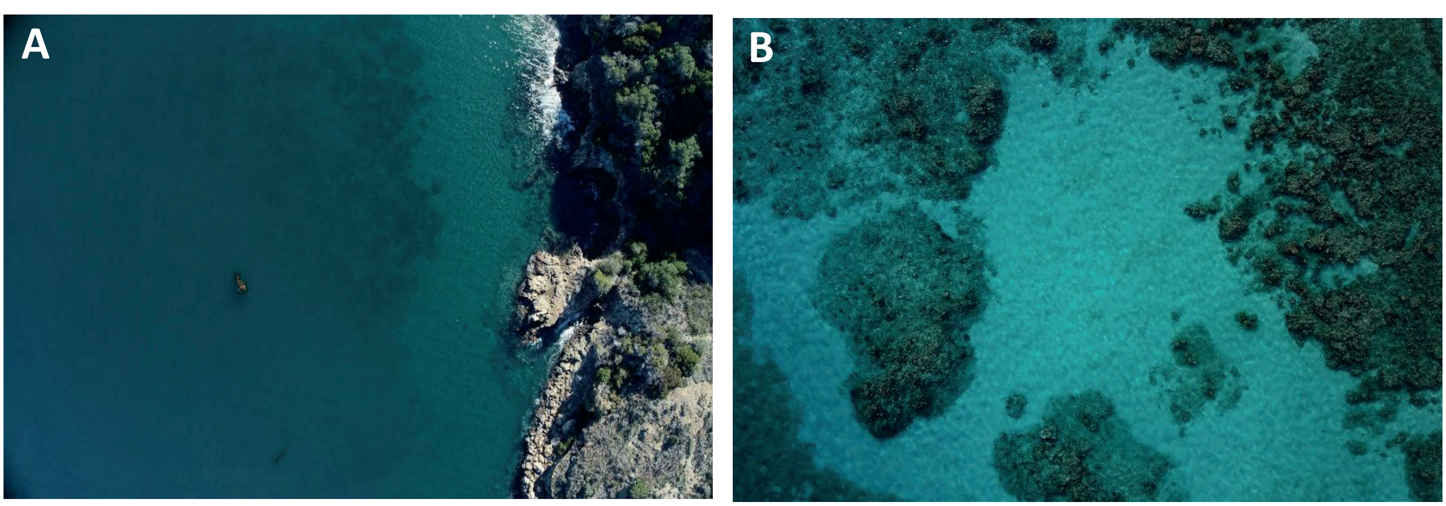


Figure 7.8. The water depth on the left side of both images is approximately 4 m. Notice how the water clarity prohibits visibility of the seafloor at Santa Cruz Island (A). The water clarity at Buck Island, USVI (B), enabled imaging of the seafloor at the same water depth.

7.6 Flying at a Higher Altitude Increases Chance of Success

For SfM bathymetry, it is recommended to fly at a higher altitude to increase the chance that all images are stitched together successfully. In most of the field sites mapped for this project, there were numerous patches or regions of the site which contained limited to no texture. This was either due to a homogeneous, textureless seafloor or suspended sediment prohibiting the imaging of the seafloor. In these regions, it is important that SfM processing is able to find images on either side of these patches which have corresponding keypoints.

The importance of flying height was evident at the Pozo Anchorage field site, offshore Santa Cruz Island. This site was a linear beach with active wave breaking, creating a sediment plume in the inner surf zone. This sediment plume made it difficult to visualize the seafloor until 20–30 m from shore. This site was mapped at 75% overlap/sidelap, with flying altitudes of 50 m, 75 m, 100 m, and 120 m. The 50 m and 75 m missions were unable to resolve any bathymetry, due to the inability to match images from both sides of the sediment plume. Figure 7.9 depicts three images from neighboring flightlines for both the 50 m (Figure 7.9a–c) and 100 m flights (Figure 7.9d–f). Red and yellow stars are placed to indicate potential key points in each image. Notice how for the 50 m flight, no images share the same key point in the field of view. Now notice how for the 100 m flight, images Figure 7.9e and Figure 7.9f, both capture a key point just offshore of the sediment plume. This point, and others in the region, can be used to compute relative orientations between the cameras. This simple case happens across every field site. Where key points and features in the water may be sparse, a higher flying altitude will increase the number of distinct features and keypoints which will be imaged, thereby increasing the chance of SfM success.

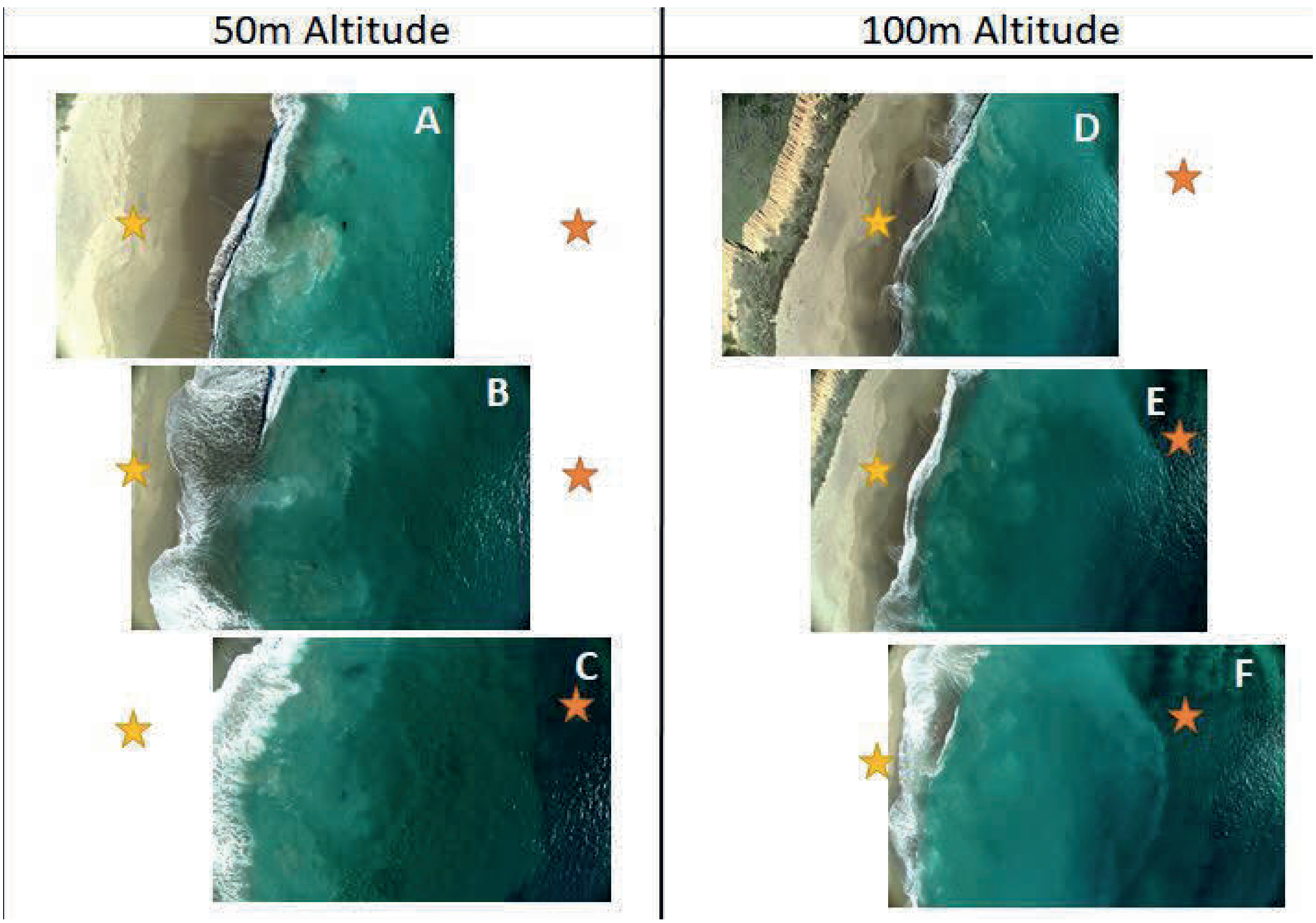


Figure 7.9. Images from neighboring flight lines are shown for both the 50 m (left) and 100 m (right) flights. Notice how the images for the 50 m flight do not overlap in any region where keypoints (stars) are present, resulting in no tie points being computed between them in SfM processing. For this reason, the 100 m altitude data was able to generate a bathymetric data product, while the 50 m altitude data was not.

7.7 Results from SfM Bathymetry can be Inconsistent

Even when all of the above considerations are taken into account to maximize the chance of a successful mapping mission, there are still instances where a dataset may fail to produce accurate results. Consider this example from St Croix. A highly textured field site with submerged coral and distinct sand channels was mapped with a DJI S900 with PPK GNSS and a Sony A6300. Active wave breaking was occurring directly offshore of the 150 m cross-shore position, and therefore, the inner area was selected to be mapped. The site off Whale Point (Figure 7.10) was mapped with 75% overlap and sidelap, at 75 m altitude. The results were compared with a recent bathymetric lidar dataset (Figure 7.11). The elevation error across the dataset is characterized by large errors of over 1 m, both positively and negatively, throughout the site. This site (Figure 7.10) had significant wave height of approximately 0.75 m, and a moderate wind chop, which could have led to these errors. The dataset from this site was not the only site that demonstrated occasional unreliable depth measurements with SfM processing. It is recommended that the considerations above are taken into account to maximize the chance of successfully mapping a region.

