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NEARSHORE BATHYMETRY ESTIMATION USING UNMANNED LIDAR PAYLOADS

by

Justin A. Crisp II

September 2023

Thesis Advisor:

Christopher G. Smithtro

Co-Advisor:

Mara S. Orescanin

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**NEARSHORE BATHYMETRY ESTIMATION USING
UNMANNED LIDAR PAYLOADS**

Justin A. Crisp II
Major, United States Marine Corps
BS, Florida International University, 2013

Submitted in partial fulfillment of the
requirements for the degree of

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September 2023**

Approved by: Christopher G. Smithtro
Advisor

Mara S. Orescanin
Co-Advisor

Frank A. Narducci
Chair, Department of Physics

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ABSTRACT

The Naval services are facing a significant challenge due to the increasing need for access to the littorals. However, conventional surveying and mapping methods have their limitations and challenges. This research examined how Light Detection and Ranging (LiDAR) sensors, especially near-infrared (NIR) LiDAR, can provide a standalone solution to estimate nearshore bathymetry. This approach shows a promising path to improving coastal access capabilities for intelligence collection.

The data collection involved unmanned aerial system (UAS) that were equipped with LiDAR payloads. These UAS scanned specific coastal sections at consistent altitudes with varied velocities (2–5 m/s). The data collected underwent processing with LiDAR-specific software tools and finally a custom MATLAB algorithm developed during this research. The results showed that NIR LiDAR could approximate surf zone bathymetry with some degree of accuracy, especially when flying at higher speeds (5 m/s). However, at slower velocities (2 m/s), there was a tendency to overestimate bathymetry.

The viability of this approach was validated by comparing the obtained results with offshore echo sounder bathymetry measurements and onshore LiDAR elevation data. The combination of these data sources produced a compelling proof-of-concept visualization, illustrating the potential of NIR LiDAR as a valuable tool for enhancing coastal mapping and surveying capabilities.

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LIST OF ACRONYMS AND ABBREVIATIONS

ALB	Airborne light detection and ranging bathymetry
BKBC	Bottom Kinematic Boundary Condition
COTS	Commercial Off the Shelf
DFSBC	Dynamic Free Surface Boundary Condition
EGM96	Earth Gravitational Model 1996
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
KFSBC	Kinematic Free Surface Boundary Condition
LAZ	Laser file
LiDAR	Light Detection and Ranging
LWT	Linear Wave Theory
MBA	Monterey Bay Academy
MSL	Meas Sea Level
NAVD88	North American Vertical Datum 1988
NDBC	National Data Buoy Center
NIR	Near Infrared
NIWC	Naval Information Warfare Center
NOAA	National Oceanic and Atmospheric Administration
PNT	Position, Navigation, and Timing
PRR	Pulse Repetition Rate
RADAR	Radio Detection and Ranging
RTK	Real Time Kinematic
SONAR	Sound Navigation and Ranging
UAS	Unmanned Aerial Systems
UTM	Universal Transverse Mercator
WGS84	World Geodetic System 1984
ZULU	Time Zone Indicator for Universal Time

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I. PURPOSE AND INTENTION

A. MOTIVATION

Humanity has a fraught but rewarding history with the sea. Early civilizations relied heavily on the ocean for many aspects of life, from food to transportation and even war. Through this time, the behavior of the ocean was a great source of fear and mystery until humans realized the sea, although untamable, could be understood and safely navigated. From this point, humans put considerable effort into exploring and better understanding the ocean's mysteries and behaviors, leading to the early formulation of oceanography as a practice and science.

In ancient history, predicting surf zone conditions, wave patterns, and coastal water currents helped early sailors navigate efficiently on their voyages. The methods continued, as even seabird migrations and whale migration routes served as navigation markers. With the arrival of the 19th century, safer navigation and, more importantly, understanding the ocean were required with the development of more advanced ships. This, in turn, drove the study of oceanography and coastal dynamics on a more scientific path. Scientists started to develop and deploy instruments like tidal gauges, current meters, and wave buoys, all to collect accurate data on coastal conditions. Eventually, this data would be used to generate tide tables and coastal charts and be used by scores of navigators during that time.

The littoral environment, which is the coastal zone where the land meets the sea, is a critical area for naval operations. As such, the United States Navy and Marine Corps should research the littoral environment to better understand its characteristics and how it affects naval operations.

There are several motivating aspects of researching the littoral environment. Firstly, the littoral zone is a complex and dynamic wash of physical, chemical, and biological processes that interact with one another. Understanding these processes is essential for safe and effective naval operations, including ship navigation, mine countermeasures, and amphibious landings.

Secondly, the littoral zone is a critical area for national security, as many countries have territorial waters that extend into this area. Researching the littoral environment can provide valuable intelligence on potential threats, such as enemy submarines, mines, or other hazards.

Finally, advances in technology, including sensors, unmanned vehicles, and autonomous systems are opening new opportunities for exploring and researching the littoral environment. By investing in research and development in this area, the Navy and Marine Corps can take advantage of these technologies to improve its operations and enhance its understanding of the littoral environment.

In conclusion, the history of humanity and its relationship with the ocean and the Navy and Marine Corps' use of the sea in every aspect of its daily operations should warrant research into the littoral environment, with the goal to better understand its complexity, enhance its operational capabilities, and support its mission to protect national security and preserve the health of our sailors and Marines.

B. INTRODUCTION

During World War II, the military recognized that accurate predictions of surf zone conditions would be critical for successful amphibious operations. Scientists were commissioned into the naval service to work on oceanography projects around the United States [1]. Their research efforts eventually led to the development of the bathythermograph, the advancement of Sound Navigation and Ranging (SONAR) technology, and a better understanding of ocean and coastal processes.

The methodologies, tools, and knowledge attained have continued to help the United States military via increased navigational accuracy, mine detection and countermeasures, intelligence gathering, and humanitarian operations. Moreover, accurate predictions of littoral conditions continue to help military forces operate safely and effectively in coastal waters, which is especially important for the intended focus of amphibious operations in the future. In the decades following the World Wars, technological advances and computer modeling have greatly improved our ability to predict surf zone conditions. Numerical models simulate waves, current, and tidal patterns

in coastal waters. These models use data from various sources, including satellite observations, buoys, and weather forecasts. This information is used to create detailed predictions of surf zone conditions, which are used by various organizations, including the military, coastal managers, engineers, and sailors.

The use of the electromagnetic spectrum plays an important advancing role in our understanding of the ocean and its coastal regions. Light Detection and Ranging (LiDAR) is no exception. LiDAR has proven itself in various aspects of meteorology, climate research, archeology, and most importantly, oceanography.

The coastal zones of the world's countries are dynamic, and their depths are difficult to estimate accurately without great cost and physical presence (for example multibeam sonar endeavors). These zones, specifically the surf zone, are continuously shaped via nearshore processes including waves, currents, and tides. Few avenues for estimating bathymetry are available outside traditional and physically intensive manual measurements. However, rapid changes to the shoreline compound this challenge, quickly degrading any data obtained.

This research intends to determine if Near Infrared (NIR) LiDAR from UAS can be used to improve upon the nearshore bathymetry estimation processes. The study aims to show that Commercial Off the Shelf (COTS) systems are effective when paired with Unmanned Aerial Systems (UAS). Our goal is to develop a model that accurately predicts the bathymetry remotely. A remote method for collecting nearshore data will enhance battlespace awareness without the need for reconnaissance personnel. Having the ability to remotely determine the bathymetry for secluded or denied areas would be a valuable tool for the Naval services when planning operations in future littoral environments or unexpected humanitarian operations.

This thesis explores the key concepts and theories of nearshore bathymetric estimation utilizing NIR LiDAR and will examine the complex dynamics of the coastal environment. The thesis begins with a review of relevant literature on LiDAR and its use in the nearshore. The literature review will provide an overview of existing research, highlighting gaps this research will fill.

The Methodologies chapter includes a description of how the LiDAR collections were set up, executed, and processed. Moreover, it identifies the coastal locations used in this work, highlighting why these locations provide an ideal setting for my research and what makes the different collection sites unique and challenging.

The next chapters present the results and conclusions, stressing both qualitative and quantitative results. The results provide a deeper understanding of nearshore environments and how they can be applied to Naval amphibious operations.

II. LITERATURE REVIEW

Bathymetry information plays a significant role in understanding seafloor topography and its evolution, with important implications for various marine applications, including coastal management, navigation, and habitat mapping. Traditional methods of bathymetric data collection in or around the surf zone often rely on expensive and time-consuming surveys by crewed ships, large or small [2]. However, recent technological advances, especially unmanned systems equipped with imaging and remote sensing LiDAR payloads, have opened new possibilities for efficient bathymetry estimation at an affordable cost.

Unmanned aerial systems (UAS) and other unmanned systems have received increasing attention in ocean exploration and research. These vehicles enable high-quality data collection in nearshore environments, where conventional methods may face limitations due to shallow water, rugged terrain, and other operational challenges that may increase the danger of associated human interaction [3]. Moreover, their ability to operate autonomously or under remote control enhances safety, reduces human involvement, and allows for extended data collection durations.

A. LIDAR

Imaging and LiDAR payloads are among the leading technologies used by unmanned systems to compute bathymetry statistics. Light Detection and Ranging (LiDAR) is a remote sensing technology that uses laser pulses to measure distances and map objects and surfaces with three-dimensional LiDAR systems, including a laser source, scanning mechanism, receiver, and data processing components. LiDAR works by emitting short, intense laser pulses to the target area. These laser pulses are typically in the near-infrared or green wavelengths, although others can also be used depending on the application [3]. The resulting laser pulse propagates until it encounters an object, such as a surface or vegetation. After hitting the target, the laser pulses undergo a reflection process, where a portion of the energy is returned to the LiDAR system. The LiDAR receiver detects the returning laser pulses and measures the time it takes to return to the system. This time-

of-flight information and the known speed of light allow LiDAR to calculate the range between the sensor and the object by repeating this process for multiple laser pulses and using scanning technology [3]. The LiDAR system can generate a dense point cloud dataset containing millions of individual points with accurate telemetry. Each point in the cloud is categorized by its X, Y, and Z coordinate, which is used to plot each point and generate the point cloud.

In addition to range measurements a LiDAR system can capture other features of reflected laser pulses. These characteristics include the intensity of the backscattered signal, which provides information about the brightness or surface properties of the object, and the angle at which the laser pulse was reflected, called the scan angle.

This literature review examines the status of nearshore bathymetry estimation using unmanned imagery and LiDAR payloads. Moreover, the intent is to identify this field's approaches, challenges, and progress through literature and existing research efforts. In addition, the potential of combining multisensory and data fusion techniques for more accurate and efficient bathymetric mapping using unmanned systems will also be explored.

Throughout this review, it becomes clear that LiDAR and its applications in oceanography and, more importantly, the surf zone are not new or emerging from any standpoint. LiDAR has been used extensively on multiple platforms, ranging from space vehicles to UAS, all to research the planet, its oceans, and, concerning this research, its littoral regions. Only some applications are specific to bathymetry estimation, but the key connecting factor is LiDAR, and insightful information can be gleaned from each unique application.

B. SPACE BASED LiDAR

Traditional bathymetry methods involve SONAR, RADAR, or other measurement techniques that utilize surveying equipment or methodologies to take in-situ measurements. However, space-based LiDAR offers distinct advantages regarding global coverage, high accuracy, and rapid data acquisition. Space-based LiDAR bathymetry is an innovative technology that enables underwater topography measurement and mapping from space. With this understanding, a group of researchers utilized the ICESat-2 LiDAR

payload and the already proven Multi-Spectral Imagery (MSI) capabilities of Sentinel-2 to train empirical models and then produce bathymetric maps of sites in the South China Sea as well as the Caribbean [4]. The ICESat-2 was initially designed to measure the rate of change of Earth's ice sheets and sea ice. After five years of data recording, they ultimately fulfilled their mission in 2009 [5]. This group of researchers created an algorithm to detect and extract the point cloud data from the raw and noisy ICESat-2 data sets. They then refined and calibrated the data allowing the team to correct for refraction in the water column and the surface. The data generated from this process was matched with preprocessed Sentinel-2 MSI and taken as the priori bathymetry points to determine bathymetry with remotely sensed methods. During their research, many limiting factors affected the accuracy of the study, specifically, those associated with the orbital altitude, Sun glint, water column conditions, and water transparency [4].

C. GROUND BASED LiDAR

Ground-based LiDAR systems have also played a key role in measuring water and sand levels of the shoreline, as well as wave heights in the surf zone. Applications such as this have further opened the door to exploring surf-zone hydrodynamics. Specifically, researchers provided a pathway to measure inner surf-zone waves and wave setup [6]. LiDAR alone in a stationary position was able to estimate the wave height of the inner surf zone to within about 10% of onsite measurements. Moreover, when the group compared the LiDAR dataset with pressure sensors in focus areas, it allowed for estimating the mean water level associated with shore setup with a difference of 0.05 m to actual values [6].

D. AIRBORNE LiDAR

Focusing on the specifics of this research, airborne applications of LiDAR have been making substantial headway in bathymetry data collection and estimation for quite some time. Airborne LiDAR bathymetry (ALB) has provided researchers with datasets with high spatial density and, more importantly, the ability to collect in areas of limited or no access [7]. Many systems have been used for such applications like the Experimental Advanced Airborne Research LiDAR (EAARL) developed by The National Aeronautics and Space Administration (NASA) specifically designed to scan shallow coastal

environments [8]. Moreover, a group of researchers employed a Shoals-100T LiDAR payload to estimate depth. The system is comprised of both a NIR and green wavelength laser scanning system [9]. Each scan produces a surface and bottom scan associated with NIR and green wavelengths, respectively. These scans have corresponding top and bottom peak waveforms that have different amplitudes. These amplitudes were shifted, and time corrected to differentiate the surface and bottom returns from each other. A non-linear square fitting was used concerning the Gaussian functions generated during the correction previously mentioned. This process generated two more peak positions associated with the time that was ultimately subtracted from each other, divided by two, and multiplied by the speed of light in water to estimate the water depth. When analyzing the green laser data for both top and bottom returns, the researchers found that their ratio of success in determining the surface of the water and the bottom surface was found at a maximum water depth of 2.7 m, providing successful results roughly 47% of the time [9]. Compared to other depth estimation methods conducted, like Raman regression methods, the researchers found that the NIR and green LiDAR methods provided the best results [9].

E. LINEAR WAVE THEORY

Given that the base assumptions and analysis in this research will pertain to Linear Wave Theory (LWT), it would be beneficial to explain its premise. Linear Wave Theory describes how waves propagate to the shore from deep water, where waves are generated, to their breaking point in the surf zone. First and foremost, a wave, as represented in LWT, is a motion with a restoring force attached (in this case gravity), so its amplitude does not change over time (but can change in space). As a wave propagates to the shore (and depth decreases), there is a change in many aspects of the wave and ocean characteristics. Those are wave velocity, length (L), height (H), energy, depth (h), and phase speed (celerity). Furthermore, orbital and particle movements associated with each wave change as it approaches the shore [10], [11], [12]. In contrast, the wave period (frequency) remains constant, a critical assumption for all linear wave mechanics.

Mathematical relationships were derived to better explain the changes in characteristics, with a few key assumptions: that being, rotation is unimportant, and wave

frequencies are much higher than the Coriolis frequency. The fluid is assumed homogeneous, meaning the fluid density is constant. The fluid flow is assumed to be described with a velocity potential. The fluid is assumed to be irrotational and incompressible, with small amplitudes. Lastly, the bottom is assumed flat [12].

In the case of LWT, the Mass Conservation equation is one of the primary governing equations [12]. It is given by:

$$\nabla \cdot \vec{v} = 0 = \nabla^2 \phi, \quad (1)$$

where $\vec{v}$ is the vector velocity of water, ϕ is the velocity potential, and ∇^2 is the Laplacian operator. In this system, x is defined as cross-shore, y is alongshore, and z is vertical (positive up). By taking the velocity components (u,v,w) associated with the wave velocity and orbital velocity, boundary conditions can be generated with the definition[10]:

$$u = -\frac{\partial \phi}{\partial x}; v = -\frac{\partial \phi}{\partial y}; w = -\frac{\partial \phi}{\partial z}. \quad (2)$$

To solve the governing equation (1), boundary conditions must be established concerning the water surface (interface) and the bottom. The bottom condition is known as the Bottom Kinematic Boundary Condition (BKBC) and is paired with the flat bottom assumption, where no vertical flow is allowed [10], [12]. Thus, BKBC is represented by:

$$w|_{z=-h} = 0 = \frac{\partial \phi}{\partial z} \Big|_{z=-h}, \quad (3)$$

where $z = -h$ is the bottom surface. The surface/interface, defined by the variable η , has two boundary conditions, kinematic and dynamic, since it is deformable. The first condition is the Kinematic Free Surface Boundary Condition (KFSBC) [10], [12], which is given by:

$$w|_{z=\eta} = \frac{\partial \eta}{\partial t} \quad (4)$$

where $\eta(x,t)$ is the water elevation at a particular time and position, or more aptly described as the displacement of the free surface.

Further analysis requires that equation (4) be taken with the assertion that velocities must match in the linearization process. The second boundary condition needed at the surface level is that of matching pressure across the boundary, where $z = \eta$. This can be established by setting the atmospheric pressure equal to that on the surface. Given the assumption listed above, pressure in the system can be determined using Bernoulli's equation applied at $z = \eta$. This ultimately yields the Dynamic Free Surface Boundary Condition (DFSBC) [10], [12] represented by

$$\frac{P_a}{\rho} = \frac{\partial \phi}{\partial t} \bigg|_{\eta} - g\eta \quad (5)$$

where P_a is the pressure, and at the pressure $P_a = 0$, ρ is the water density, g is the gravitational acceleration, and η is water elevation.

Taking equation (1) as the governing equation, and equations (3)-(5) as boundary conditions, the system is closed, and it is possible to formulate a solution. By trying a solution that holds the form for η , given by

$$\eta = a \sin(kx - \omega t), \quad (6)$$

as well as a solution for ϕ , that is given by

$$\phi = \frac{a\omega}{k} \frac{\cosh(k(h+z))}{\sinh(kh)} \cos(kx - \omega t), \quad (7)$$

it is possible to determine that equations (1), (3)-(4) are solved trivially. When these proposed solutions are evaluated in equation (5), the surface gravity wave dispersion relation for surface gravity waves, also known as the “Full Theory,” emerges:

$$\omega^2 = gk \tanh(kh), \quad (8)$$

where $\omega = 2\pi/T$, $k = 2\pi/L$, and h is the magnitude of water depth [10], [12]. Also noting that this is the intermediate water approximation, valid between the boundaries for deep and shallow water.

Using this dispersion relation, definitions can be formed that characterize the deep, intermediate, and shallow water boundaries that comprise the near shore, ultimately allowing for the estimation of water depth (h) from the equation derived from equation (8). In deep-water, where depth tends to infinity,

$$\omega^2 = gk; (kh > \pi) . \quad (9)$$

In shallow water, where depth approaches zero, the relationship becomes:

$$\omega^2 = k^2 gh; \left(kh < \frac{\pi}{10} \right) . \quad (10)$$

Further manipulation of equation (10) by substitution of the phase velocity equation given by

$$c = \frac{\omega}{k} . \quad (11)$$

Solving for h , the water depth, yields the equation that will be used in this research to estimate the bathymetry. This equation is given by:

$$h = \frac{c^2}{g} . \quad (12)$$

In conclusion, the first estimate of depth using wave kinematics will involve solving for h in equation (12) by estimating the wave velocity, c . This initial method was selected because of no dependence on the wavelength in the formulation of c in contrast to using the Full Theory. This is a fair assumption in the surf zone, where depths are expected to be small such that equation (10) is valid. By utilizing existing research and theories, the hope is to shed some light on the limitations and factors affecting its performance. With this knowledge, the intent is to better understand how to optimize its use and unlock its full potential concerning bathymetric estimation. Overall, the belief is that NIR LiDAR has a

promising future in surf zone applications, and the hope is to contribute to its continued development through this research.

III. METHODOLOGY

A. INTRODUCTION

The methodology section of this document will address the framework, processes, and assumptions used to conduct this research. This work used an unmanned imaging and LiDAR payload called the Mini-VUX 2 (Figure 1) produced by RIEGL. The LiDAR uses a wavelength of 905 nm at a pulse repetition rate (PRR) of 100 to 200 kHz. Its field of view is 360 degrees, which is achieved by rotating the laser reflector assembly at 10 to 100 revolutions per second, allowing for a maximum effective measurement rate of up to 200,000 measurements per second at 200 kHz.

The unmanned aerial vehicle used was the Alta-X (Figure 2) produced by FreeFly Systems. The UAS features 4 motors producing a maximum continuous power of 17,706 watts. This affords the UAS the ability to lift a maximum gross weight of 34.9 kg and remain in flight for roughly 11 minutes at maximum weight capacity. The power for the system is provided by two 12 cell batteries with a nominal voltage of 44.4 watts.

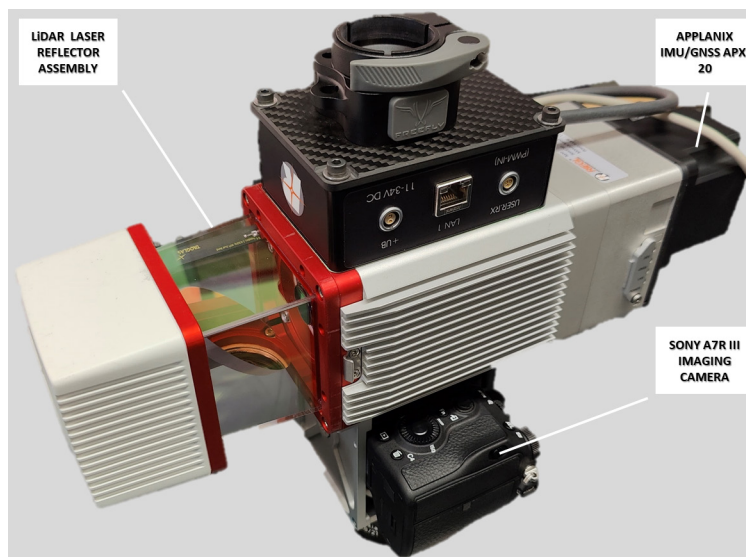


Figure 1. RIEGL Mini-VUX 2 laser scanning system. The system contains an internal IMU/GNSS accurate to 0.02-0.05 m and a secondary nadir imaging camera system, all of which is contained in a compact form factor weight roughly 2.5 kg.



Figure 2. Freely Systems ALTA-X quadcopter with the attached RIEGL LiDAR payload. This UAS system boasts 4 motors generating 17,760 watts of max continuous power lending to a maximum gross takeoff weight of 34.9 kg and a total flight time configure as seen of roughly 10.75 minutes.

These systems were used to gather accurate data on the nearshore and its wave properties, essential for understanding the underwater topography and its dynamic life cycle. This payload was deployed affixed to the undercarriage of the UAS, which was operated from a safe distance. This approach can minimize risk concerning human interference and, more importantly, error, and ensure the data collected is reliable and consistent. Overall, this methodology effectively gathers data on the nearshore and can provide valuable insights into the underwater landscape.

B. LOCATION

This research spanned two beaches to collect the required LiDAR data along central Monterey Bay. The northernmost site was the Monterey Bay Academy (MBA), which is a private school and housing community. The southernmost site was Pajaro Beach. Both are shown in Figure 3. Each site had restricted access and was free of surface vessels and

artificial obstructions that could impede data collection. Furthermore, each location presented specific and unique traits.

Pajaro Beach, Watsonville, CA is located at a latitude of 36.851 N and a longitude of -121.810 E. This beach presents a dynamic nearshore system where the Pajaro River enters Monterey Bay, creating diverse wave characteristics and surf zone morphology. This site is non-traditional given that this beach is in a constant state of change, resulting from the adjacent Pajaro River mouth. The beach slope is the highest ($\sim 1/20$) at its most northern point due to the variety of vegetated dunes that have built up from aeolian transport and separate the beach from the adjacent coastal community. Closer to the river mouth (that migrates), the beach slopes are much less ($\sim 1/100$) owing to lower elevation sand berms near parts of active river migration. Monterey Bay is well-known for the presence of rip currents and combined with the presence of a migrating river mouth, the area commonly has complex surf zone bathymetry.

The second site (MBA beach) is just a few miles north, located at latitude 36.906 N and longitude -121.846 E. This site presented a more traditional representation of a nearshore environment, providing energetic, well-formed waves free from obstructions or other parallel processes. The slope of MBA beach is ($\sim 3/200$) at the northern most point increasing to ($\sim 1/50$) around the midpoint of the area of interest, with a final slope of ($\sim 3/125$) at the southernmost point. Moreover, these locations are heavily monitored by other oceanographic agencies and researchers, with ground truth surveys conducted regularly and offshore wave buoys, providing data available to subsidize the results of this research. Together, these locations are ideal for conducting nearshore research and documenting the wave characteristics of the area.



Figure 3. Monterey Bay research locations near Watsonville, CA. The northern site is the Monterey Bay Academy located at latitude 36.906 and longitude -121.846, while the southern site in Pajaro Beach located at a latitude of 36.851 and longitude of -121.810.

C. WEATHER

This research did not implement Go, No-Go launch criteria; however, after many flights, it was found that steady-state winds posed no major issues to collection, as the drone does a great job countering steady winds. Unfortunately, wind gusts between 15–20 knots will severely distort the point cloud data as these small but quick movements produce errors in both water surface conditions and UAS position. Moreover, if the nearshore conditions produce a lot of ocean foam or white capping with thick mist or ocean spray above the waves, the LiDAR payload will not receive as many returns and there will be prominent gaps in the point cloud. To mitigate any data distortion due to winds, the local

aviation weather data for the surrounding airfield was used to predict the beach wind conditions.

D. FLIGHT AND COLLECTION SETUP

Three initial steps are needed to set up a LiDAR collection flight with the Alta-X and the RIEGL LiDAR. The first is setting up a Global Positioning System (GPS) base station; the second is setting up and calibrating the GPS antennas on the Alta-X and the RIEGL LiDAR; and finally, calibrating the LiDAR's internal Inertial Navigation System (INS). It is paramount these three steps take place to ensure the accuracy of the collection and that the most legible point cloud is processed.

Flight setup starts with establishing a fixed GPS base station near or at the location of the collection. Two different methods can be used to set up a GPS base station. An off-site, permanent system can be used, like the National Oceanic and Atmospheric Administration (NOAA) Continuously Operating Reference Stations (CORS) Network (NCN), which is used as a reference for position, navigation, and timing (PNT) data. This data is published online and readily available on various sites nationwide. If the established fixed GPS station is within 7 km or less, it provides viable PNT data needed to process the trajectory. Alternatively, a better option is to use a GPS mobile system as the primary PNT base source. The on-site GPS base station must be established 30 minutes before the flight and remain established 30 minutes post-flight. Following this time requirement ensures that an accurate PNT fix will be ongoing during the flight and that the trajectory, once processed, will be as accurate as possible. Whether fixed off-site or mobile on-site, a base station ensures that a stationary PNT fix is established and stable, thus providing a baseline for future processing of a UAS trajectory. Ultimately, the stability of the GPS signal ensures accurate heights and distances are recorded in the trajectory and the point cloud data. For this research, both methods were used. The primary concern is that with the base stations fixed at off-site locations, the distance between where the collection happens and where the base station might be is too large, and thus, errors will permeate the data. As mentioned previously both GPS methods were used to determine the best suited for research application. The CORS fixed station was roughly 8.1 km away when flying at the

Pajaro Beach location, and 14.27 km from the Monterey Bay Academy location. These distances necessitated the use of an onsite base station. Ultimately, a mobile GPS puck (shown in Figure 4) was used, as it is more flexible and better suited for this application.



Figure 4. GPS puck used as a static base station. This puck was mounted on a tripod roughly 5 ft high in a position near the UAS launch site.

Next, the Alta-X quadcopter and the RIEGL LiDAR system will be set up using their internal GPS receivers. The Alta-X uses an internal GPS fixed to the quadcopter and a GPS antenna fixed to the controlling computer. Both systems can operate without needing to remain static, due to their employment of real time kinematic positioning (RTK) software.

The RIEGL system requires five minutes of non-movement before the flight. This time allows the RIEGL payload to acquire an accurate GPS fix. These five minutes must be performed while the UAS is static before takeoff and after landing has occurred. Moreover, when coupled with dynamic calibrations, this five-minute pre- and post-flight static calibration is an accurate start and stop point for the UAS trajectory. It improves the accuracy of the point cloud data in post-processing. This length of time is essential to ensure the accuracy of each scan.

The RIEGL LiDAR payload also has a built-in INS. This system must be calibrated pre- and post-collection while airborne. Once all the GPS attributes of the flight have been set up and the proper time has elapsed, the INS calibration can begin. The calibration consists of flying in a right-angle-shaped pattern. The first leg is flown at maximum velocity with an abrupt stop (inducing high acceleration/deceleration), followed by a max velocity return to the starting position with an abrupt stop. Next, the aircraft must rotate 90°, repeating the process. This maneuver must be performed pre- and post-flight to ensure the INS has been broken free from any initial and final position, thus completing the calibration. The resulting trajectory will be seen as a right angle or something akin to an L-shape during post-processing. These key markers will also serve as another starting and stopping point of the flight's trajectory, a visual marker for general situational awareness in the processed image.