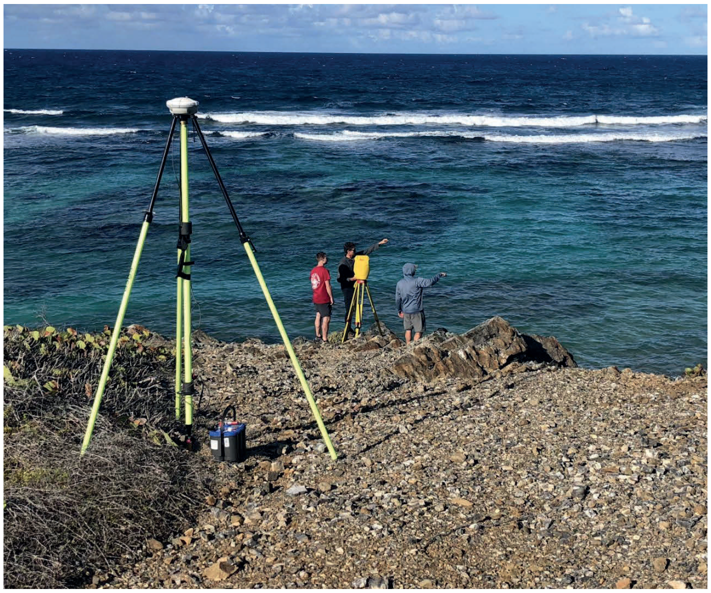


Figure 7.10. The Whale Point, USVI field site experienced large errors in some of the processed datasets, which could have been due to the wave action in the area of interest. Here members of the project team (L-R: Matt Sharr, Chase Simpson, and Bryan Costa) organize a survey plan for acquiring a ground truth dataset. Credit: Oregon State University.

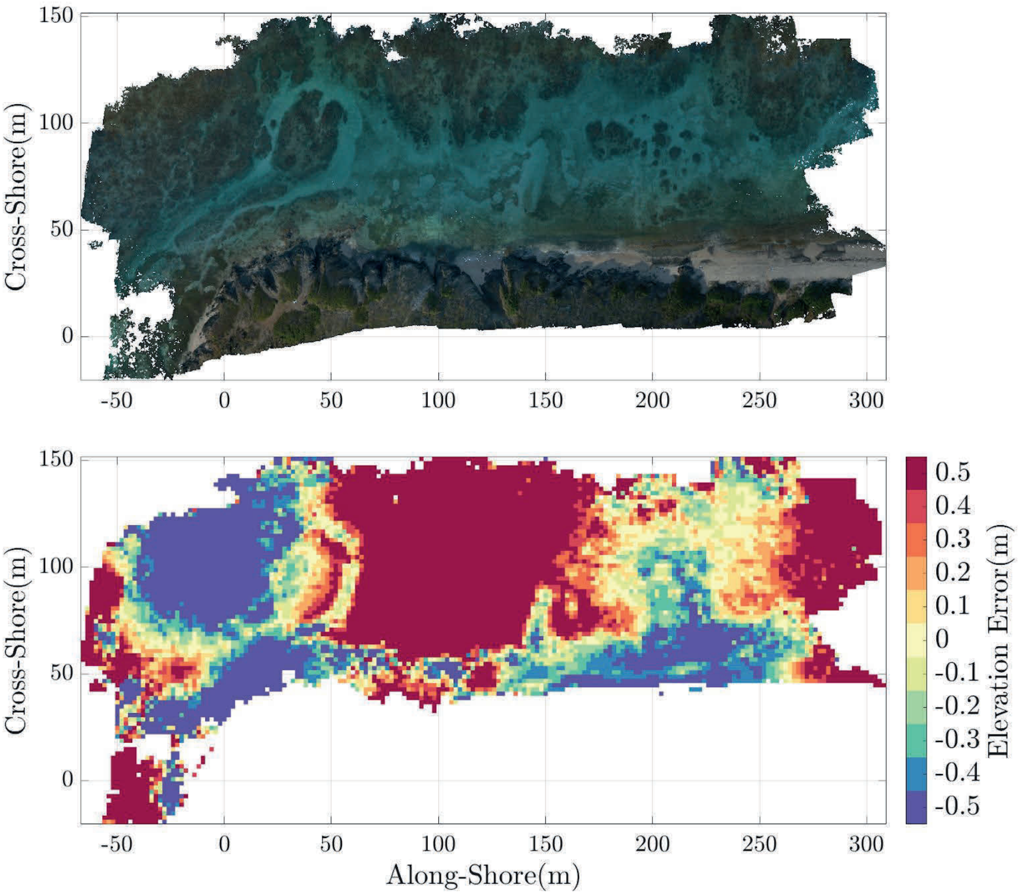


Figure 7.11. A dataset from the Whale Point, USVI field site demonstrates large errors in the computed elevations. The cause of this error is likely due to wave induced errors, but depicts the sometimes unreliable nature of using SfM for bathymetry retrieval.


sUAS image showing shoreline of Buck Island, St. Croix.
Photo Credit: Oregon State University.

Chapter 8 Limitations and Future Work

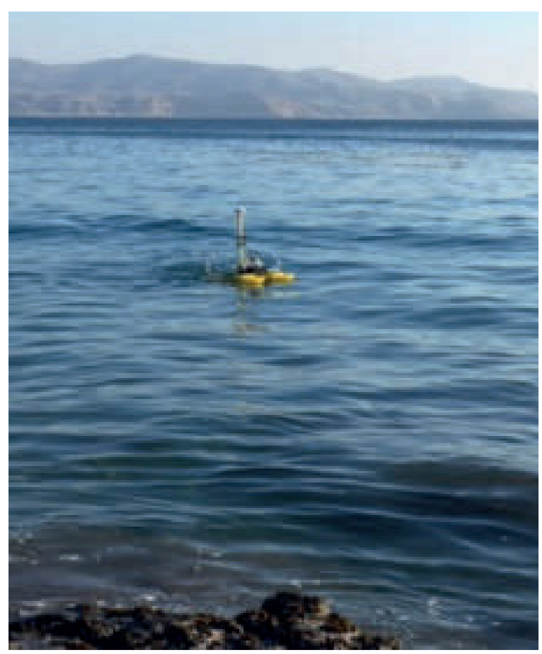
While the research underlying this report was successful in establishing a set of recommended operating procedures and guidelines for sUAS and SfM-based bathymetric mapping, it has also illuminated the need for further research and development in certain areas. One such recommendation is to conduct a detailed sensitivity analysis for all parameters in the acquisition and processing pipeline to determine the sensitivity of the output bathymetric point cloud to the various parameters and combinations of acquisition and processing parameters. The significance of this analysis is that it will enable efficiencies to be gained when the output does not depend heavily on certain parameters, and higher-quality results to be obtained, by focusing on a small number of critically-important parameters. In concert with the sensitivity analysis, it is recommended to conduct a total propagated uncertainty (TPU) analysis for SfM-bathymetry. SimUAS, a simulated sUAS image rendering workflow developed by the project team in previous research (Slocum and Parrish 2017) may be valuable in both the sensitivity and TPU analysis.

It is also important to note that, while many of the recommended parameter settings listed in this report are based on rigorous testing, others were selected based on the experience of the project team members, but have not been rigorously investigated. Hence, additional work is recommended to further test and refine these parameter recommendations. In particular, the following parameters are recommended for further analysis and potential refinement: polarization filter orientation, overlap/sidelap percentage, and flying altitude (when surface texture is consistent throughout the AOI).

Another area in which further research is needed is in developing and testing methods of transforming bathymetry produced using these methods to a specific vertical datum. For most coastal and marine applications, including nautical charting and inundation modeling, it is necessary for geospatial data to be vertically referenced to a tidal datum. Soundings on NOAA nautical charts, for example, are referenced to mean lower low water (MLLW) tidal datum, while heights are referenced to mean high water (MHW). Meanwhile, depths obtained from sUAS imagery and SfM photogrammetry, following the methods described in this report, are generally relative to the vertical datum of the aircraft trajectory and/or the ground control points (GCPs). Often this will be an ellipsoidal/3D datum (e.g., NAD 83 [2011] or WGS 84 [G1762]) or an orthometric datum (e.g., NAVD 88). Conversion of the data to a tidal datum can be achieved using a variety of methods, from water level observations (e.g., from a tide gauge) to in situ water level GNSS "shots" to modeling approaches, using the SfM-derived DEM and shoreline, to use of NOAA's VDatum tool. Research should be conducted to investigate and document approaches that enable final data requirements to be met, without significantly increasing field data collection time or costs.

Another important area for future research is developing dedicated SfM software for bathymetric mapping. In this software, the refraction correction would not be a separate step completed outside of the main SfM workflow, but would be directly incorporated into the SfM reconstruction process. This dedicated SfM bathymetric mapping software would simultaneously reduce processing time, increase accuracy, and streamline the overall workflow.

Current research by the project team is also investigating the ability to generate accurate bathymetry in regions with low bottom texture, where traditional SfM has suffered. Current research by Wayne Wright, is investigating the use of multiple sUAS with synchronized cameras, which act as a stereo camera with a variable baseline distance (Wright and Battista 2018). The advantage of this synchronized cameras



Seafloor Systems Hydrone ASV offshore of Santa Cruz Island, CA. Photo Credit: Oregon State University.

method, dubbed "FLASH SfM" by Wayne Wright, is that it can leverage the texture of the caustics that are constant between the synchronized imagery. Additional research at Oregon State University leverages the wavelength dependent radiometric attenuation of light through the water column to infer bathymetry in regions with low texture. These methods are similar to traditional SDB methods, and can help fill gaps and filter noise in traditional SfM point clouds using just one RGB camera.

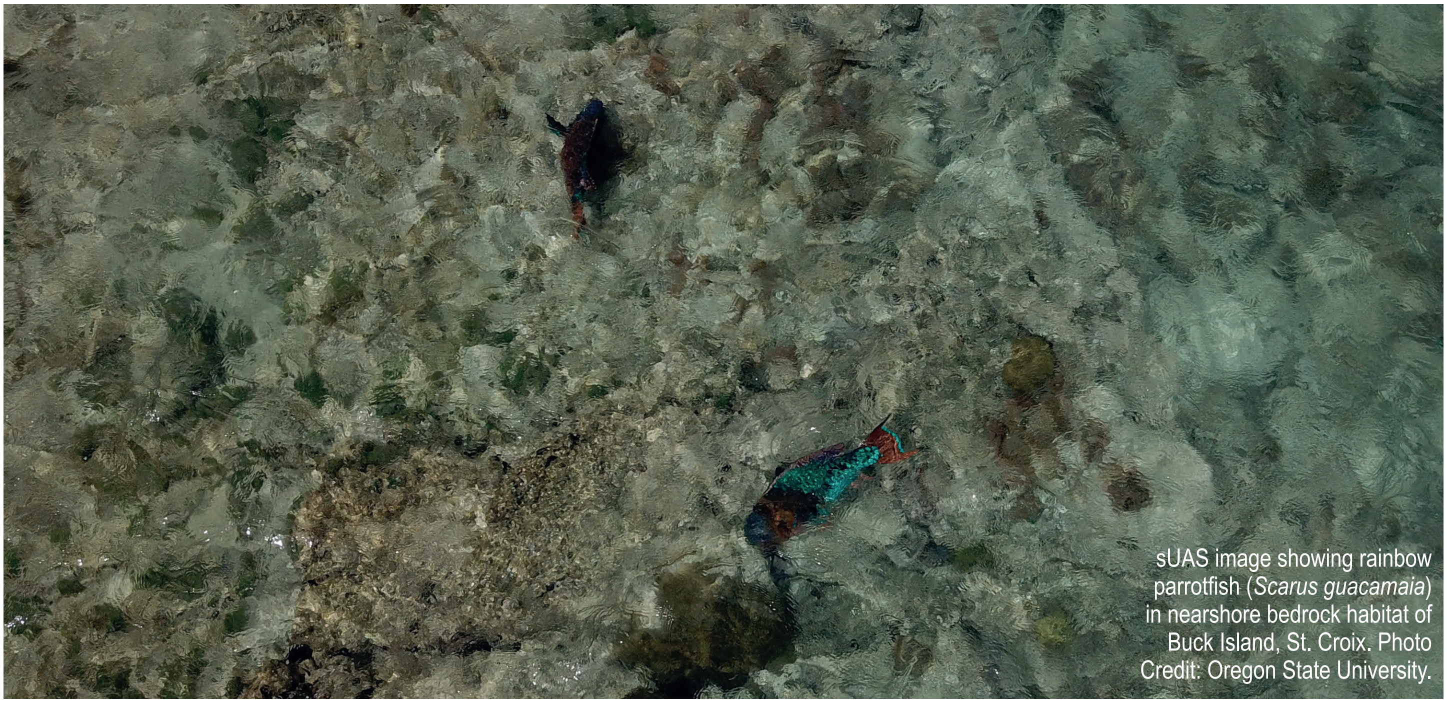
Another topic to explore in future work is potential efficiency gains achievable through cloud computing. In this project, cloud computing was not investigated, as the available services, performance capabilities, costs, and government policies regarding their use are all still rapidly evolving. However, due to the high-computational burdens (i.e., long runtimes) of SfM software, as well as the need to frequently perform SfM processing in the field, cloud computing may offer substantial benefits for sUAS-SfM coastal mapping projects.

New types of sUAS airframes should also be investigated. Efficiencies in coastal mapping may be achievable using "hybrid" aircraft that support vertical takeoff and landing, but that convert to a high-endurance fixed-wing aircraft (e.g., though rotation of the propellers) when airborne. Additionally, advances in battery technology should continue to be investigated, as batteries are generally the limiting factor in flight times.

A final topic that is recommended for future research is adding fluid lensing (Chirayath and Earle 2016) as a preprocessing step to correct the imagery for distortions due to water surface waves and improve SNR before running SfM. Fluid lensing was not considered in this report, as it was deemed too computationally expensive for operational use in a wide range of coastal/nearshore mapping projects and programs. However, computational efficiency is highly likely to improve with improved hardware and software, as well as cloud computing capabilities, as noted above. Hence, in the near future, it may be possible to obtain improved results by including fluid lensing in the workflow.

sUAS image showing nearshore coral reefs, Buck Island, St. Croix.
Photo Credit: Oregon State University.

Project team member deploys GCP target in shallow water offshore of Buck Island, St. Croix. Photo credit: NOAA NCCOS



sUAS image showing rainbow parrotfish (*Scarus guacamaia*) in nearshore bedrock habitat of Buck Island, St. Croix. Photo Credit: Oregon State University.

sUAS image showing sandy beach along Santa Cruz Island, CA. Kelp can also be seen floating offshore. Photo Credit: Oregon State University.

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Appendices

Project team members collecting depth data south of St. Croix. This data was used to independently validate SfM derived depths. Photo Credit: Oregon State University.

Appendix A Alternative Methods for Shallow-water Bathymetry

A.1 Sonar

Sonar (sound navigation and ranging) is a technique for using acoustic energy to detect and range to objects. In hydrographic surveying and general bathymetry mapping, echosounders (a type of sonar) are used to measure the two-way travel time of acoustic pulses to calculate water depths (soundings). The earliest form of echo sounding, dating back to approximately the 1930s, is single beam echo sounding. Today, most hydrographic surveying organizations, including the NOAA hydrographic survey fleet, utilize multibeam echosounders (MBES), which can produce high-resolution bathymetry across wide swaths—at least, in relatively deeper (>20 m) waters.

For most bathymetric mapping and hydrographic surveying applications, MBES surpasses other technologies, in terms of the achievable spatial resolution, coverage, and accuracy. However, the superiority of MBES diminishes in very shallow, nearshore waters (<20 m). Since MBES swath width is a function of water depth, the ability to efficiently achieve full bottom coverage in shallow waters is reduced. A greater challenge, however, relates to the potential dangers of operating boats close to shore—especially in close proximity to coral, rocks, and other submerged hazards, and in the surf zone. These considerations have led NOAA to establish a navigation area limit line (NALL), which serves as a shoreward boundary for conducting sonar surveys. By definition, the NALL is at least as far offshore as the 3.5 m depth contour, and it can be further offshore, depending on the scale of the nautical chart, the presence of other hazards, and the discretion of the Commanding Officer or Chief-of-Party (NOAA 2014).

A.2 Bathymetric Lidar

Bathymetric lidar (light detection and ranging) is an active, airborne remote sensing technique used for surveying and mapping shallow water (generally, 0–30 m depth, although some high-power systems are capable of mapping depths in excess of 70 m in very clear waters). A green-wavelength (almost always, 532 nm) laser is used to range from the sensor on the aircraft to the seafloor, accounting for the change in direction (refraction) and speed of light at the air-water interface. Laser range vectors and pointing angles are combined with post-processed global navigation satellite system (GNSS) aided inertial navigation system (INS) data to generate accurate 3D spatial coordinates of points on the seafloor. Although there continues to be some level of debate about the ability to meet object detection requirements with bathymetric lidar, it has been well-established that high-end bathymetric lidar systems are capable of meeting International Hydrographic Organization (IHO) Order 1 total vertical uncertainty (TVU) standards (IHO 2008). While bathymetric lidar can be a nearly ideal technology for acquiring nearshore bathymetric data in areas of reasonably clear water, it can be expensive to deploy, particularly in remote locations or for repeated surveys. Lidar systems are being deployed on satellites (e.g., NASA ICESat-2 Advanced Topographic Laser Altimeter System [ATLAS]; Forfinski-Sarkozi and Parrish 2019, Parrish et al. 2019), but their capabilities are still being tested for mapping nearshore bathymetry.

A.3 Total Station/GNSS traditional surveying

Among the most common instruments for land surveying are total stations and GNSS receivers. To achieve the level of accuracy required for most surveying applications requires so-called "survey grade" GNSS, which generally means carrier-phase based relative positioning in the form of static, real-time kinematic (RTK), or post-processed kinematic (PPK) surveys. While these types of ground-based surveying technologies are capable of providing accuracies from a few centimeters down to millimeters in some cases, total stations and GNSS only capture information at discrete points and are not designed to work underwater (GNSS-Acoustic or GNSS-A positioning is not considered here.) Hence, they are only viable for nearshore bathymetric surveying at discrete points in the shallowest areas in which a person can stand with a survey rod. Additionally, this method of shallow-water surveying can be dangerous in the presence of breaking waves, rocks, coral, and other submerged hazards.