E. DATA COLLECTION

The overall intent of coupling a LiDAR payload to a UAS is for fast and easy data acquisition of the nearshore. Using a setup like this allows for measuring wave speed (celerity), a critical factor in determining the bathymetry remotely. With this methodology and the processing utilized, discussed later, the intent is to determine wave speed, and therefore invert depth using (10), along the trajectory in the surf zone.

Remote data collection is straightforward and fairly short in duration. The aircraft is pre-programmed to fly a specific trajectory with specific attributes, like speed and altitude. A typical flight lasts between 11 and 15 minutes, with one-quarter to one-half recording data needed for bathymetry estimation. Each trajectory is flown as close to parallel to the shore as possible. Ensuring a parallel trajectory to the shore, coupled with the assumption that waves propagate perpendicular to the shore will allow for detailed scans of wave crests. The UAS is flown between two and five m/s for ample collection. The set altitude is 50 m, allowing the collection of a 100 m wide swath of the nearshore. The length of each swath is varied but ranges from 400 to 600 m. The orientation of each flight path was determined pre-flight in the ALTA-Q ground control program. This program hosts satellite imagery that was then used to plot a trajectory as close to shore

parallel as possible. This approach supports scanning the waves based on the underlying assumption that each wave will propagate shore normal, meaning the crest of each wave will be parallel to the shore as the direction of propagation is at 90 degrees to the shore.

Given that the UAS battery is limited in the amount of time that can be flown safely on a single charge, the aim is to collect two swaths per flight or fly two separate flights with the spacing of the collected swaths. Multiple swaths overlapping close to each other, if not touching, add errors to the final analysis, due to the post processing program's tendency to stack scans on top of each other. This stacking adds erroneous elevation value to each scan, skewing the output. Once the flight is concluded, the aircraft lands, and the post-flight procedures are executed. All data is saved on an internal secure digital (SD) card that can be removed for data processing.

F. DATA ANALYSIS

The following section describes the process for analyzing the LiDAR point clouds. Two processes will be discussed; the first is a back-of-the-napkin calculation used to estimate the bathymetry quickly and refine the process for later more-refined analysis. The second describes the refined process, which eliminated the time-consuming, tedious nature of hand-based calculations.

1. Key Assumptions

The underlying foundation for the analysis assumes both intermediate and shallow water wave characteristics, as proposed in linear wave theory previously discussed in Chapter II. This basis will be used during the analysis, followed by key underlying assumptions. The first assumption is that the shore has a constant slope past the surf zone, which in the case of this research yields a ballpark estimate of how deep the surf zone could be. This also is a gross overestimate and provides a simple “ground truth” for comparison. The second assumption is that waves propagate normal to the shore (“shore normal”). With this shore normal propagation, the wave crests should be parallel to the shore leading to the third assumption that the flight path of the UAS is parallel to the wave crest. These assumptions will become clear as the following sections outline the analysis process.

2. Trajectory

The trajectory of each flight is processed via proprietary software developed by APPLANIX called POSPAC, as represented in Figure 5. The initial unprocessed UAS trajectory is displayed in magenta, while the output trajectory after post processing and error correction is displayed in green.

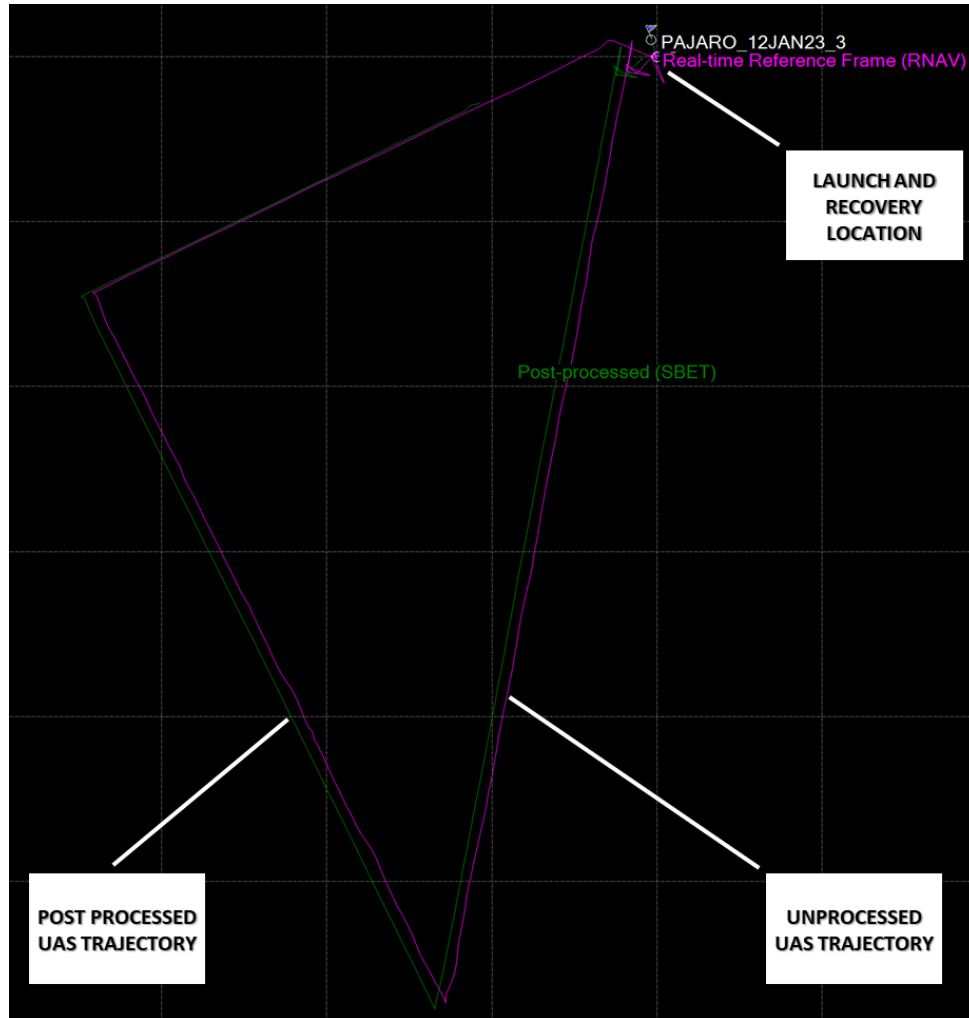


Figure 5. Standard 2-D POSPAC trajectory output. The initial unprocessed UAS trajectory is displayed in magenta, while the output trajectory after post processing and error correction is displayed in green.

This software allows the user to export the trajectory from the payload, while importing the GPS base station data. Both data sets are then used to refine the accuracy of

the payload's trajectory. This refinement incorporates World Geodetic System 1984 (WGS84) three-dimensional coordinate reference frame data into the payload's trajectory. WGS84 is an Earth centered and fixed terrestrial reference system. The WGS84 reference system uses a set of model parameters to describe the shape and size of Earth, while also describing both the gravitational and geomagnetic fields of Earth [13]. It is important to note that the trajectory data will serve as the connection between the collected point cloud data and the WGS84 datum. This process provides a more accurate representation of latitude, longitude, and height concerning the payload recordings. On average the refinement process increases the trajectory data accuracy to within 0.05-0.1 m of the true flight path.

3. Point Cloud Rendering

The initial LiDAR point cloud is rendered via another RIEGL proprietary software package called RiProcess, as seen in Figure 6. This program takes the refined trajectory and overlays the corresponding LiDAR point cloud data. This software allows the user to remove undesirable collection parameters; for example, turns less than a specific angle or speed greater or less than a given value. The result is a collection of trajectory segments paired with point cloud data that can be viewed and exported for later processing. Figure 6 depicts the scanned swaths of land and water as the UAS flies its predetermined trajectory. The process of rendering the point cloud also highlights the importance of having accurate trajectory data, given that it will not be accurately placed if its trajectory is not accurate.

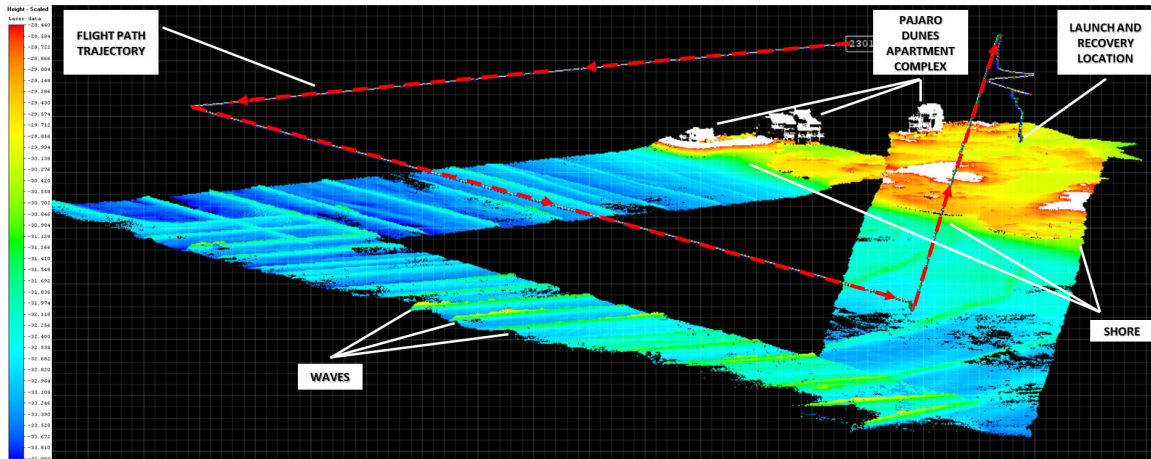


Figure 6. 35-degree view of an initially processed point cloud in RiProcess. The color scheme is tied to the height of objects in the scan with respect to a WGS84 ellipsoid. The color bar represents vertical change in meters.

4. Exportation

Another refinement step is required before the trajectory can be utilized in further processing of the point cloud. The exportation step requires the trajectory utilizing WGS84 be further refined using Earth Gravitational Model 1996 (EGM96). This model considers surface gravity data to improve the height accuracy by implementing the EGM96 gravity data in the WGS84 ellipsoid. Once the payload's trajectory data is refined, it is exported for the next step in point cloud rendering and exportation.

Given that the RiProcess is proprietary, exportation is specific to this instrumentation. This software incorporates extra data sets that may not be easily interpreted by 3rd party programs. Regardless, the exportation from RiProcess was performed using a common LiDAR file format, LAZ 1.4, to ensure interoperability with third-party programs.

5. Initial Analysis

The initial analysis of the LiDAR point cloud was done with a program developed by Applied Imagery called Quick Terrain Modeler (QTM). This program accepts the exported LAZ 1.4 file for further manipulation and processing. This section highlights the major steps used to estimate water depths (bathymetry) using linear wave theory.

The preliminary step is to establish a constant slope estimate of what the bathymetry could be using the point cloud land data, which isn't part of the actual bathymetry estimation process, but serves as a gauge for ground truth estimation. This was done by taking the assumed constant slope of the beach as it meets the water, which is determined from the scans of the shore. The slope of the beach can then be calculated using mensuration tools within QTM. Extrapolating this slope under the water and past the surf zone allows for the approximation of the water depth in and past the surf zone. This approximation allows for a ballpark estimation of the surf zone's depth. It must also be noted that a constant slope assumption usually overestimates water depths. A detailed description of beach slope and ground truth water depths will be discussed in the results section of this document.

At this point, the next step was to take a transect of each wave scan as shown in Figure 7. The figure shows data taken over a 92 second period of the UAS flight trajectory. The wave movement with respect to the UAS trajectory is bottom left to top right. Therefore, the waves appear angled (nearly perpendicular) to the flight trajectory. The darker greens, yellows and reds depict wave crests, while the lighter greens and deep blues represent wave troughs.

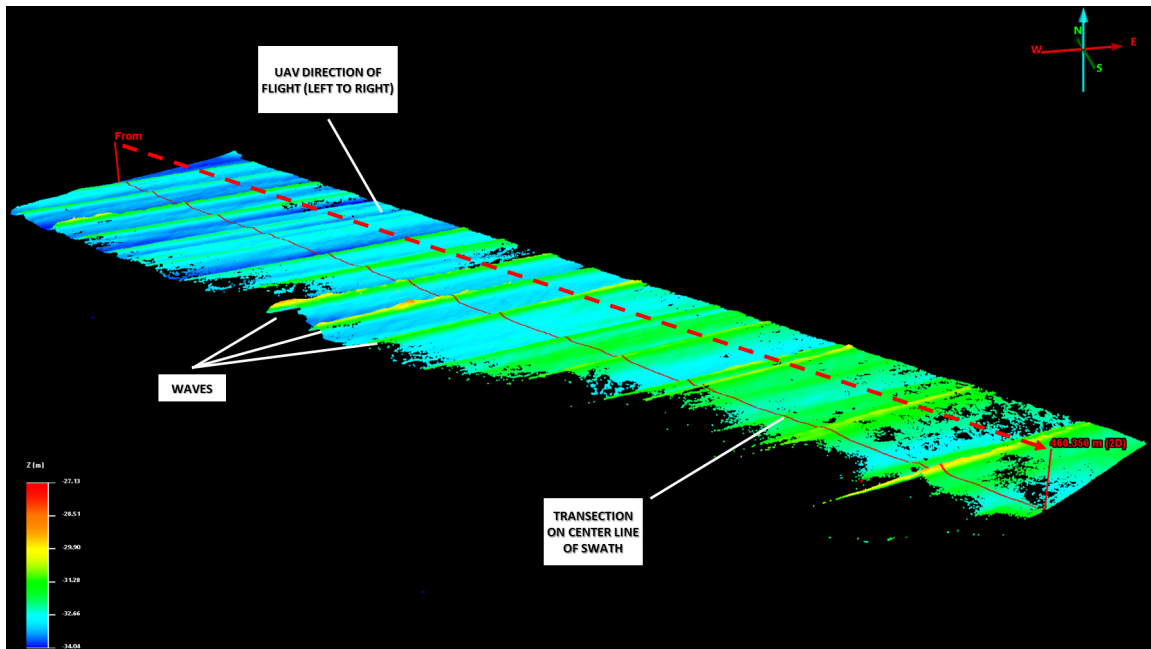


Figure 7. QTM point cloud wave transection. The entire scan shows waves taken over a 92 second period of the UAS flight trajectory. The beach in this figure is in the direction of the top right corner. Moving from top right corner to bottom left corner equates to moving offshore to deeper water. The wave movement with respect to the UAS trajectory is bottom left to top right. Therefore, the waves appear angled or perpendicular to the flight trajectory. The darker greens, yellows and reds depict wave crests, while the lighter greens and deep blues represent wave troughs. The color bar represents vertical change in meters.