A.4 Satellite derived bathymetry

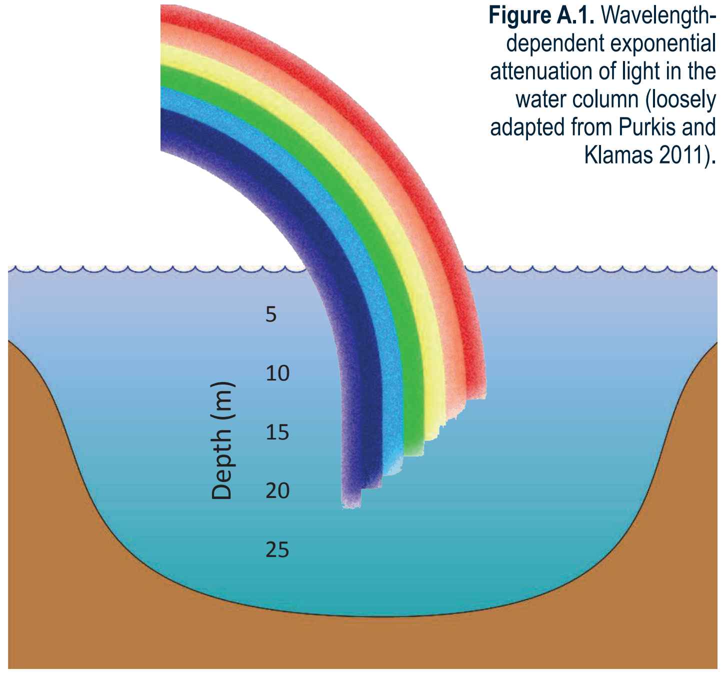

Figure A.1. Wavelength-dependent exponential attenuation of light in the water column (loosely adapted from Purkis and Klamas 2011).

Satellite derived bathymetry (SDB), which can also be taken as an abbreviation for spectrally-derived bathymetry, is the term for a broad range of techniques for retrieving bathymetry from multispectral (or, less frequently, hyperspectral) satellite imagery. A large number of SDB algorithms and procedures exist, and new ones continue to be developed, as SDB is currently an active area of research. Some SDB algorithms are highly empirical in nature, whereas others are more theoretical, but all are based on the wavelength-dependent exponential attenuation of light in the water column, as illustrated in Figure A.1. A common approach, used in algorithms such as the one presented in Stumpf et al. (2003), involves determining linear relationships between reference depths and logarithms or ratios of logarithms of different spectral bands, such as the blue and green image bands. The linear model is then used to compute bathymetry, pixel-by-pixel, from the input multispectral imagery. Common preprocessing steps include sunglint removal and atmospheric correction.

As with all optical remote sensing techniques for bathymetric mapping, water clarity is a limitation. Another challenge with SDB is that most techniques require reference or seed depths. It is important to note that sUAS-SfM bathymetry and SDB are highly complementary. sUAS-SfM works best when the seabed is highly textured, such as over coral reefs, rocks, or distinct bedforms. Meanwhile, SDB often works better over homogeneous bottom types, such as sand, because the depth retrieval is less likely to be confused by changing bottom types.

A.5 Other Approaches

sUAS are now being used to map bathymetry in shallow-water regions using a number of spectral (Shintani and Fonstad 2017), photogrammetric (Casella et al. 2016), and speed-of-wave-crest (Matsuba and Sato 2018) techniques. One approach in particular, called the NASA fluid lensing (Chirayath and Earle 2016), interrelates with the techniques presented in this report. Briefly, the fluid lensing algorithms remove the distortions due to surface waves in imagery of submerged objects or surfaces by taking advantage of time-varying optical lensing (Chirayath and Earle 2016). This technique has been shown to improve the signal-to-noise ratio (SNR) and to remove distortions prior to inputting sUAS imagery of submerged scenes into SfM software (Chirayath and Earle 2016). Despite the great promise of fluid lensing and the impressive results presented in the published literature, fluid lensing was not considered in this work, due to the computational complexity, which can necessitate high-performance computing facilities. Because the methods presented here are designed to be operationally feasible for a wide variety of projects and programs, the focus was purposefully narrowed to approaches that utilize commercial off-the-shelf software (COTS) on readily-available and relatively-inexpensive workstations (although generally with a higher-end CPU and graphics cards). However, fluid lensing as a pre-processing step to the techniques presented in this report is a recommended topic for future research (see Chapter 7).

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Appendix B Mission Reports

The project team generated mission reports upon completion of each field effort. Examples of these reports have been provided in this appendix.

NCCOS Mission Trip Report: Buck Island, St. Croix, U.S. Virgin Islands

OPTIMIZING OPERATIONAL WORKFLOWS FOR BATHYMETRIC MAPPING USING UAS

FUNDED BY NOAA OFFICE OF ATMOSPHERIC RESEARCH (OAR)

PROJECT BACKGROUND

Many agencies, including NOAA, need elevation and depth information to make decisions along our nation's coastlines. These nearshore areas are often inaccessible and/or inefficient to map using sound navigation and ranging (SoNAR) mounted on ships. LiDAR (light detection and ranging) can often be prohibitively expensive to collect, especially in remote tropical locations around the United States territories and freely associated states. Photographs acquired by small unmanned aerial systems (sUAS) combined with Structure from Motion (SfM) software offers a potentially inexpensive method to fill this critical data gap at spatial resolutions that far exceed other technologies (Figure 1). However, SfM results are highly dependent on the environmental conditions (e.g., wind, waves, sun angle, turbidity), acquisition parameters (e.g., camera type, GPS accuracy, flying height, look angles, photo overlap), and processing techniques that are applied. Additional research is needed to identify optimal sUAS payloads and parameters, as well as post-processing workflows before being implemented more widely across NOAA. The objective of this 2 year project (July 2017-May 2019) is to develop standard methods and operating procedures (SOPs) for mapping nearshore elevations and depths using sUAS and SfM technologies.

Figure 1. sUAS imagery collection. (Left) Diagram depicting how sUAS collects high resolution photographs. (Right) Map showing sUAS imagery (inside the red polygon) overlaid on imagery collected using a fixed wing plane for the same geographic area. sUAS platforms and cameras can collect images that are 50 times more resolved than aerial-based sensors (e.g., 0.5x0.5 m versus 1x1 cm, respectively) and 200 times more resolved than satellite-based sensors (e.g., 2x2 m versus 1x1 cm, respectively).

...a and Bryan Costa, conducted field operations on St. Croix, U.S. Virgin ...to April 4, 2018 with partners from Oregon State University (Chris Parrish, ...n), Wayne Wright Consulting (Wayne Wright), NOAA Office of Coast ... Park Service (Clayton Pollock) and VI Department of Natural Resources ... of the mission was to test the impact of various acquisition parameters ...s on the elevation/depth surfaces derived from sUAS photos using SfM ...ll be used to inform SOPs developed at the end of the project. Six ...ed over the mission (Figure 2) in the Buck Island Reef National Monument ... Park (EEMP), including Isaac Bay, Rod Bay, Jack Bay, and Whale Point. ...Chase Simpson and Wayne Wright piloted the sUAS (Figure 3) and ...fforts. Clayton Pollock provided boat and logistical support for the Buck ...rovided field support for the East End Marine Park (EEMP) sites.

...otographs were collected using sUAS on St. Croix, USVI. Panoramic photos of the field sites are in

OSU Mission Trip Report: Buck Island, St. Croix, U.S. Virgin Islands

Oregon State University OSU

UAS Mapping and Control Surveying on St Croix, VI, USA

Mar 19 Apr 04, 2018

OSU Trip Report

Prepared By:
Christopher Parrish
Chase Simpson
Richard Slocum

April 11, 2018

ersonnel Chris Parrish, Chase Simpson, and Richie Slocum conducted field-
ween Mar 19, 2018 and Apr 04, 2018. The fieldwork was in support of a
nine a standard operating procedure(SOP) for utilizing imagery from Un-
d Structure from Motion(SfM) processing algorithms to map bathymetry.
Battista(NOAA), Bryan Costa(NOAA), Clayton Pollock(NPS), Nate Hol-
, and Wayne Wright(Wayne Wright Consulting). March 19-27 was focused
d, while Mar 28-April 2 was focused on data acquisition at locations in the
n the Eastern side of St Croix.
otal of 82 flights to acquire data using two UAS platforms, the DJI Mavic
s flown with a visual observer and a pilot in command(PIC) with a part 107
attained to allow for flights on Buck Island, as it is a national monument
Service. In order to best develop a SOP, a variety of the flight plans were
rying the numerous acquisition parameters such as sidelap/overlap, camera
round sampling distance, oblique camera angle, and UAS GNSS Accuracy.
based on the results from simUAS, a computer graphics based workflow
acy assessments, which indicated that these parameters may correlate with
maps. The results of the experiments performed on the USVI will serve to
UAS results, as well as direct future simUAS experiments. The results from
l in combinarion twith the simUAS results as the qualitative foundation for
c mapping from a UAS platform.
l traditional surveying equipment including two Trimble R8-2 GNSS Re-
Station with a 360 prism, and a Hydrolite-TM echosounder. With the
OAA team, Ground Control Points(GCPs) were surveyed and groundtruth
f the sites.

r next steps

n in Table 1, which outline the steps involved in organizing and processing

e 1: Preliminary post-fieldwork tasks for OSU.