Next, the wave crests were identified from the transects, as seen in Figure 7. Focusing on the most pronounced waves, the sharpest peaks, and the distances between those peaks, values can be derived for the wavelength and height. In the end, this method was not used as part of the final bathymetry estimation process but may later serve as a viable method to derive values need for use in (6) the “Full Theory.” Figure 8 depicts what a wave transect looks like, noting the sharp peaks as wave crests and the deep valleys as wave troughs.

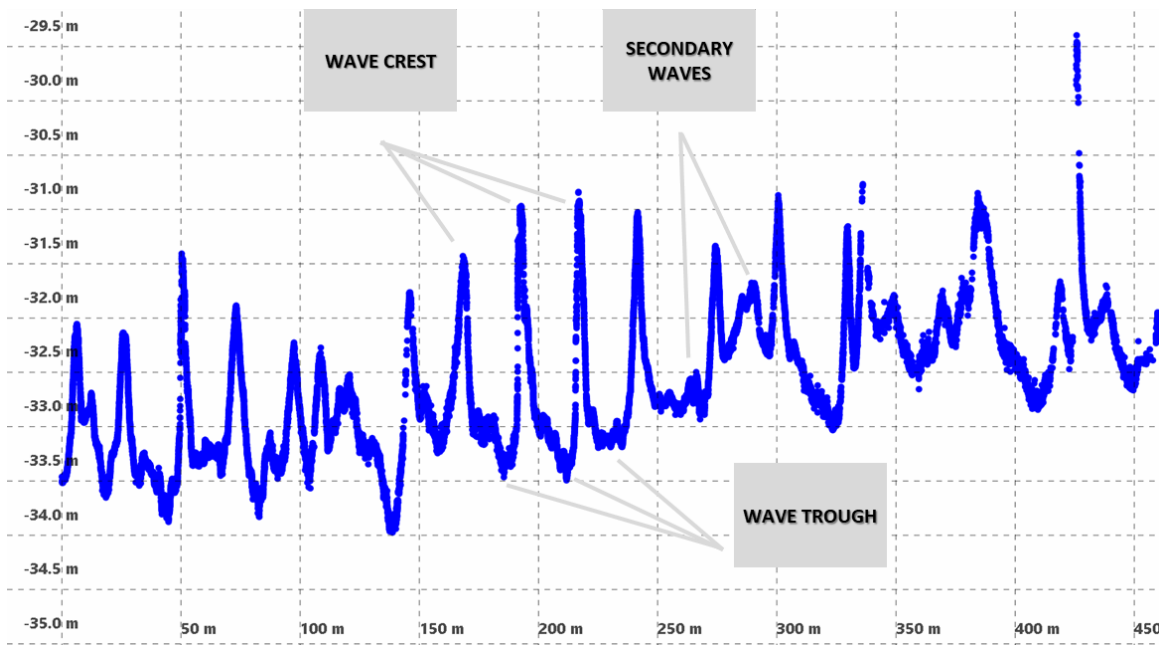


Figure 8. Side profile of the QTM wave transect taken in the previous figure. The dotted blue line is a few inches wide throughout the entire swath. Gaps in the line represent missing data; i.e., a point where there was no laser return.

The values of wavelength and height could theoretically be estimated from Figure 8 by using QTM's measurement tool. As the UAS moves parallel to the wave crest (i.e., perpendicular to wave propagation direction), the resulting scan will show waves propagating at angles relative to the UAS flight path.

The angles the waves make relative to the movement of the UAS are tied to both wave velocity and UAS velocity. To determine the velocity of the wave we assume the wave crest is a straight-line from the top to the bottom, or small straight-line segments of the scan. QTM's drawing function facilitates the application of right triangles concerning the wave crest and determining the lengths of each side of the right triangle. This process requires drawing a straight-line on a given wave crest, representing the hypotenuse of a right triangle. This drawing process is repeated to determine the base and height of the triangle. Knowing the length of each leg allows for determining the angle between the flight path, represented by the triangle's base and the hypotenuse of the triangle. Figure 9 displays the process in QTM. As the wave and UAS progress forward in time the resulting

wave vector moves at an angle from bottom left to top right if the UAS is travelling left to right. Figure 9 displays the movement of the UAS velocity vector from left to right as the left most red dashed arrow. This arrow intersects the right most dashed arrow which is the wave velocity vector. The vector combination yields the resultant velocity vector.

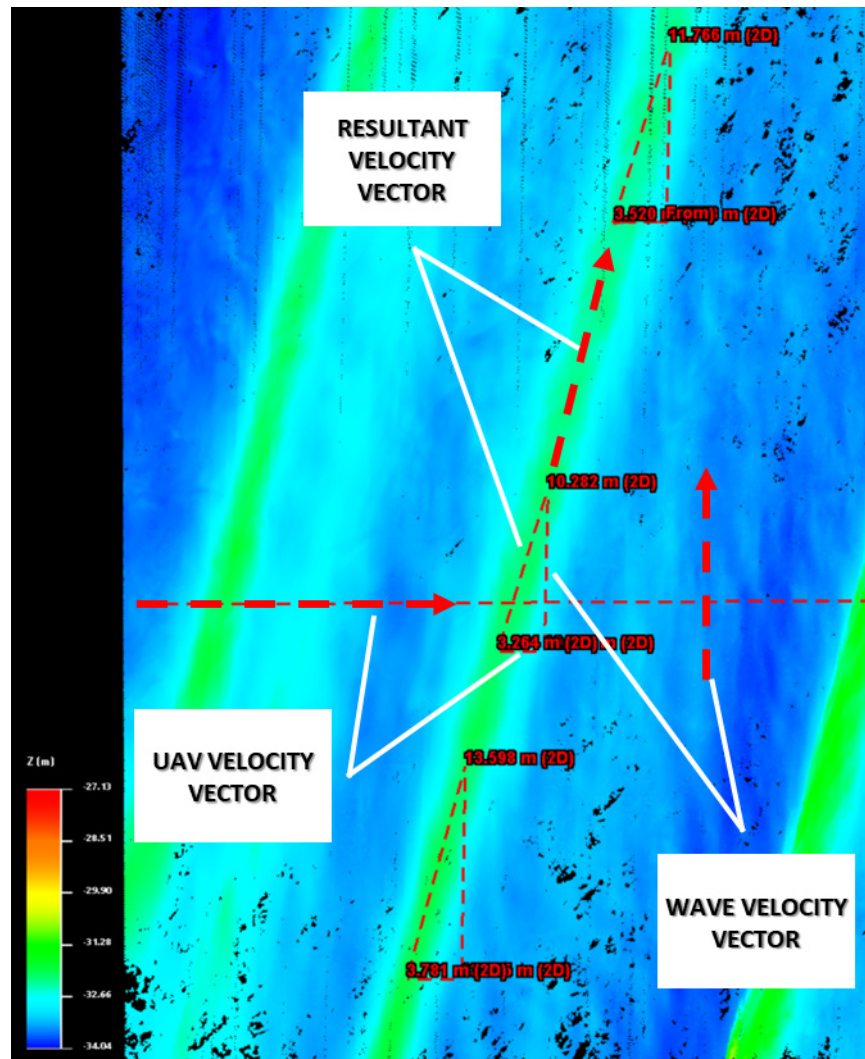


Figure 9. Right triangles applied to the wave crest. The vertical axis represents the cross-shore direction, with the beach in the direction of the top of the figure. As the wave and UAS progress forward in time, the resulting wave vector moves at an angle from bottom left to top right if the UAS is travelling left to right. The color bar represents vertical change in meters.

Once this angle was determined, the velocity of the wave as it propagated to shore was also estimated by taking the velocity of the UAS as the base of the triangle and using standard laws of trigonometry given by

$$\sin(\theta) = \frac{opp}{hyp}; \cos(\theta) = \frac{adj}{hyp} . \quad (13)$$

Equation (13) is used to determine the angles associated with each right triangle and later resolve each side of the triangle into velocity vector using the Pythagorean theorem

$$a^2 + b^2 = c^2. \quad (14)$$

Once an estimate of the wave velocity is found using equation (14), an estimate of the depth (h) is calculated using equation (12). These equations were paired with the data retrieved from the QTM transect to estimate the bathymetry at various points along each wave crest. This process laid the foundation for the algorithm utilized in MATLAB, discussed in detail in the next section.

6. MATLAB Analysis

The computer-based analysis was performed using a program written within MATLAB. The LiDAR point cloud data from QTM was exported via a CSV file to accurately plot the data. This file contains latitude, longitude, and height values for the various points in the data cloud and once exported, can be read into MATLAB and plotted. The first function in the code converts the latitude and longitude in the CSV file to x and y position in meters based on the WGS84 ellipsoid. These converted values are then mapped to a uniform grid, which is used to orient the point cloud such that flight trajectory is parallel to the x-axis.

The MATLAB program then uses a built-in function called “find peaks” to determine the local maxima for each row of data, which identifies the wave crests in the scan. It creates a three-dimensional image of the data, with black dots signifying the crest for each row, as seen in Figure 10.

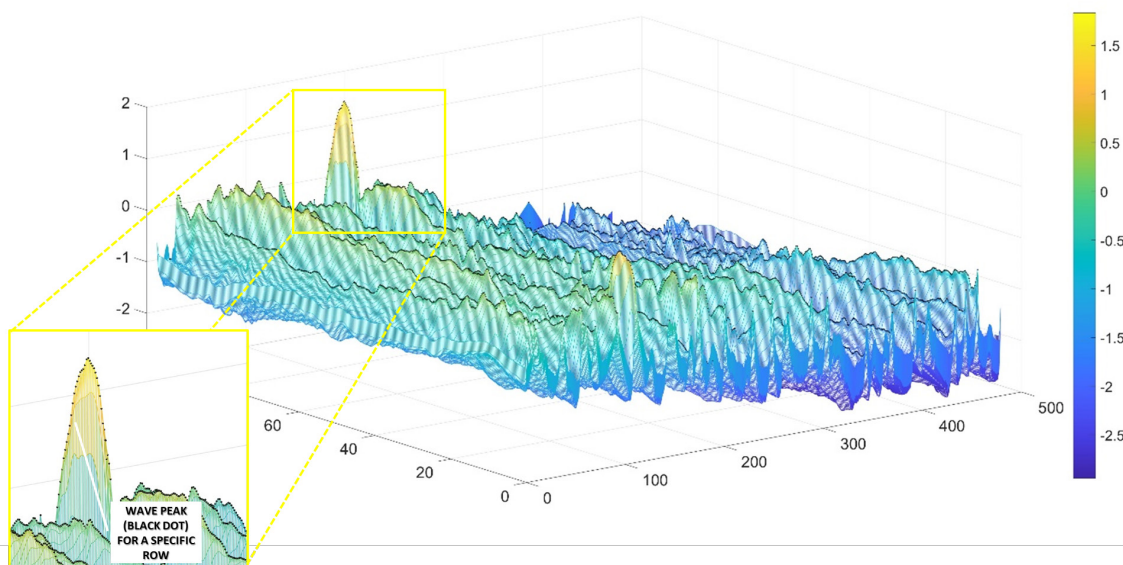


Figure 10. MATLAB generated 3-D point cloud of the scanned wave section.

The X-axis represents along-shore distance, while the Y-axis is the cross-shore component, both in meters. The black dots represent the wave peaks associated with that specific row. When iterated multiple times, the program can generate a line of wave peak data points, as represented in the zoomed in portion. The color bar shows vertical change in meters.

Once the wave peaks are identified, another built-in function called “cluster data” is used to group individual wave peak data points into groups. These groups, which represent the individual wave crests, are then plotted. An example is shown in Figure 11.

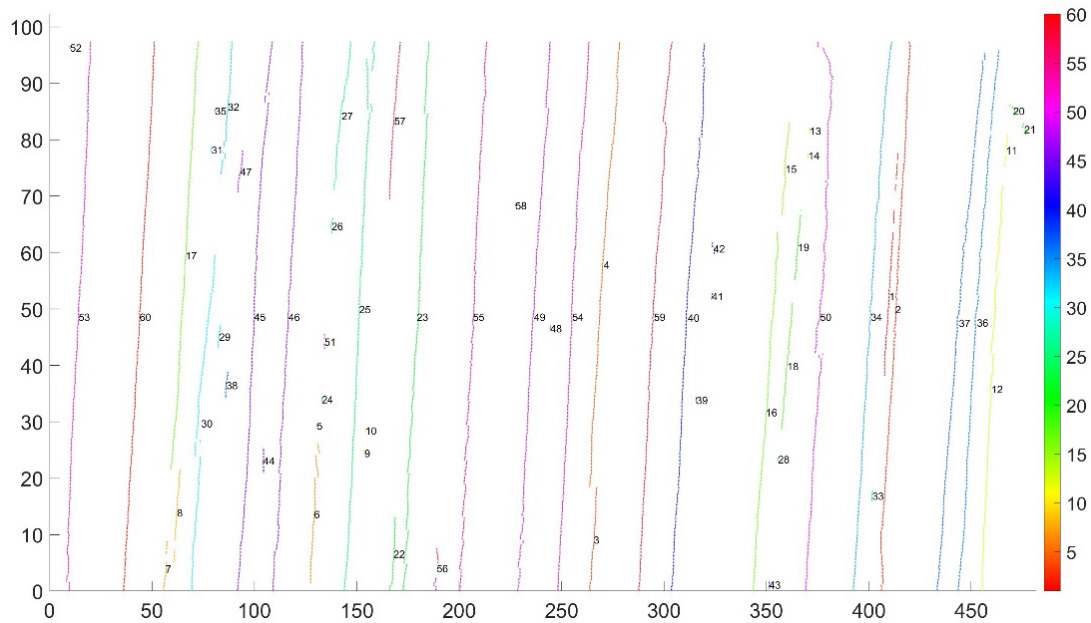


Figure 11. MATLAB generated 2-D plot of sorted wave peaks. The X-axis shows the along-shore distance, while the Y-axis shows the cross-shore distance, both in meters. This plot shows 60 wave crests. The value of 60 is adjustable by the user when prompted. Any discontinuities represent assumed new wave crest and are plotted as a separate new number. The color bar represents the number of the wave crest.

The program allows the user to clean up the plotted wave crest line by removing or merging sections of lines that may be in error or not viable for analysis. The final wave groups are then fit with a polynomial of 1st, 2nd, or 3rd order. These results presented in Chapter IV used first order fits exclusively, examples of which are shown in Figure 12.