OSU Task	Date
Process Control Data	20-Apr
Provide link with "Best" Pictures/Videos	20-Apr
Develop Processing Plan	20-Apr
Organize All Raw Data + Pictures/Video	27-Apr
Finish Preliminary Processing Data	27-Jun
Summarize Results in Report	27-Jul
Develop New simUAS Experiments	27-Jul

3 Goals and Experiment Design

The goal of the data acquisition in the USVI was to acquire UAS data and corresponding groundtruth data which would provide a foundation for the development of a SOP for UAS mapping of bathymetry. With this goal in mind, data was acquired at six locations, under a variety of environmental conditions, and with various systematic variations in UAS acquisition parameters. While most of the UAS imagery was acquired in scenarios which intuitively seemed favorable for SfM processing, data was also acquired in locations which could yield poor results from SfM. For example, significant wave heights and breaking waves at Whale Point will likely generate inaccurate SfM results. The intention with acquiring data at field sites with unfavorable

NCCOS Mission Trip Report: Santa Cruz Island, California

LEVERAGING DRONES & EMERGING TECHNOLOGIES TO MAP SHALLOW-WATER ENVIRONMENTS IN CHANNEL ISLANDS, CA

TRIP REPORT (DECEMBER 11-18, 2018)

EXECUTIVE SUMMARY

Several organizations, including the National Oceanic and Atmospheric Administration (NOAA), need imagery, elevation and depth data to inform management decisions in the coastal zone. However, many near-shore areas are difficult to access, making them challenging and expensive to map with existing technologies. As a result, many data gaps exist in near-shore areas of the United States. Autonomous platforms (also known as drones) could potentially fill these gaps and map coastal regions accurately, safely and cost-effectively. When combined with Structure from Motion (SfM) software, autonomous aircraft (small Unmanned Autonomous Systems or sUAS) and boats (Autonomous Surface Vessels or ASV) are capable of producing centimeter-scale photo-mosaics, elevation and depth surfaces for near-shore environments. However, additional research is needed to identify environmental and operational limitations of these systems before being implemented more widely across NOAA.

NOAA's National Center for Coastal Ocean Science (NCCOS) and Oregon State University (OSU) previously tested sUAS and SfM technologies in tropical environments to identify optimal sUAS payloads and processing workflows. Initial results from this work were promising (click here), leading to follow on research in the Channel Islands, CA. The objective of this subsequent field work was to understand the potential limitations of sUAS and potential benefits of ASVs and in more remote locations and challenging, temperate environments.

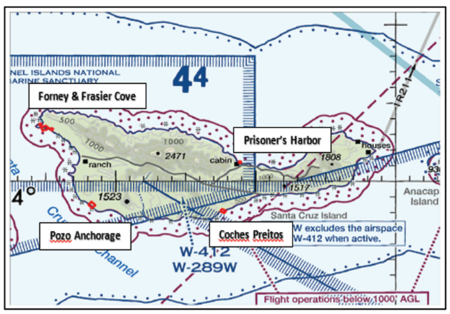


Figure 1. Four project sites (red polygons) were mapped around Santa Cruz Island, California using a sUAS and ASV.

Between December 11-18, 2018, four geographic areas were mapped using sUAS and ASV around Santa Cruz Island, CA (Figure 1). NCCOS and OSU led this fieldwork, in collaboration with the Nature Conservancy (TNC), University of California, Santa Barbara (UCSB), Channel Islands National Park (CINP), and NOAA Channel Islands National Marine Sanctuary (CINMS). Several thousand digital aerial images were collected using a DJI Phantom 4 Pro RTK sUAS (Figure 2). These images will be used to generate nearshore elevation and depth surfaces (Figure 3) in SfM software. The Seafloor Systems HyDrone ASV (Figure 4) was used to collect thousands of depth soundings (Figure 5). These soundings will be used to independently validate the depths derived from the sUAS imagery and SfM software. Next steps for this project include using these datasets to define the environmental and operational

...s, and to better understand how and where these technologies ...AA's existing seafloor mapping capabilities.

...m 4 Pro RTK ... on Santa Cruz

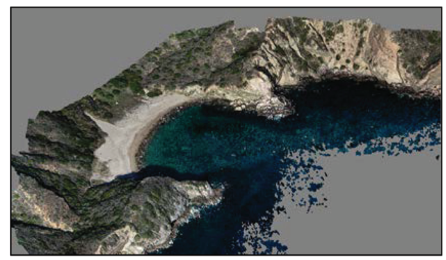


Figure 3. A 3D model created using sUAS imagery and SfM software for Coches Preitos Anchorage. This model will be processed further into absolute elevations and depths.

Figure 4. Photograph of the Seafloor Systems HyDrone ASV, which used in the field work on Santa Cruz Island.

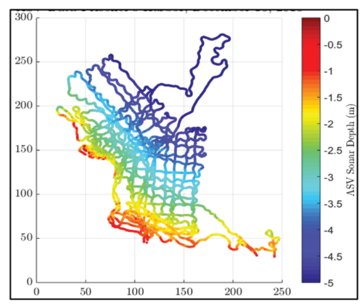


Figure 5. Depth soundings were collected using a singlebeam ecosounder mounted on the ASV. This data will be used to validate the depths derived from the sUAS imagery and SfM software.

FIELD MISSION

On Dec 10, Oregon State University (Chris Parrish and Richie Slocum) and NOAA NCCOS (Bryan Costa) gave a presentation at NOAA CINMS in Santa Barbara, CA. The presentation described the objective of the field mission on Santa Cruz Island, and showcased the technology to our partners, including the sUAS and ASV. Attendees included staff from NOAA CINMS, NOAA Office of Coast Survey, UCSB Marine Science Institute, TNC and the CINP. On December 11, Chris Parrish, Richie Slocum and LTJG Jen Kraus (NOAA NCCOS) (Figure 6) boarded a NPS vessel headed to Santa Cruz Island. While onboard, the team met with Todd Jacobs (NOAA CINMS Deputy Superintendent), who joined for the day to provide valuable insights on sUAS operations.

Figure 6. Left to Right: LTJG Jennifer Kraus (NOAA NCCOS), Richie Slocum (OSU) and Dr. Chris Parrish (OSU).

OSU Mission Trip Report: Santa Cruz Island, California

SIMoN Sanctuary Integrated Monitoring Network

Title *Leveraging Drones and Autonomous Boats for Mapping and Monitoring of Shallow Water Environments in the Channel Islands*

Overview

- Abstract

Repeat mapping of shallow water environments is essential for monitoring damage and recovery from episodic events (e.g., major storms), as well as chronic coastal erosion and habitat degradation. Bathymetric data covering the shallowest areas (<5 m water depth) can be challenging to collect, yet is critically needed for benthic habitat mapping. These data are also of interest to NOAA s Office of Coast Survey (OCS), in areas such as the Channel Islands, where offshore breakers can prohibit vessels from surveying to the navigation area limit lime (NALL). Topobathymetric lidar from conventional (manned) aircraft is often an effective technology, but it can be too expensive for repeat monitoring at high temporal frequencies. Furthermore, the mobilization times can be prohibitive when data are needed immediately after a storm other disaster.

Small, lightweight, autonomous vehicles both airborne and waterborne offer the potential to overcome these challenges. Specifically, small autonomous surface vehicles (ASVs) and unmanned aircraft systems (UAS) offer the advantages of being highly portable and enabling efficient, cost effective repeat data acquisition at high spatial resolutions. Small ASVs, with very shallow drafts (≤15 cm) can safely transit all but the very shallowest waters, while UAS can safely overfly the site. The combination of ASVs and UAS, leveraging the strengths of each, may provide the optimal data collection technology for repeat monitoring of shallow, nearshore environments. However, to effectively leverage these technologies, research is needed to define optimal data acquisition and processing strategies, test payloads/sensors, and develop processing algorithms to generate the final geospatial data products. This project builds on previous research conducted by NOAA's National Center for Coastal Ocean Science (NCCOS) and project partners are Oregon State University in the U.S. Virgin Islands, in which UAS and structure from motion (SfM) software were tested for bathymetric mapping. The current project involves extending this work to the Channel Islands National Marine Sanctuary (CINMS), and testing the combination of UAS and ASVs for shallow water mapping.

- Project Contact Info

NOAA

Tim Battista: tim.battista@noaa.gov

Bryan Costa: bryan.costa@noaa.gov

LTjg Jen Kraus: jennifer.kraus@noaa.gov

ctions to the bathymetric points and systematically
acquisition parameters and settings. The results are
ommended procedures for using UAS and ASVs in NOAA
nitoring programs.

ct for monitoring trends to be assessed. However, it is
dures developed in this work will facilitate effective, long

groundwork for best practices for shallow water mapping
pport of NOAA seafloor mapping programs. With the
ners from CINMS, TNC, and UCSB, we were able to
quire data in the five project sites. Initial processing is
l by Fall 2019.

p products will be provided as processing and analysis are

Methods

See above

Location/GPS coordinates

Project site	Approximate center coordinates (ϕ, λ)
Prisoners Harbor	34° 01' 14" N, 119° 41' 10" W
Forney Cove	34° 03' 23 N, 119° 55' 05 W
Pozo Anchorage	33° 58' 28 N, 119° 51' 43" W
Fraser Point	34° 03' 32" N, 119° 55' 33" W
Coches Prietos Anchorage	33° 58' 05 N, 119° 42' 21" W