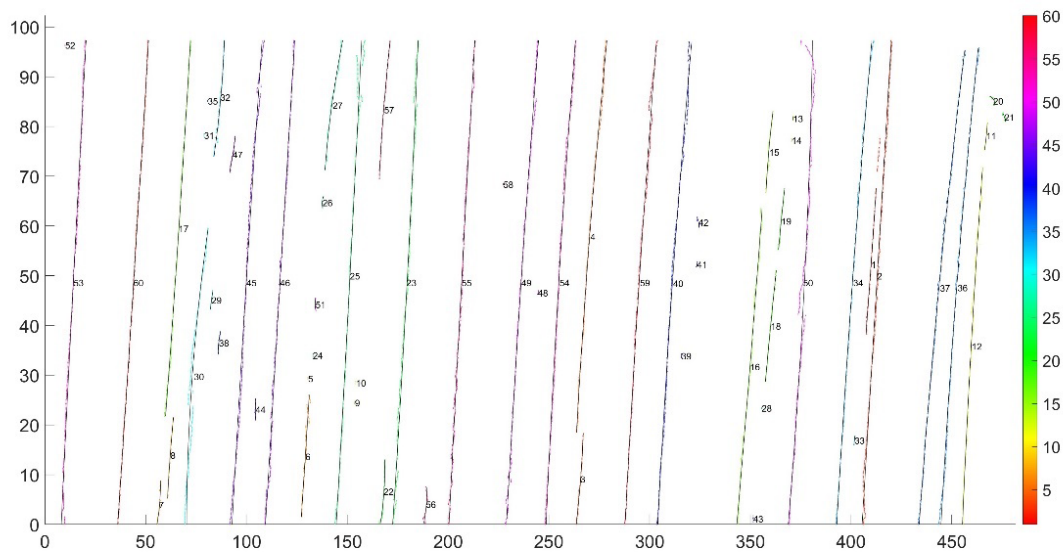


Figure 12. MATLAB generated 2-D plot of sorted wave peaks with a corresponding first-order fit applied. The X-axis shows the along-shore distance, while the Y-axis shows the cross-shore distance, both in meters. The color bar displays the number of counted wave crests.

The program then calculates the slope of the fitted lines; these slopes provide the equivalent information as the angles described in Chapter III.F.5. When combined with the UAS velocity, the slopes provide an estimate of the wave velocity. As before, the wave velocity is used to estimate the depth at each point on the curve, using equation (12). A contour plot is generated showing the estimated water depth based on the calculated velocities of the wave, like that seen in Figure 13.

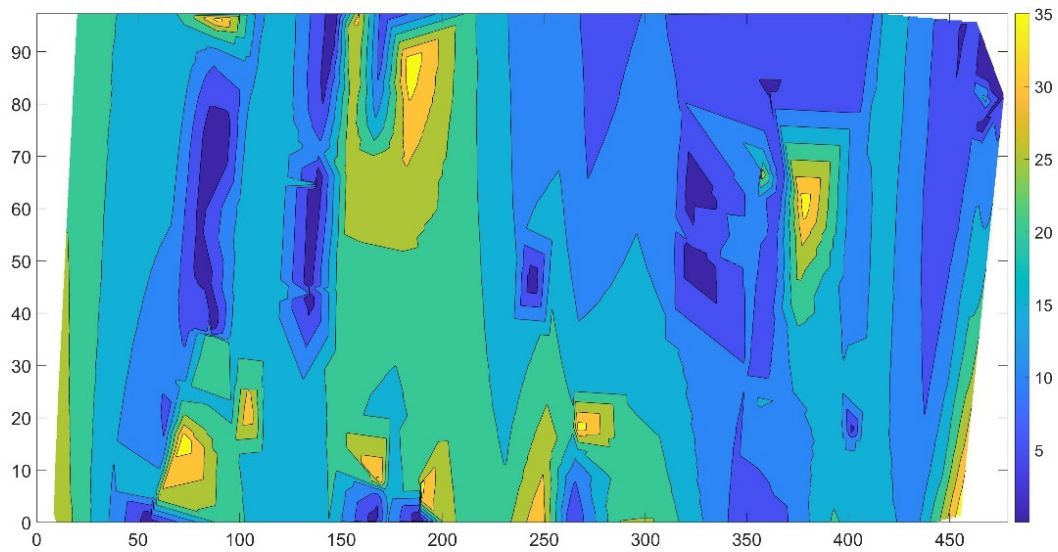


Figure 13. MATLAB generated depth contour. This contour is derived from the calculated wave velocity, determined after the ordered fit is applied. The X-axis shows the along-shore distance, while the Y-axis shows the cross-shore distance, both in meters. The color bar displays the estimated depth in meters. In this plot the beach is located on the top of the figure and transitions to deeper water moving on the Y-axis from 90 to 0.

IV. RESEARCH RESULTS

This research spans a two-year timeframe at two distinct locations, with a substantial portion of the viable data collected during the initial months of 2023. Several pivotal aspects necessitate explanation as an introductory opening to the subsequent findings. A comprehensive overview of each data collection site will be presented through illustrative graphics that depict the scan locations, vis-à-vis their corresponding beaches and orientations. Within each overview, a call-out box will showcase the figure number and date of scan acquisition, facilitating easy cross-reference. The boundaries of the scan area will be visually bounded by yellow boxes, serving as prominent indicators. Notably, the satellite imagery employed in these overview figures will offer each site's most pertinent visual representation during the specific time of scan capture.

The research outcomes are presented in chronological order of collection, offering a side-by-side comparative analysis labeled as A and B. Side A portrays the data points corresponding to wave crests from the LiDAR scans, with the corresponding estimated bathymetry values beneath each point. Simultaneously, side B illustrates the bathymetric plot derived from these wave crest data points through interpolation. Each plot's X and Y axes denote longitude and latitude coordinates. The color bar featured in each figure conveys the scaled bathymetry estimates in meters for both A and B sides. The color spectrum ranges from deep blue, symbolizing shallow waters, to vibrant yellow, signifying deeper waters.

The wave crest data points and the interpolated mesh bathymetry are superimposed onto a generic base map of each site, pinpointing the exact scan locations. However, it is essential to emphasize that these generic base maps are employed solely to orient the reader to the site's geographical context, devoid of any representation of actual site characteristics at the time. This approach will facilitate the reader's understanding of the context of the research findings.

To enhance the comprehension of sea state and tidal characteristics during the collection period, a point of reference has been furnished in Table 1. This table presents

the date, time, and location for each flight in the first four columns. The UAS flight velocity, average height derived from LiDAR scans, and standard deviation are in the next three columns. Finally, the NOAA recorded mean sea level, tide transitions, and National Data Buoy Center (NDBC) wave heights are listed in the final columns. The LiDAR records time and subsequently stamps each scan in Greenwich Mean Time (GMT) format. To facilitate readability a conversion to local time has also been provided in the table. In both cases, the time is provided in a 24-hour (hour, minute, second) format.

Table 1. Tide reference data for each date and site.

				LiDAR derived data			NOAA	Tide transition				NDBC
date	GMT	local	site	velocity (m/s)	mean (m)	stddev (m)	tide (msl,m)	low	low- high	high	high- low	wave ht (m)
9/9/2022	210946	140946	MBA	5	-32.72	0.683	0.171	X			X	2.27
10/21/2022	174513	104513	MBA	2	-29.49	0.323	0.45				X	2.455
10/21/2022	180434	110434	MBA	2	-31.33	0.807	0.368				X	2.455
1/12/2023	194917	114917	PAJARO	5	-0.47	0.2536	0.465		X	X		2.88
1/12/2023	195109	115109	PAJARO	5	-0.48	0.2419	0.499		X	X		2.88
1/12/2023	195259	115259	PAJARO	5	-0.857	0.493	0.499		X	X		2.88
1/12/2023	201649	121649	PAJARO	2	-1.535	0.616	0.5			X		2.88
1/12/2023	204304	124304	PAJARO	2	-32.7	0.672	0.536			X		2.85
2/10/2023	192310	112310	PAJARO	5	0.55	0.785	0.239		X	X		1.96
2/10/2023	192500	112500	PAJARO	5	5.784	2.669	0.25		X	X		1.96
2/10/2023	192652	112652	PAJARO	5	6.023	1.012	0.25		X	X		1.96
6/20/2023	154406	74406	PAJARO	4	-3.795	19.632	-0.912	X	X			2.56

A. MONTEREY BAY ACADEMY

The MBA data were collected on September 9, 2022, and October 21, 2022. These outcomes encompass three distinct yet adjacent scanned sections. Figure 14 illustrates the spatial arrangement of each scan with yellow boxes, that include the scan's date and its

corresponding figure number. Notably, Figure 14 illustrates the broader expanse where waves habitually crest at this beach, emphasizing the alignment of each scan in relation to this pivotal breaking point. Moreover, it depicts the resilience of the beach morphology to large scale sediment transport.

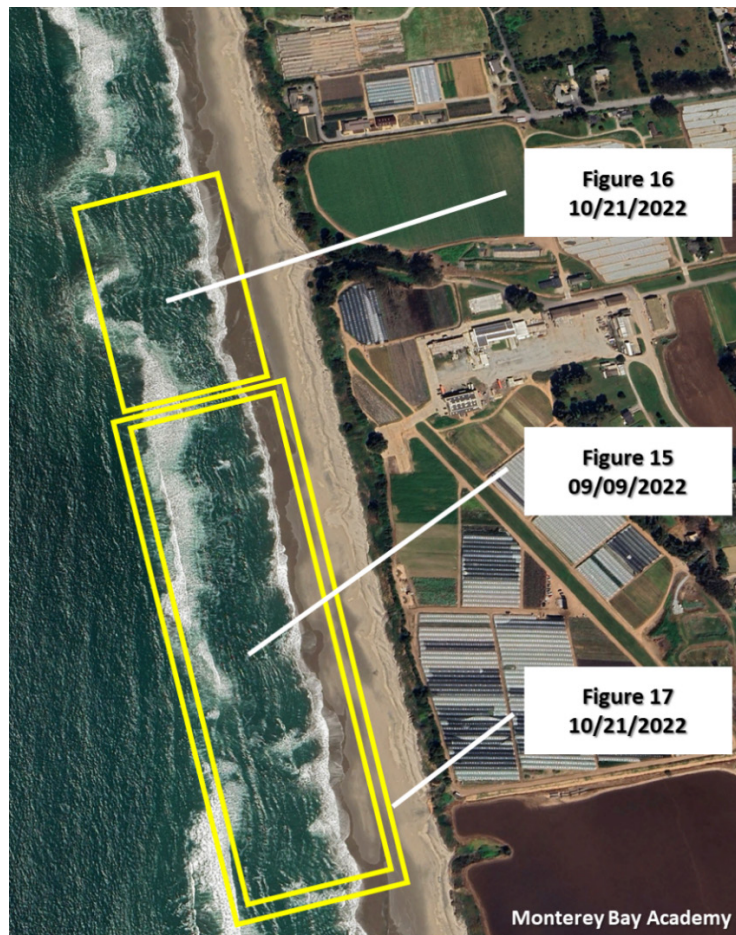


Figure 14. The northern Monterey Bay research site at the MBA. Located at latitude 36.906 N and longitude -121.846 E, during the months of September and October 2022.

The bathymetry estimation at MBA for September 9, 2022 (Figure 15) provides estimates of the underwater topography ranging in depths from 1–5 m. The scan was conducted at a velocity of 5 m/s and a pre-programmed altitude of 50 m, ensuring coverage of the target area. To establish an accurate reference point, the Mean Sea Level (MSL) for the specific date and time was determined as 0.171 m, transitioning from high to low tide.

This MSL value was sourced from the NOAA Monterey station 9413450, and all future MSL values will be sourced from the same location, ensuring consistency in the analysis.

The bathymetry estimation of 0.75 to 5.5 m was calculated using the MATLAB algorithm. Figure 15-A identifies significant water depths associated with various wave crests, particularly within the 4 to 5.5-meter range, potentially identifying key points in underwater terrain. Additionally, Figure 15-B provides a representation of the subtle yet gradual shift in bathymetry from the beach-oriented edge of the mesh plot toward the seaward side. This natural progression from shallow to deep water aligns with the expected profile of a typical beach region.

However, it is important to note specific anomalous data points in the figures. Instances of deep water near the shore, as depicted in Figure 15-A and then interpolated in Figure 15-B, are likely attributed to erroneous data points stemming from the line fit procedures detailed in Figure 11 and Figure 12 of the MATLAB code. While enhancing the bathymetric estimation's accuracy, these processes may inadvertently introduce outliers by introducing sections where the slope is undefined, (i.e.), perpendicular to the UAS trajectory. Figure 15 represents the anticipated bathymetry for the designated bay section. By merging data collection, thorough analysis, and sophisticated algorithms, this depiction offers valuable insights into the underwater landscape of the area, laying the foundation for further research.

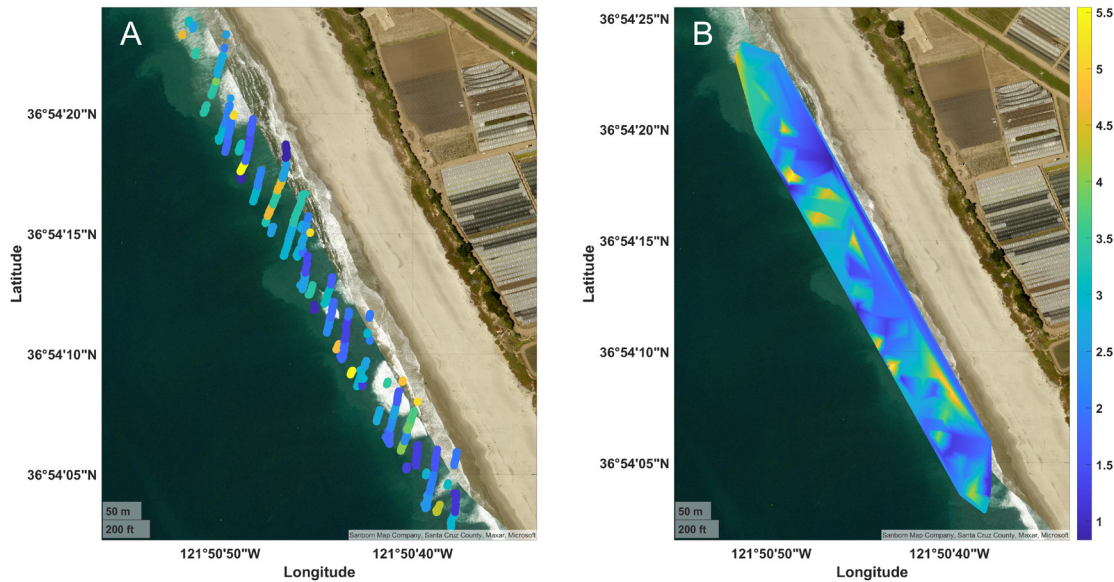


Figure 15. 09/09/2022 MBA bathymetry results (color bar in m). The UAS velocity for this scan was 5 m/s at an altitude of 50 m.