Appendix C Example Data Structure

```
|-- 20180319_USVI_UAS_BATHY
    |-- 01_RAWDATA
    |   |-- yyyymmdd_SITEID
    |       |-- 01_UAS
    |       |   |-- HHMM_DRONE_ID
    |       |       |-- 01_MISSIONPLANNING
    |       |       |-- 02_MAPIMAGES
    |       |       |-- 03_EXTRAIMAGES
    |       |       |-- 04_AUTOPILOTLOG
    |       |       |-- 05_CARRIERPHASEGNSS
    |       |-- 02_CONTROL
    |       |   |-- 01_CORSBASE
    |       |   |-- 02_SONAR
    |       |   |-- 03_TOTALSTATION
    |       |   |-- 04_TRIMBLE_STATIC
    |       |   |-- 05_TRIMBLE_ROVER
    |       |   |-- 06_WAYNEGNSS_STATIC
    |       |-- 03_MEDIA
    |       |-- 04_FIELDLOGS
    |           |-- yyyymmdd_siteid_initials.txt
    |-- 02_PROCDATA
    |   |-- 01_CONTROLPROC
    |   |   |-- yyyymmdd_SITEID_procid
    |   |       |-- starnetprojects.txt
    |   |-- 02_RECOLORIMAGES
    |   |-- 03_PHOTOSCAN
    |       |-- yyyymmdd_SITEID_procid
    |-- 03_DELIVERABLES
        |-- 01_GEOSPATIAL
        |   |-- 01_GCPS
        |   |   |-- yyyymmdd_SITEID
        |   |       |-- yyyymmdd_siteid_GCPS_meta.txt
        |   |       |-- yyyymmdd_siteid_coords.csv
        |   |       |-- yyyymmdd_siteid_map.jpg
        |   |-- 02_GROUNDTRUTH
        |   |   |-- yyyymmdd_SITEID
        |   |       |-- yyyymmdd_EARLB.las
        |   |       |-- yyyymmdd_EARLB_metadata.txt
        |   |       |-- yyyymmdd_sonar.csv
        |   |       |-- yyyymmdd_sonar_metadata.txt
        |   |       |-- yyyymmdd_topo.csv
        |   |       |-- yyyymmdd_topo_metadata.txt
        |   |-- 03_POINTCLOUD
        |   |-- 04_ORTHO
        |-- 02_WEB
        |-- 03_MEDIA
        |   |-- 01_OFDRONES
        |   |-- 02_FROMDRONES
        |   |-- 03_FIELDSITE
        |   |-- 04_TOTALSTATION
        |   |-- 05_GPS
        |   |-- 06_KAYAK
        |   |-- 07_PERSONNEL
        |   |-- 08_MISCELLANEOUS
        |-- 04_REPORT
            |-- 01_FIG
            |-- 02_TAB
            |-- 03_DOC
            |-- 04_PPT
```

Figure C.1. Example data structure for data collected by the project team in the USVI.

Appendix D Project Documents

In order to execute the field work, various documentation submissions and approvals were required. This appendix provides examples of the required documents for authorized execution of mission operations such as Categorical Exclusion approval, NPS and CINMS research permits, and FAA forms for AUV operations.

D.1 Memos

NOAA Categorical Exclusion Memos

U.S. Virgin Islands

UNITED STATES DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL OCEAN SERVICE
National Centers for Coastal Ocean Science
Silver Spring, Maryland 20910

MEMORANDUM FOR: The Record

FROM: Margo Schulze Haugen.
Acting Deputy Director

SUBJECT: Categorical Exclusion for the UAS Program NCCOS Project #731 Optimizing Operational Workflows for Bathymetric Mapping with UAS

ENCLs: (1) NPS Buck Island Permit BUIS 2018-SCI 0012 (expiration Dec 31, 2018)
2) Aviation Safety Plan for Buck Island St. Croix, USVI (Operational dates: March 1 31, 2018)
(3) USVI DPNR/CZM email clearance for UAS activities in St. Croix East End Marine Park

NOAA Administrative Order (NAO) 216 6A, Environmental Review procedures, requires all proposed projects to be reviewed with respect to environmental consequences on the human environment. This memorandum addresses the determination that the activities described below for Unmanned Aerial Systems (UAS) Program NCCOS Project #731, Optimizing Operational Workflows for Bathymetric Mapping with UAS , qualifies for a categorically exclusion and thus is not subject to further review under the National Environmental Policy Act (NEPA).

Categorical Exclusion:
This project's activities fall within the scope of the E3 Categorical Exclusion defined in the Companion Manual for NAO 216-6A, Appendix E as activities to collect aquatic, terrestrial, and atmospheric data in a nondestructive manner. This project is applicable because it involves operating UAS under under the terms and conditions of the flight safety plan and permits to non-destructively collected aerial imagery in a manner that ensures no impact to the environment.

Purpose and Need:

To meet mission critical observational goals, NOS and NMFS need more complete and resolved baseline information about the health, quantity, and distribution of shallow water marine environments. Bathymetry (depth) is one of the most basic layers and the starting point for many of NOS s and NMFS s analyses and requirements. However, depths in shallow (<20 m), remote nearshore environments are often too difficult (acoustic sonar) and/or costly (lidar) to accurately map using existing technologies. Unmanned Aerial System (UAS) imagery, processed in structure from motion (SfM) software has the potential to fill this informational need, and derive depths in shallow environments safely and cost effectively. During this evaluation study, NCCOS intends to develop

(SOPs) for using UAS to observe seafloor properties in waters too
vigate with ships or small boats.

ght Consulting and Oregon State University (OSU) with support by the
), National Park Service (NPS), and National Oceanic and Atmospheric
es Wayne Wright is the mission commander and Pilot in Command
trol of this mission. Chris Parish is the Visual Observer (VO) and
t.

h objectives in two phases. The first phase includes only office based
State University s (OSU) SimUAS (simulated UAS) image rendering
tion and processing workflows for deriving accurate shallow

ld activities that will result in a refinement of the procedures in phase 1,
gery and ground truthing. UAS imagery will be acquired at three general
USVI. Flights will be conducted over the submerged reef environment
d Buck Island National Monument (Figure 2), Jack Bay and Cramer
d Marine Park (Figure 3).

evation (30m to -30m), topographic complexity, habitat variability,
urbidity, wave exposure), and are easily accessible by boat (Buck Island)
rk, Jack Bay). Imagery will be acquired in the shallow water areas
o separate UAS rotary wing aircraft (senseFly albris and 3DR solo) and
e, eighteen (18) hours of flight time is required with each aircraft a

ndor Wayne Wright Consulting, measures approximately 2 feet in
less, and are electrically powered. NOAA routinely uses these aircraft for
missions and marine resource inventories. Our research project proposes
uad-copter aircraft at heights ranging 30 to 400 feet above sea level
mately 14 mph airspeed. NOAA propose to fly six, 30 minute missions
rate days in March 22 and 26, 2018. During these missions, NOAA will
a 500 meter line of site radius of the landing/take off site.

Channel Islands National Marine Sanctuary

UNITED STATES DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL OCEAN SERVICE
National Centers for Coastal Ocean Science
Silver Spring, Maryland 20910

MEMORANDUM FOR: The Record

FROM: Margo Schulze-Haugen
Deputy Director

SUBJECT: Categorical Exclusion for the UAS Program NCCOS Project #731
Optimizing Operational Workflows for Bathymetric
Mapping with UAS

ENCL: (1) NOAA Channel Islands NMS Permit CINMS 2018-011
(2) USFWS IPaC resources lists
(3) National Park Service communication email – nesting birds
(4) Aviation Safety Plan for Channel Islands, CA
(Operational dates: December 11 - 18, 2018)

NOAA Administrative Order (NAO) 216 6A, Environmental Review procedures, requires all proposed projects to be reviewed with respect to environmental consequences on the human environment. This memorandum addresses the determination that the activities described below for Unmanned Aerial Systems (UAS) Program NCCOS Project #731,"Optimizing Operational Workflows for Bathymetric Mapping with UAS , qualifies for a categorically exclusion and thus is not subject to further review under the National Environmental Policy Act (NEPA).

Categorical Exclusion:
This project's activities fall within the scope of the E3 Categorical Exclusion defined in the Companion Manual for NAO 216-6A, Appendix E as activities to collect aquatic, terrestrial, and atmospheric data in a nondestructive manner. This project is applicable because it involves operating Unmanned Aerial System (UAS) and Autonomous Surface Vehicles (ASV) under the terms and conditions of the flight safety plan and permits to non-destructively collected aerial imagery and aquatic imagery in a manner that ensures no impact to the environment.

Purpose and Need:

To meet mission critical observational and management goals, NOS and The Nature Conservancy (TNC) need more complete and resolved baseline information about the health, quantity, and distribution of shallow water marine environments. Bathymetry (depth) is one of the most basic and fundamental layers needed for management and analyses. However, depths in shallow (<20 m), remote nearshore environments are often too difficult (acoustic sonar) and/or costly (lidar) to accurately map using existing technologies. UAS imagery and ASV, processed

software has the potential to fill this informational need, and
nments safely and cost effectively. During this evaluation study,
ersity (OSU) intend to develop Standard Operating Procedures
/ to observe seafloor properties in waters too shallow and/or
s or small boats. OSU is under a Cooperated Grant to NCCOS
nd OSU have previously conducted this approach in Buck Island
roix, USVI (2018), but propose to test in a new geographic region
ogies potential.

e University (OSU) with support from the Nature Conservancy
at Santa Barbara (UCSB), Department of the Interior (DOI),
nd National Oceanic and Atmospheric Administration (NOAA)
tuaries (ONMS). Chris Parrish (OSU) is the mission commander
d is in Operational Control of this mission. Richie Slocum (OSU)
the project.

h objectives in two phases. The first phase includes only office
regon State University s (OSU) SimUAS (simulated UAS) image
nal acquisition and processing workflows for deriving accurate

ld activities that will result in a refinement of the procedures in
ASV acquired imagery and ground truthing. UAS and ASV
d western portion of Santa Cruz Island, California, part of the
Channel Islands National Marine Sanctuary and Santa Cruz Island Reserve. Surveys will be conducted over the submerged habitats out to a distance of 500 m around Santa Cruz Island (Figures 1 and 2).