Figure 16 portrays the estimated bathymetry on October 21, 2022. The scan for this instance was conducted at a velocity of 2 m/s, maintaining a programmed altitude of 50 m. As of the specified date and time, the Mean Sea Level (MSL) stood at 0.45 m, transitioning from high to low tide. However, a notable discrepancy arises in Figure 16, where the estimated bathymetry values range between 0.1 and 0.37 m in depth. These values do not accurately reflect the expected depths characteristic of this location. Notably, the depths illustrated in Figure 16-A appear concentrated in the lower and middle segment of the scan and, crucially, appear closer to the shoreline than expected. The gradual shift toward shallower waters on the seaward side of the scan accentuates this. Figure 16-B further illustrates this gradual transition and the focus on deeper waters in the lower half of the scan. The marked disparity in the bathymetry outcomes between Figure 16 and the previously mentioned Figure 15 can be attributed to the difference in scanning velocity. This topic will be revisited in the forthcoming discussion section.

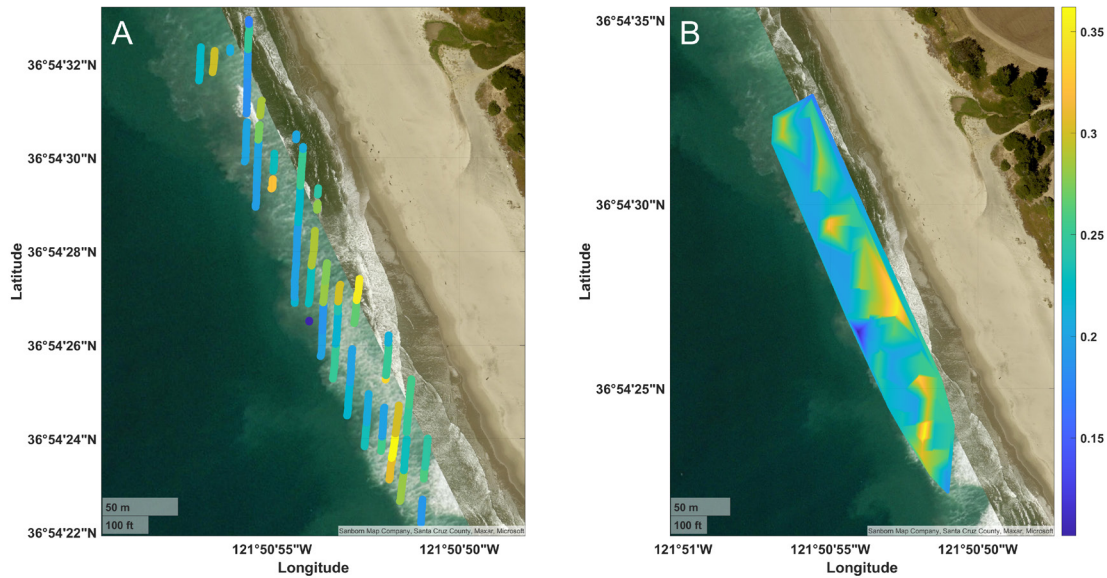


Figure 16. 10/21/2022 MBA bathymetry results (color bar in m). The UAS velocity for this scan was 2 m/s at an altitude of 50 m.

Figure 17 represents the subsequent segment of the estimated bathymetry on October 21, 2022. Like the previous scan, this iteration was conducted at a velocity of 2 m/s, maintaining the programmed altitude of 50 m. The MSL recorded for this specific date and time was 0.368 m, transitioning between high and low tide conditions. In both Figure 17-A and 17-B, a noticeable disparity in estimated depths becomes apparent from the scan's lower to upper extent, spanning from 0.04 to 0.22 m. Interestingly, the upper section of Figure 17-B consistently exhibits slightly deeper waters than its lower counterpart, indicating a potential shoaling phenomenon from north to south. Figure 17-A depicts fewer instances of relatively deep water, a characteristic exacerbated by the interpolation process between Figure 17-A and 17-B.

Figures 16 and 17, having the same UAS velocity, exhibit similar bathymetry estimate ranges. This similarity between the two outcomes provides some reassurance; however, it also underlines the issue of varying velocities and its impact on bathymetry estimates. The persistent coherence between these findings prompts a degree of comfort, yet still underscores the overarching concern of UAS velocity-related discrepancies. The subsequent sections of this document will delve into a commentary of these observations,

attempting to shed light on the underlying causes of the observed variations in bathymetric estimations across different velocities.

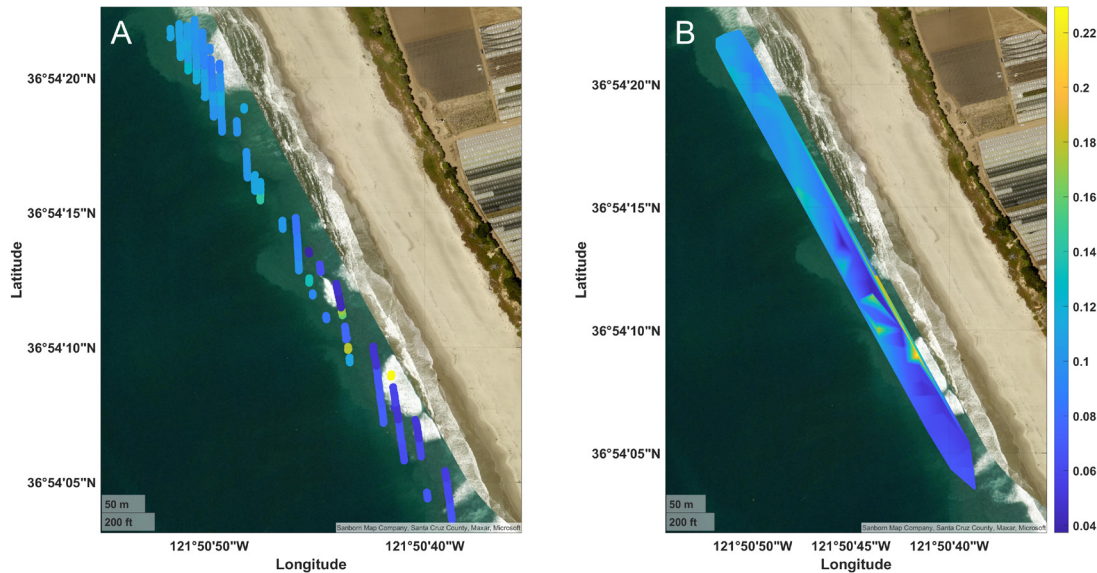


Figure 17. 10/21/2022 MBA bathymetry results (color bar in m). The UAS velocity for this scan was 2 m/s at an altitude of 50 m.

B. PAJARO BEACH

Figure 18 presents an overview of the Pajaro Beach collection site. The figure offers five distinct scan boxes, each captured on January 12, 2023. Delineated by dashed lines, certain boxes stand as spatial subsets within or overlapped with other scan areas. Beyond its geometric arrangement, Figure 18 also illustrates the beach environment proximate to the time of data collection. Attributes include rip channels, beach cusps, and multiple wave propagation patterns.

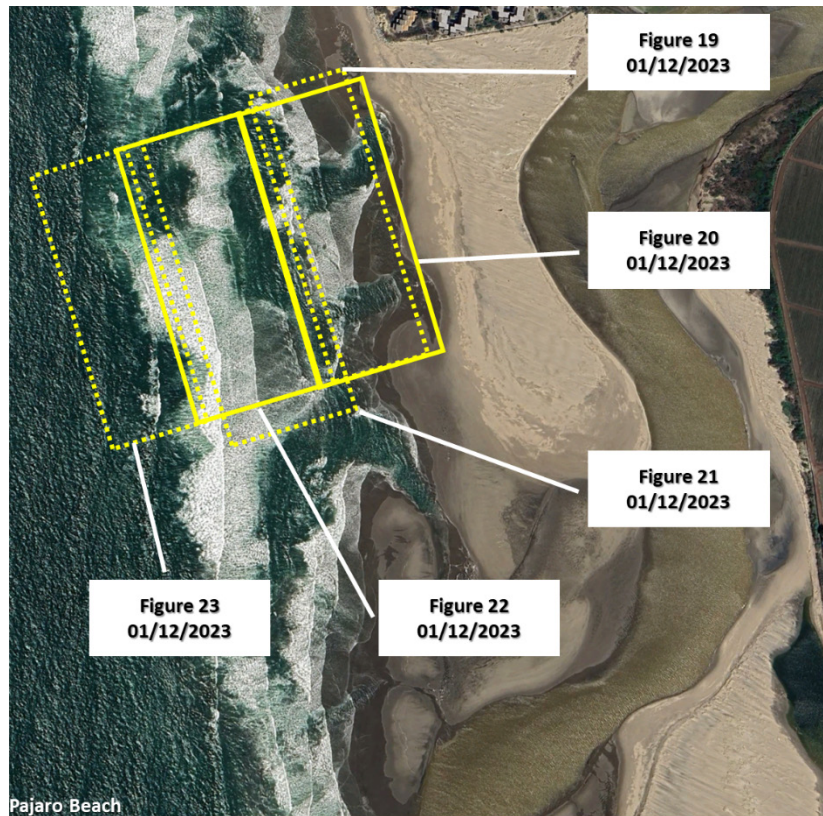


Figure 18. The southern Monterey Bay research site at Pajaro Beach. Located at latitude of 36.851 and longitude of -121.810. All taken during the month of January 2023.

Figure 19 summarizes a snapshot of the underwater landscape, captured in flight at a steady velocity of 5 m/s and an altitude of 50 m above the surface. This data acquisition coincides with an MSL of 0.465 m, marking the transition from low to high tide on that day. Within the contours of Figure 19, the bathymetric estimates span a spectrum ranging from 0.5 to 6 m in depth, painting an intricate portrayal of the submerged terrain.

Within Figure 19-A a distinct pattern emerges, where the northern sector of the scan harbors a concentration of deeper water depths, while shallower expanses characterize the southern counterpart. This intriguing variation in depth could be attributed to the presence of well-defined rip channels, a phenomenon discernibly evident in the background satellite image from April 2023 in Figure 18. Alternatively, the presence of the river outlet and the known sediment transport of its outflow could explain the shallower waters on the bottom portion of the interpolated data.

A focal point within Figure 19-A unveils an anomaly characterized by a pocket of exceptional depth amidst the surrounding data points. This conspicuous feature is further confirmed by the interpolated bathymetry depicted in Figure 19-B, where the yellow hue signifies this region's pronounced depth. The interaction of these elements within Figure 19 offers some insight into the underwater dynamics of the surveyed area, suggesting varying depths and distinctive underwater structures.

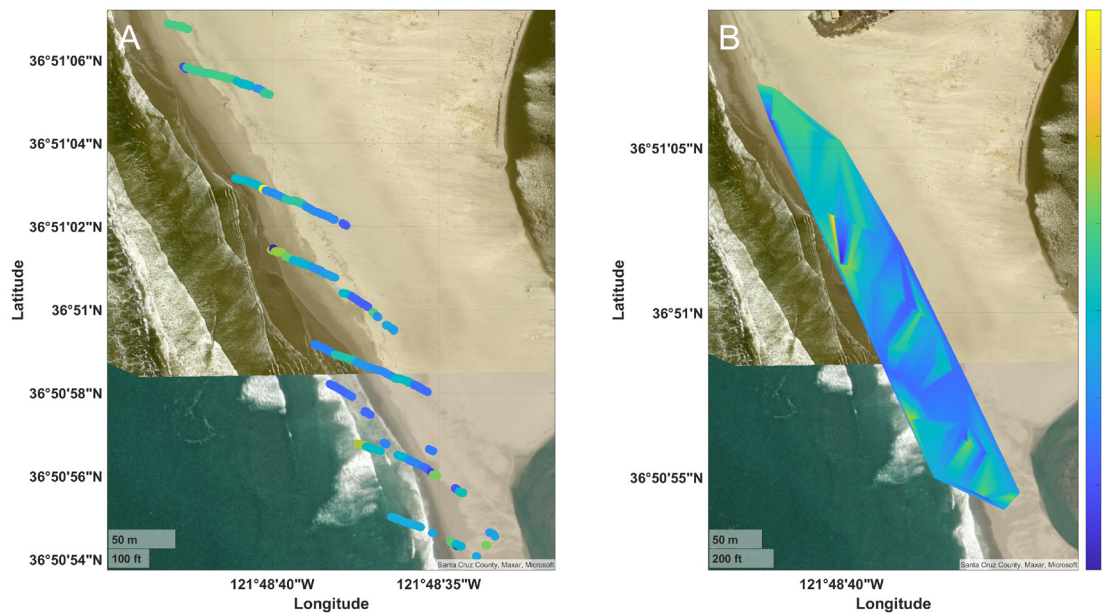


Figure 19. 01/12/2023 Pajaro Beach bathymetry results (color bar in m). The UAS velocity was 5 m/s at an altitude of 50 m.

Figure 20 was captured under analogous conditions of velocity and altitude, as portrayed in Figure 19, with a noteworthy deviation characterized by a seaward shift of approximately 25 to 50 m. During the specific timeframe of this data acquisition, the Mean Sea Level (MSL) stood at 0.499 m, exhibiting a progressive transition from low to high tide. Within the contours of Figure 20, the estimated depths once again span a dynamic range extending from 0.5 to 6 m, with a discernible emphasis on the emergence of deeper underwater realms.

The composition of Figure 20-A unveils interwoven regions marked by greater water depth; upon comparing this depiction with Figure 20-B and considering the insights gleaned from Figure 19, it becomes apparent that a gradual progression exists toward deeper waters moving from the shoreline to the seaward side. This trend aligns with the anticipated dynamics of water deepening as one ventures farther out to sea.

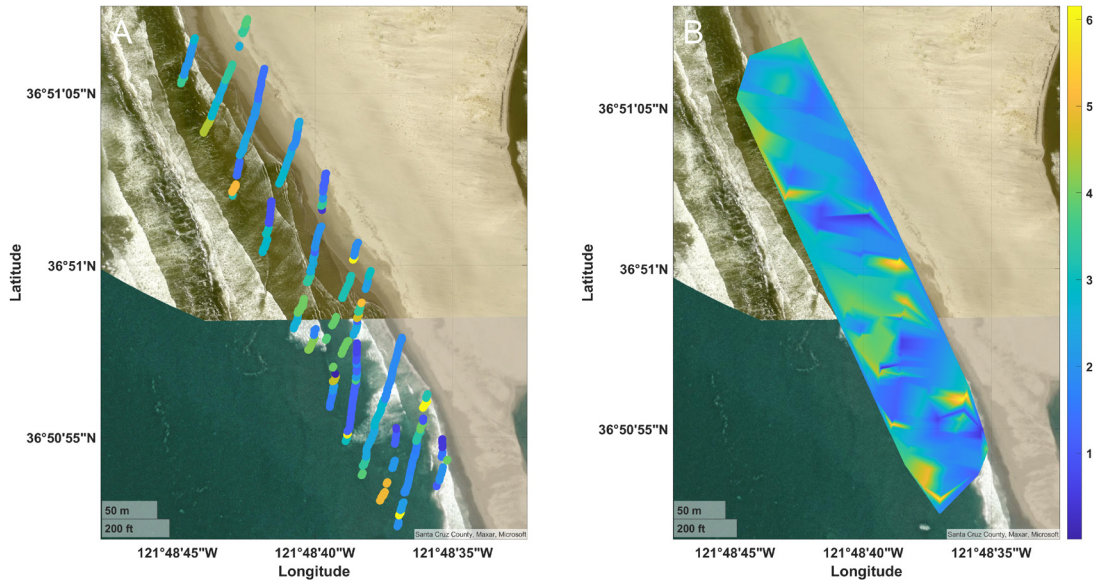


Figure 20. 01/01/2023 Pajaro Beach bathymetry results (color bar in m). The UAS velocity was 5 m/s at an altitude of 50 m.

Figure 21 corresponds to the same conditions as depicted in Figures 19 and 20. This rendition, however, includes another significant seaward shift, surpassing 15 m in magnitude. The Mean Sea Level (MSL) and tide transition mirror those illustrated in Figure 20. The estimations of bathymetry for this scan are indeed promising, showcasing a range of values spanning 1.5 to 14.5 m.

The insights gleaned from Figure 21-A are particularly illuminating, as they highlight a proliferation of data points signifying deeper waters in tandem with wave crests. Meanwhile, Figure 21-B shows the interpolated results. The progression from Figures 19 through 21 collectively aligns with the expected ground truth values.

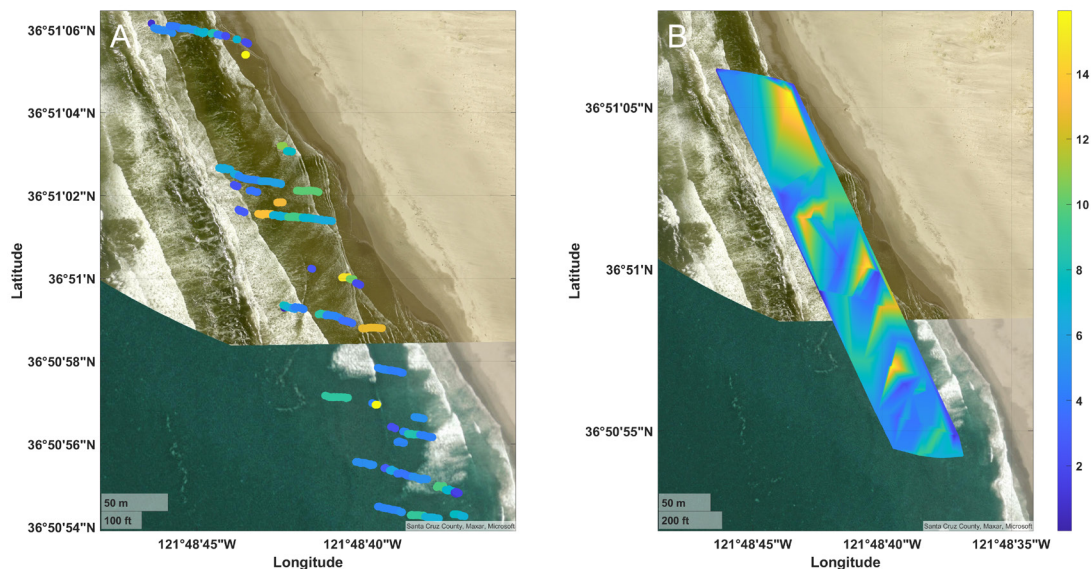


Figure 21. 01/12/2023 Pajaro Beach bathymetry results (color bar in m). The UAS velocity for this scan was 5 m/s at an altitude of 50 m.

The results shown in Figure 22 were collected while flying at a distinctly slower velocity of 2 m/s and maintaining the prescribed altitude. Positioned close to the location depicted in Figure 21, this scan coincided with the pinnacle of high tide on January 12, 2023. The estimated depths shown in Figure 22 range from 4.5 to 35 m, slightly overlapping the results in Figure 21. However, the depths are significantly greater.

The depths illustrated in Figure 22-A frequently exceed 20 m, particularly at the top of the figure. This pattern appears even more pronounced in Figure 22-B, where the concentration takes on a distinct contour, accompanied by a perceptible shoaling effect that moves from the upper to lower limits of the figure.

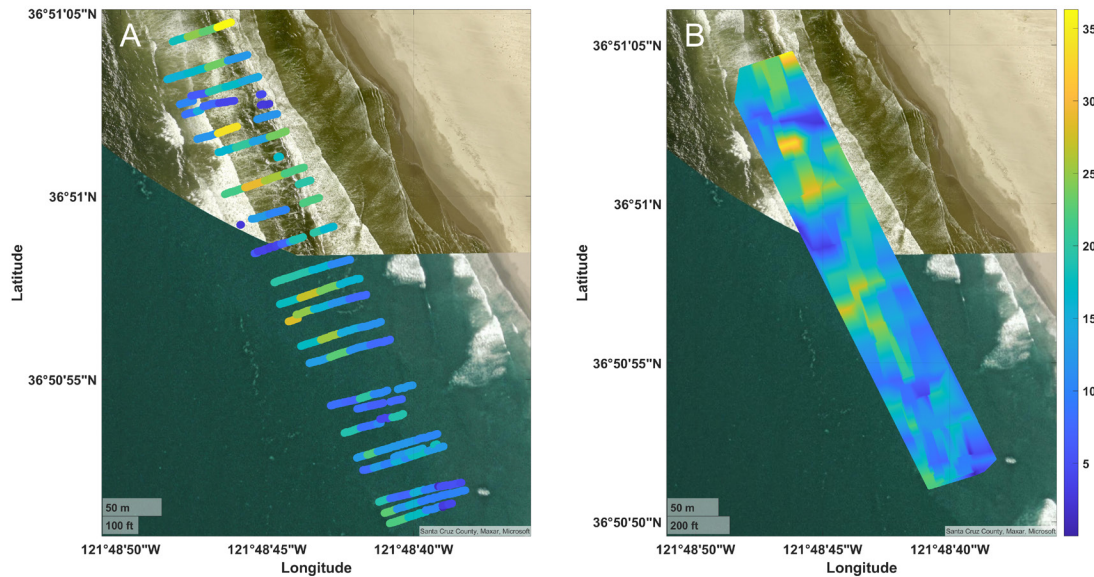


Figure 22. 01/12/2023 Pajaro Beach bathymetry results (color bar in m). The UAS velocity for this scan was 2 m/s at an altitude of 50 m.

The trajectory of Figure 23 mirrors that of Figure 22, adopting an identical configuration albeit with a seaward shift off approximately 25 to 50 meters. Similar tendencies persist, where Figure 23-A reports extreme depths at the scan's top, middle, and bottom extents. Figure 23-B, meanwhile, offers an insight into the interpolated coverage area, drawing attention to a substantial expanse of shallow water within one of the deeper portions of the scan. This incongruity, apparent amid the scan's broader characteristics, raises a flag of suspicion regarding its accuracy. In Figures 22 and 23, the results systematically overestimate the anticipated depths for this specific area by a significant margin.

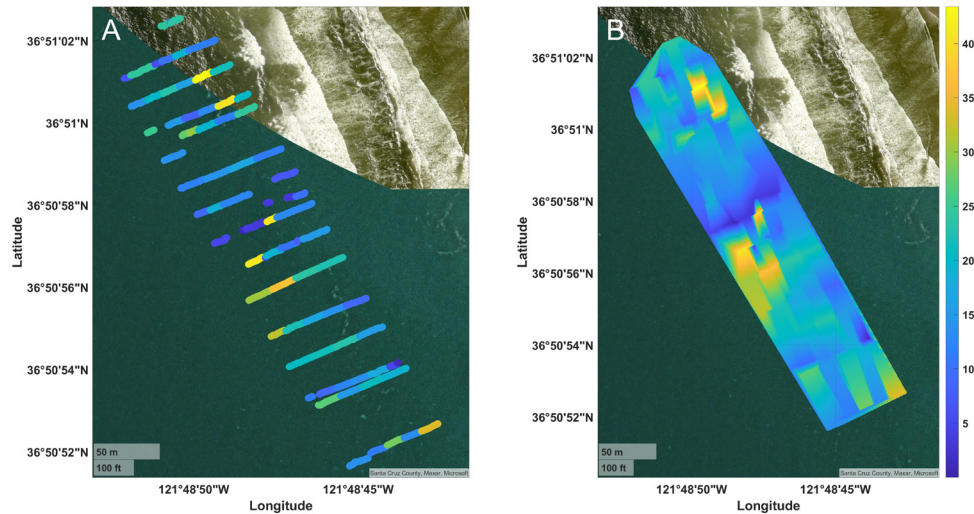


Figure 23. 01/12/2023 Pajaro Beach bathymetry results (color bar in m). The UAS velocity for this scan was 2 m/s at an altitude of 50 m.

Finally, Figure 24 again shows an overview of the Pajaro Beach collection region, but this time depicting the boundaries of four scans, three of which were executed on February 10, 2023, with the fourth scan undertaken on June 20, 2023.

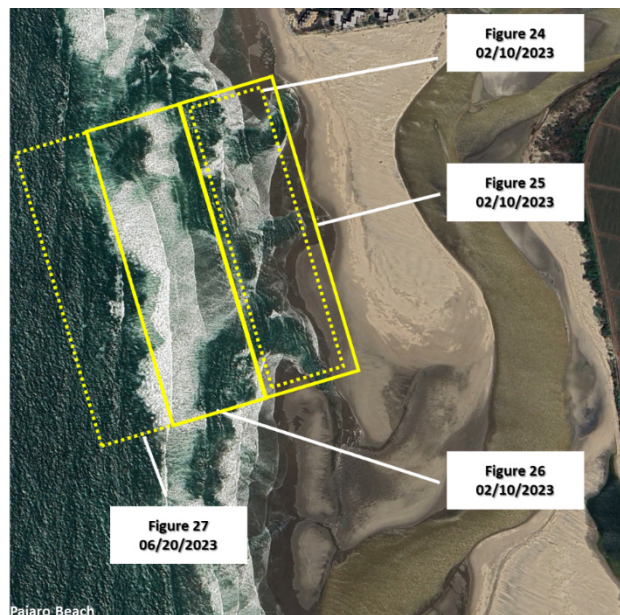


Figure 24. The southern Monterey Bay research site at Pajaro Beach. Located at latitude of 36.851 and longitude of -121.810. All taken during the months of February and June 2023.

The data represented in Figure 25 was captured on February 10, 2023, with the UAS moving at a velocity of 5 m/s. The MSL at that specific time was 0.239 m, transitioning from low to high tide. The estimated bathymetry ranges from 0.5 to 10 m.

In Figure 25-A, there is a noticeable convergence of significant depth values at the central part collection, with a few additional instances towards the upper and lower boundaries of the region. Figure 25-B illustrates the interpolated representation of these noteworthy depth areas and their impact on the remaining sections of the scan. Moreover, in Figure 25-B, attention is drawn to an area of remarkably shallow water towards the lower end of the scan, coupled with a sudden spike of greater depth. There are many potential hosts for the causes of this anomaly. It could stem from missing or deleted data or anomalous points in the scan. However, it can most likely be attributed to a compounded error within the interpolation process, originating from the raw data that survived the deletion, merging and line fitting process. Both sides, A and B, imply a gradual increase in water depth from the shoreline towards the offshore side. Furthermore, Figure 25 resembles its earlier counterpart, Figure 19, instilling optimism in this methodology.

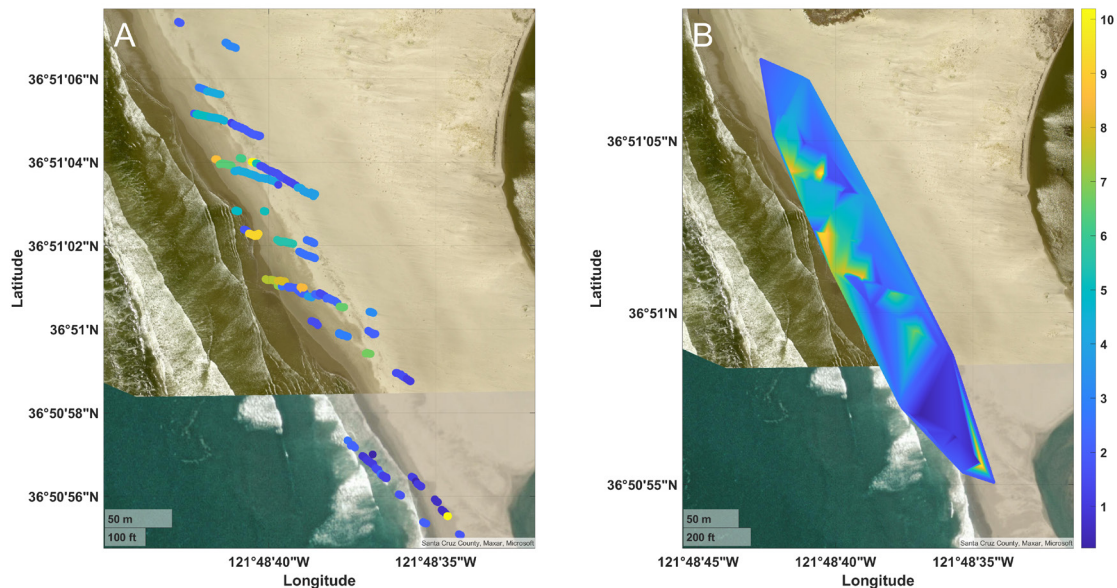


Figure 25. 02/10/2023 Pajaro Beach bathymetry results (color bar in m). The UAS velocity for this scan was 5 m/s at an altitude of 50 m.