The objective of this mission is to test the ability of small unmanned aircraft systems (sUAS) and autonomous surface vessels (ASVs) to map depths in waters too dangerous to navigate using manned ships, and too prohibitively expensive to map using manned aircraft. These autonomous platforms will collect photographs along the coastline between December 11 18, 2018 at select locations around Santa Cruz Island, California. These photographs will be used to create photomosaics and digital elevation models for these near shore areas using Structure from Motion (SfM). Operations will only occur from land owned by the Nature Conservancy (TNC). Potential project sites include: Forney s Cove, Blue Gum Cove, South end of Fraser Cove, west side of Prisoner s Harbor, Coches Prietos, Pozo Anchorage, and Valley Anchorage. These selected sites were chosen in consultation with project partners. They are within Class G airspace (Figure 2 and 3).

2

Department of Interior UAS Request (National Park Service)

United States Department of the Interior

National Park Service
Christiansted National Historic Site
Buck Island Reef National Monument
Salt River Bay Historical Park and Ecological Preserve
2100 Church Street #100
St. Croix, Virgin Islands 00820
(340) 773-1460

IN REPLY REFER TO:

August 7, 2017

To: Regional Director, Southeast Region
Through: Regional Aviation Manager, Northeast, Southeast and NC Regions
From: Superintendent, Buck Island Reef National Monument
Subject: Request for Approval for Small Unmanned Aerial System

Purpose: The purpose of this memo is to request an approval for Wayne Wright Consulting and Oregon State University (OSU) to use a small Unmanned Aircraft System (UAS) as part of a scientific research study at Buck Island Reef National Monument (BUIS). This study will document and characterize marine habitats (coral reefs, sea grass pastures) and generate 2D seafloor mosaics and 3D depth surfaces in shallow-water (<5 m) environments at selected sites within BUIS. In addition, this study will identify optimal acquisition payloads and parameters, as well as post-processing workflows of interest to the Department of Interior, National Park Service and the Department of Commerce, National Oceanic and Atmospheric Administration (NOAA).

This collaborative research was funded by the National Oceanic and Atmospheric Research UAS Program (UASPO) to optimize these parameters, payloads and techniques, and develop standard operating procedures (SOPs) that can be used to derive accurate bathymetry from UAS imagery and SfM software. This work will be executed under an "end product contract" between NOAA and Wayne Wright Consulting/Oregon State University (OSU), with support provided by NPS and NOAA.

Designated Locations and Dates: Four possible study areas have been selected within BUIS from input from NPS BUIS staff (A and C - south shore, E and F north shore). See attached study area map. Project will occur between March 15th and April 15th 2018.

---

olicy: This project complies with NPS Policy
4).

ill not interfere with NPS Operations: Field operations for
staff and all appropriate contact information is in place. A
included with this submission. Wayne Wright Consulting
Command (PIC) under his UAS and Pilot certifications,
) Part 107. Flights will be conducted over multiple test areas
5th and April 15th 2018. Flights will be conducted during
nce of the PIC, and within line-of-sight of the PIC. The UAS
beach areas proximal to the proposed study sites (sections A,
ctivities in areas where field operations may overlap with
early morning hours prior to the arrival of concessionaire
e conducted in sections E & F in the early morning or late
these areas is limited, particularly during those times.
not interfere with NPS operations, UAS will be grounded if
dy sites. This mission complies with DOI Aviation policyand
ns will be conducted in accordance with PASP including

t: Data management and processing is outlined in NPS
0. Analysis of imagery from multiple UAS payloads,
s with Global Shutters and accurate "mid shutter"
st-processed kinematic (PPK) carrier phase global positioning
AA National Centers for Coastal Ocean Science offices and

Why UAS use is consistent and appropriate with the Organic Act and NPS authorities: This research will yield important data which will support NPS resource management requirements by providing a cost-effective means to generate 2D seafloor mosaics and 3D depth surfaces in shallow-water (<5 m) environments using imagery processed in structure from motion (Sfm) software. Seafloor mapping in these environments is dangerous, impossible, and/or prohibitively expensive to access with either manned airborne or marine assets. These images will be used to detect and quantify changes in benthic community composition and health while not causing unacceptable impacts on park resources, values, and visitor experiences. This research will identify optimal acquisition payloads and parameters, as well as post-processing workflows that can then be implemented more widely across federal agencies.

Compliance: This project will comply with the conditions prescribed in the NPS BUIS research and collections permit: BUIS-2017-SCI-0010. Furthermore, this project's activities were determined to fall within the scope of the E3 Categorical Exclusion defined in the NOAA Administrative Order (NAO) 216-6A as activities to collect aquatic, terrestrial, and atmospheric data in a nondestructive manner (CE memo attached with submission). NPS BUIS concurs with this determination. Real-time observations of the UAS flight will ensure no adverse impacts to geographically or ecologically critical areas, National Historic Sites, and no adverse impacts to marine mammals, essential fish habitat (marsh, wetlands, seagrasses, corals, etc), or threatened and endangered species or their critical habitat. No impacts to birds protected under the Migratory Bird Protection Act are anticipated.

D.2 Forms and Permits

Research Permits

U.S. Virgin Islands National Park Service

SCIENTIFIC RESEARCH AND COLLECTING PERMIT
Grants permission in accordance with the attached general and special conditions
United States Department of the Interior
National Park Service
Buck Island Reef

Study#: BUIS-00079
Permit#: BUIS-2017-SCI-0012
Start Date: Jan 01, 2018
Expiration Date: Dec 31, 2018
Coop Agreement#:
Optional Park Code:

Name of principal investigator:
Name: Dr Wayne Wright **Phone:** 443-783-3319 **Email:** wayne.wright@noaa.gov

Name of institution represented:
Wayne Wright Consulting

Co-Investigators:

Name	Phone	Email
Tim Battista	240-533-0379	tim.battista@noaa.gov
Chris Parrish	541-737-5688	Christopher.Parrish@oregonstate.edu
Bryan Costa	240-533-0364	bryan.costa@noaa.gov
Richie Slocum		slocumr@oregonstate.edu
Wayne Wright	443-783-3319	wayne.wright@noaa.gov

Study Title:
OPTIMIZING OPERATIONAL WORKFLOWS FOR BATHYMETRIC MAPPING WITH UAS

Purpose of study:
sUAS (small Unmanned Aircraft Systems) imagery processed in structure from motion (SfM) software has the potential to support federal agencies resource management requirements by providing a cost-effective means to generate 2D seafloor mosaics and 3D depth surfaces in shallow-water (<5 m) environments. However, the results from SfM software can vary, and are highly dependent on environmental conditions (wind, waves, solar altitude and elevation angle, turbidity), acquisition parameters (camera type, flying height, pointing angles, GPS accuracy), and processing techniques. Additional research is needed to identify optimal acquisition payloads and parameters, as well as post-processing workflows before being implemented more widely across National Oceanic and Atmospheric Administration.

A collaborative research team was funded by UASPO to optimize these parameters, payloads and techniques, and develop standard operating procedures (SOPs) that NOAA can use to derive accurate bathymetry from UAS imagery and SfM software. This work will be led by Wayne Wright Consulting and Oregon State University (OSU), with support by the Department of Interior, National Park Service and the Department of Commerce, National Oceanic and Atmospheric Administration.

Subject/Discipline:
Maps / Cartography / GIS
Monitor Natural Resources

Locations authorized:
Four possible study areas have been selected with input from NPS BUIS (A and C - south shore, E and F north shore). See attached study area map.

Transportation method to research site(s):
Study area sites will be accessed by NPS boat to transport scientists and equipment.

Collection of the following specimens or materials, quantities, and any limitations on collecting:
Flights will be conducted during daylight hours, within 500 meters distance of the PIC, and within line-of-sight of the PIC. The UAS will be launched and recovered on the beach areas proximal to the proposed study sites (sections A, C, E, & F). Permittee will conduct research activities in areas where field operations may overlap with visitor use (sections A & C) during the early morning hours prior to the arrival of concessionaire vessels (0700-1000). Field work may be conducted in sections E & F in the early morning or late afternoon (1500-1800) as visitor use in these areas is limited, particularly during those times. However, to ensure UAS operations do not interfere with NPS operations, UAS will be grounded if visitors are on the beach with the study sites. This mission complies with DOI Aviation policy and the UAS operator understands operations will be conducted in accordance with PASP including general briefings with park staff.

Name of repository for specimens or sample materials if applicable:

Specific conditions or restrictions (also see attached conditions):

Channel Islands National Marine Sanctuary

UNITED STATES DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL OCEAN SERVICE
Channel Islands National Marine Sanctuary
University of California, Bldg 514, MC 6155
Santa Barbara, California 93106

November 30, 2018

Dr. Christopher Parrish
Oregon State University
1491 SW Campus Way
Corvallis, OR 97331

Dear Dr. Parrish:

The National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries (ONMS) has approved the issuance of permit number CINMS 2018-011 to conduct activities within Channel Islands National Marine Sanctuary (sanctuary) for research purposes. Activities are to be conducted in accordance with the permit application and all supporting materials submitted to the sanctuary, and the terms and conditions of permit number CINMS 2018-011 (enclosed).

This permit is not valid until signed and returned to the ONMS. Retain one signed copy and carry it with you while conducting the permitted activities. Additional copies must be signed and returned, by either mail or email, to the following individuals within 30 days of issuance and before commencing any activity authorized by this permit:

Sean Hastings	National Permit Coordinator
Resource Protection Coordinator	NOAA Office of National Marine Sanctuaries
Channel Islands National Marine Sanctuary	1305 East West Highway (N/ORM6)
University of California, Bldg 514, MC 6155	SSMC4, 11th Floor
Santa Barbara, California 93106	Silver Spring, MD 20910
Sean.Hastings@noaa.gov	onmspermits@noaa.gov

Your permit contains specific terms, conditions and reporting requirements. Review them closely and fully comply with them while undertaking permitted activities.

If you have any questions, please contact Sean Hastings at sean.hastings@noaa.gov. Thank you for your continued cooperation with the ONMS.

Sincerely,

Chris Mobley
Superintendent

Enclosure

Forms

FAA Form 7711-1: U.S. Virgin Islands

FAA FORM 7711-1 UAS PART 107 AUTHORIZATION Page 1 of 3
2017-P107-ESA-4156

DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRAT ON

CERTIFICATE OF WAIVER OR AUTHORIZATION

ISSUED TO
Charles Wright
6243 Ashbury Palms Drive
Tampa, FL 33647

POC PHONE NUMBER
(443) 783 3319

This certificate s ssued for the operations specifically described hereinafter. No person shall conduct any operat on pursuant o the author ty of th s certificate except in accordance with the standard and special provisions contained n this certificate, and such other requirements of the Federal Av ation Regulations not specifically waived by this certificate.

OPERATIONS AUTHORIZED
Unmanned Aircraft Systems operations in accordance with Title 14 CFR Part 107.41, except "Operations for small unmanned aircraft" Part 107.51 b(2) are limited to the altitude listed below.
Class of Airspace: **C**
At or Below: **400** feet Above Ground Level (AGL)
With a radius of: **0.25** Nautica Miles
Under the Jurisdiction of: **St. Thomas Air Traffic Control Tower**

LIST OF WA VED REGULATIONS BY SECTION AND TITLE
N/A

STANDARD PROVISIONS
1. A copy of the application made for this cert f cate sha be attached and become a part hereof.
2. This certificate shall be presented for inspection upon the request of any authorized representative of the Federal Aviation Administration, or of any State or municipal official charged with the duty of enforcing local laws or regulations.
3. The ho der of th s cer cate sha be respons b e for the strict observance of the terms and provisions contained herein.
4. This certificate is nontransferable.

Note-This certificate constitutes a waiver of those Federal rules or regulations specifically referred to above. It does not constitute a waiver of any State law or local ordinance.

SPECIAL PROVISIONS
Special Provisions 1 thru 4, inclusive, are set forth on page 2 of this authorization.

This certificate **2017-P107-ESA-4156** is effective from **May 13, 2017** to **November 30, 2017**, and is subject to cancellation at any time upon notice by the Administrator or his/her authorized representative.

BY DIRECTION OF THE ADMINISTRATOR

FAA Headquarters, AJV-115 (Region) Scott J. Gardner (Signature)

May 12, 2017 (Da e) Act ng Manager, UAS Tactical Operations Section (Title)

FAA Form 7711-1 (7-74)

CIVIL PART 107 AUTHORIZATION, DECEMBER 1, 2016

U.S. Virgin Islands NOAA Aviation Safety Plan

2018 NOAA sUAS Aviation Safety Plan for St Croix. Version 1.3 as of 2018-0202

Project Aviation Safety Plan for:
Flat Cay, St. Thomas USVI &
Buck Island, St. Croix, USVI

Charles Wayne Wright Consulting
2018, February 2

Mission: Unmanned aerial photography of submerged topography suitable for 3 dimensional digital mapping via Structure from Motion post processing techniques.

Project Operation Dates: March 1 through 31, 2018

Project Aviation Plan prepared by: Charles Wayne Wright February 2, 2018
Charles Wayne Wright

Title: Contract service provider & Remote Pilot in Command

Reviewed by Requesting Agency, Unit & Contact: NOAA NCCOS, Dr. Tim Battista

__________ Date: __________

Project Aviation Plan Reviewed by BUIS Superintendent:

by:__________ Date: __________

Title:__________

Project Aviation Plan Reviewed and Approved:

by:__________ Date: Feb 2, 2018

Title: Contractor providing the data collection service & PIC

Page 1 of 15

Appendix E Policies and Handbooks

This appendix provides links to the policies and handbooks for UAS operations for NOAA and the National Park Service

NOAA UAS Handbook (June 2017)

https://www.omao.noaa.gov/find/media/documents/noaa-unmanned-aircraft-systems-handbook-june-2017

NPS Approval Template and Guidance for the Use of Unmanned Aircraft Systems (UAS): RM-60

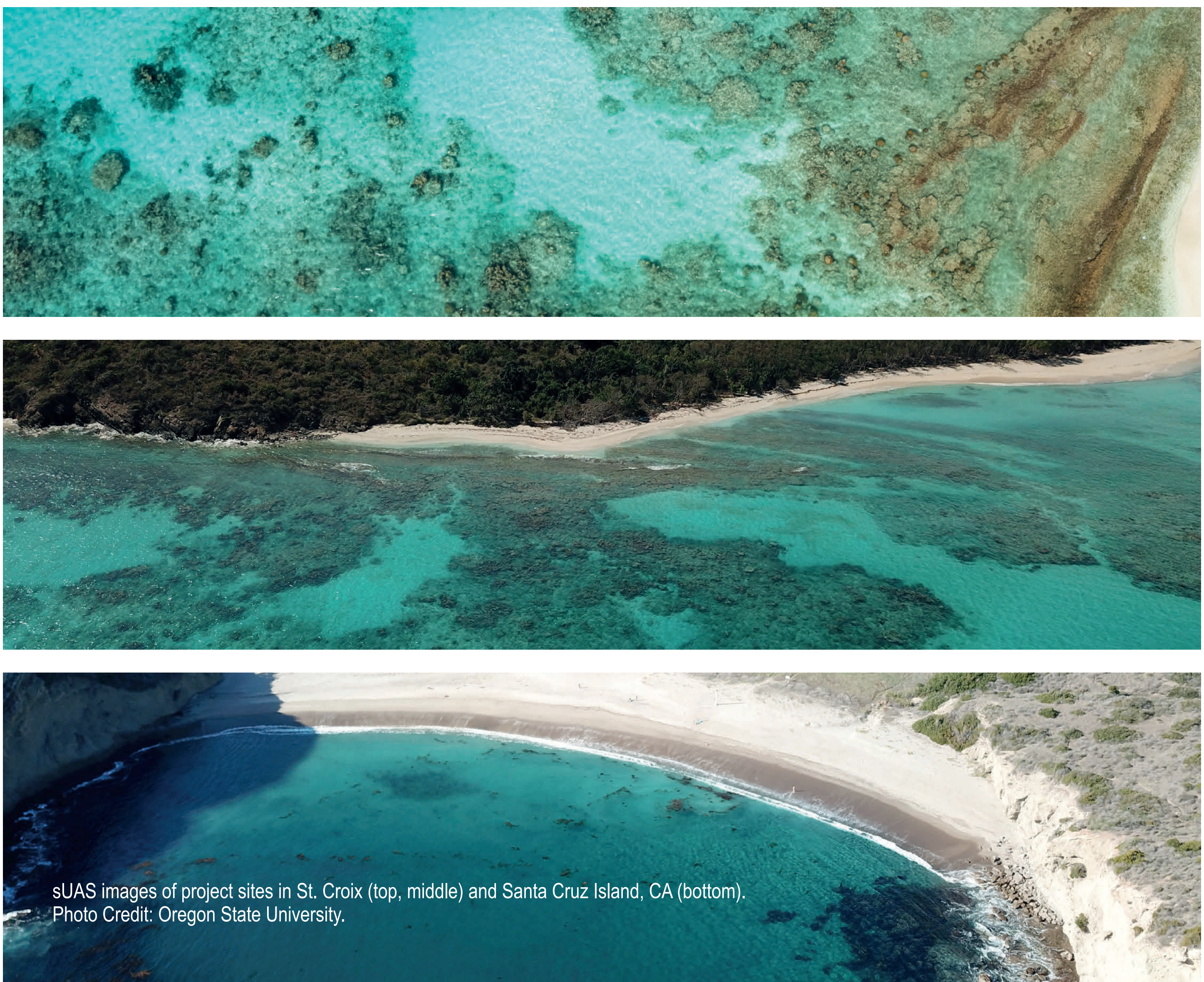
https://www.nps.gov/subjects/aviation/upload/reference-manual-60-appendix-7.pdf

NOAA NOAA Administrative Order (NAO) 216-104-A: Management and Utilization of Aircraft

https://www.corporateservices.noaa.gov/ames/administrative_orders/chapter_216/216-104-A.html

NOAA Policy 220-1-5 Unmanned Aircraft Systems (UAS) Operations

https://www.omao.noaa.gov/find/media/documents/policy-220-1-5-unmanned-aircraft-systems-uas-operations



sUAS images of project sites in St. Croix (top, middle) and Santa Cruz Island, CA (bottom).
Photo Credit: Oregon State University.

U.S. Department of Commerce
Wilbur L. Ross, *Secretary*

National Oceanic and Atmospheric Administration
Neil A. Jacobs, *Under Secretary for Oceans and Atmosphere*

National Ocean Service
Nicole LeBoeuf, *Acting Assistant Administrator for National Ocean Service*

The mission of the National Centers for Coastal Ocean Science is to provide managers with scientific information and tools needed to balance society's environmental, social and economic goals. For more information, visit: http://www.coastalscience.noaa.gov/.