Turning to Figure 26, despite being shifted seaward approximately 25 to 50 m, it parallels the results in Figure 25. The MSL during this collection stood at 0.25 m, steadily transitioning between low and high tide. The projected bathymetry ranges from 0.5 to 8.5 m.

The results in Figure 26-A exhibit a concentration of greater water depths in the lower segment of the scan, with moderate depths situated just adjacent. Transitioning to Figure 26-B, it becomes evident that a gradient exists, spanning from shallow to deep water and progressing from the upper to lower parts of the scan. A pocket of shallow water punctuates this gradient at the lower extent. Notably, Figure 26 also shares similarities in bathymetry estimation with Figure 20, which was captured in the same location.

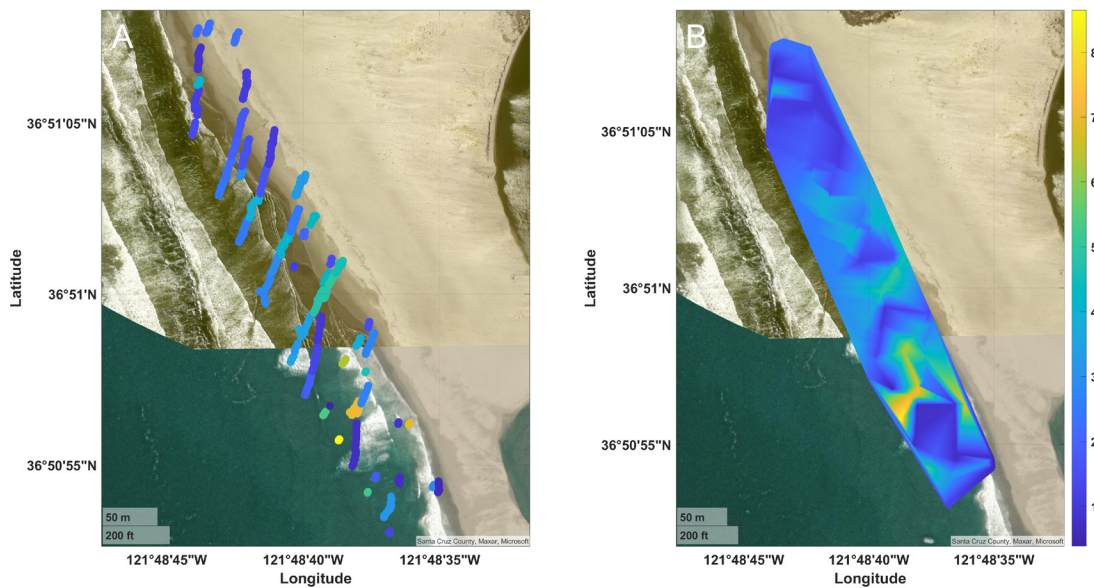


Figure 26. 01/12/2023 Pajaro Beach bathymetry results (color bar in m). The UAS velocity for this scan was 5 m/s at an altitude of 50 m.

The data in Figure 27 were collected approximately 25 to 50 m seaward of Figures 25 and 26 with the same flight condition. The MSL during this instance measured 0.25 m, consistently at high tide. The estimated underwater topography for this data collection spanned depths ranging from 0.5 to 10 m.

Figure 27-B presents fewer deeper water pocket occurrences than its counterparts in Figures 25 and 26, except for one extreme case at the lower boundary of the scan. Figure 27-B provides insight into the gradual intermingling of deep and shallow waters within the scan. A distinct transition is observable, moving from deeper waters in the upper portion to shallower waters in the lower section. Encouragingly, this figure shares numerous similarities with Figures 25 and 26 and with Figure 21 from a similar location.

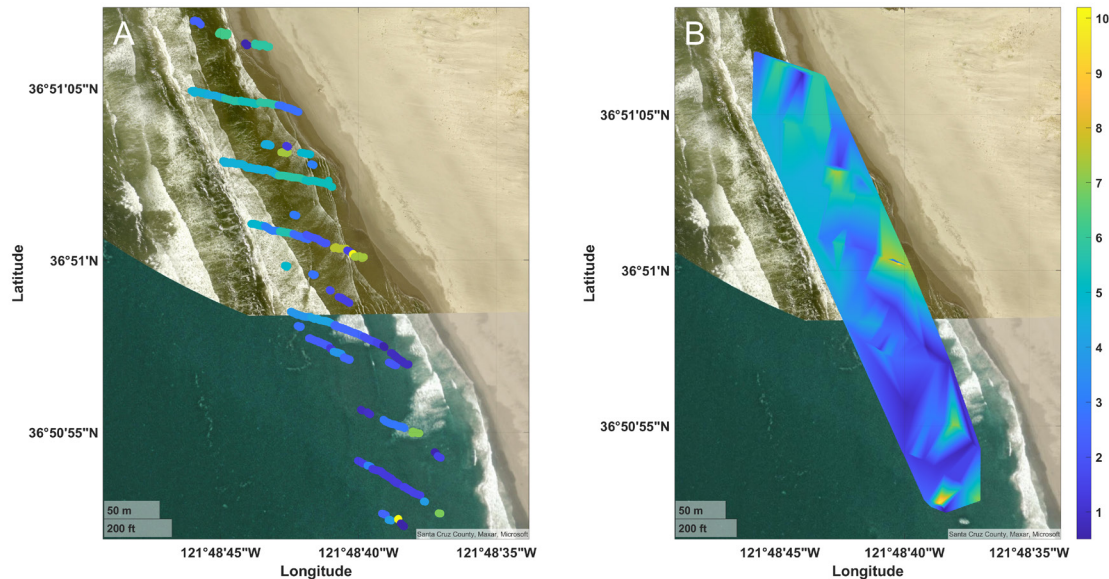


Figure 27. 02/10/2023 Pajaro Beach bathymetry results (color bar in m). The UAS velocity for this scan was 5 m/s at an altitude of 50 m.

Shifting attention to Figure 28, this data was collected on June 20, 2023, with the UAS traveling at a speed of 5 m/s and an altitude of 50 m. The MSL during this date and time stood at -0.912, indicating a low tide state. The estimated depth range for this dataset spanned from 0.5 to 7.5 m.

In Figure 28-A, a significant portion comprises intermediate water depths, while Figure 28-B portrays a disorderly mixture of water depths. This figure also identifies two distinct pockets of greater water depth and two shallow water pockets. Although it aligns with the depth estimates presented in Figures 26 and 27, neither a clear depth progression nor pattern is present.

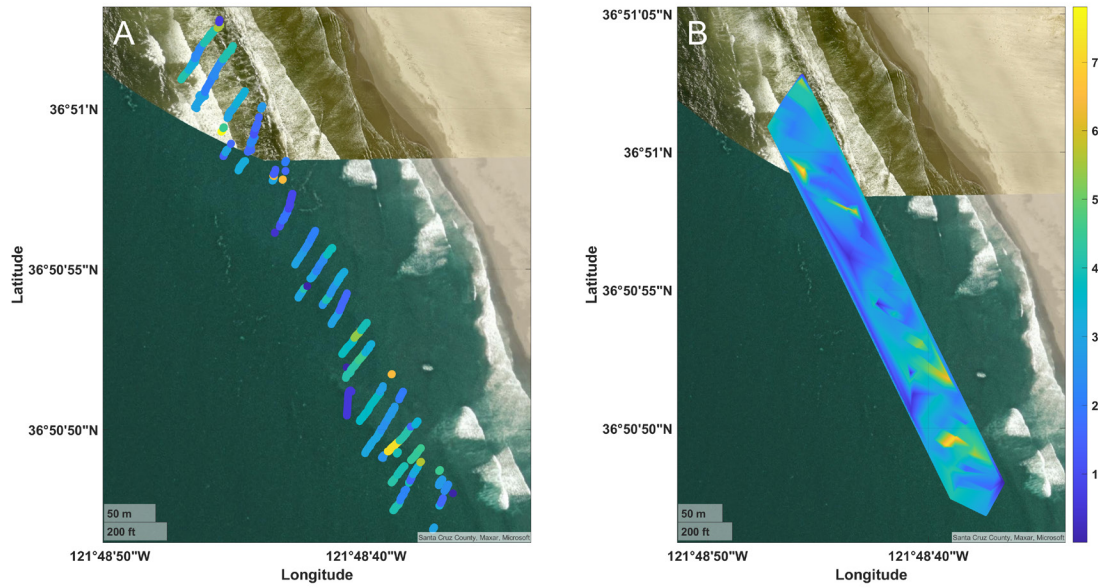


Figure 28. 02/10/2023 Pajaro Beach bathymetry results (color bar in m). The UAS velocity for this scan was 5 m/s at an altitude of 50 m.

C. COMPARISON

Figures 29 to 31 provide a comparative view of the wave crest data points captured on different dates. Moreover, all the comparisons were taken at approximately the same locations. While there may be variations in velocities in some cases, the fundamental layout of each figure remains consistent with those presented previously.

Figure 29 compares the wave crest data points obtained on September 9, 2022 (Figure 29-A) with the data collected on October 21, 2023 (Figure 29-B), both of which were flown at MBA. The data collection for side A occurred at a speed of 5 m/s, while side B was captured at 2 m/s. The contrasting estimated bathymetry values become evident when the UAS's velocity is altered. Figure 29-A aligns with the anticipated water depth for that location, thereby enhancing confidence in the methodology employed. The results in Figure 29-B indicate a significant underestimation.

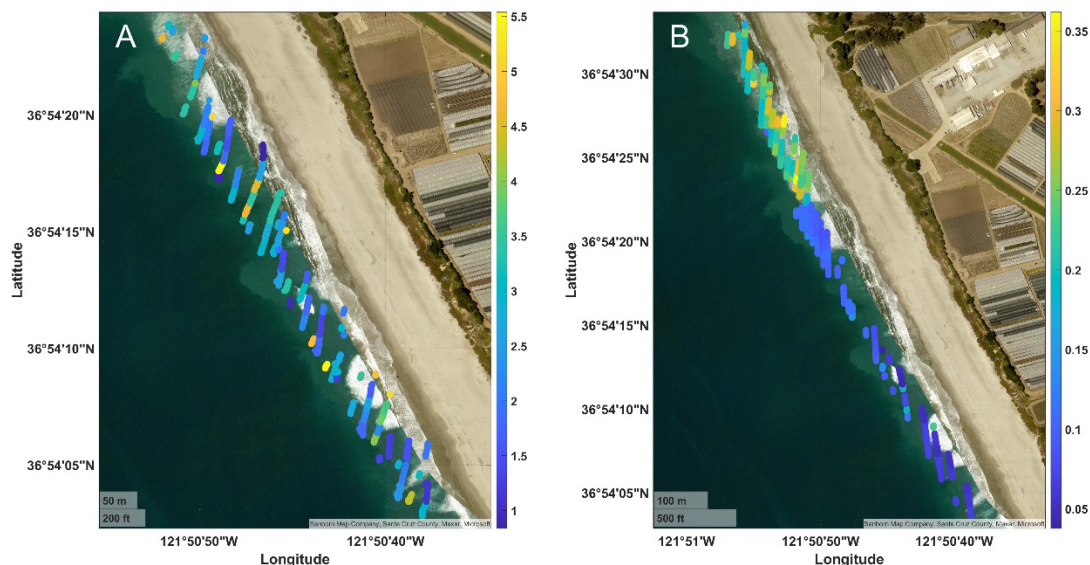


Figure 29. Result comparison of MBA data with varied velocity. Side A depicts results for a UAS velocity at 5 m/s collected 09/09/2022. Side B depicts results for a UAS velocity at 2 m/s collected 10/21/2022.

Contrastingly, Figure 30 represents a notable stride forward, as it presents a comparison between scans captured on different dates: January 12, 2023, and February 20, 2023, both at Pajaro Beach. Both aerial surveys were conducted at a velocity of 5 m/s. While the estimated water depths differ slightly, they remain closely aligned.

On the other hand, Figure 31 presents wave data points from January 12, 2023, acquired with differing UAS velocities. Figure 31-A corresponds to velocities set at 5 m/s, while Figure 31-B reflects a velocity of 2 m/s. Much like the disparity observed in Figure 29, Figure 31-B reveals a comparable incongruity in results, estimating extreme water depths. This discrepancy becomes evident as Figure 31-B significantly overestimates the bathymetry values when the UAS velocity is reduced to 2 m/s. Notably, this contrast in results contradicts the expectations set by the observations in Figure 29.

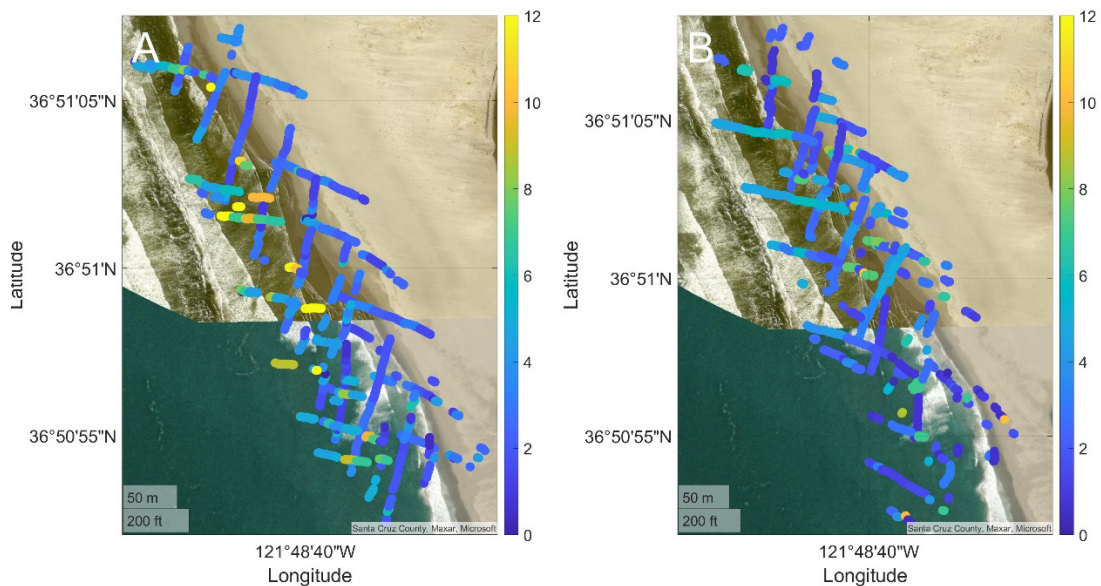


Figure 30. Results comparison for flights at Pajaro Beach roughly one month apart at 5 m/s. Side A was collected 01/12/202, while side B was collected 02/10/2023.

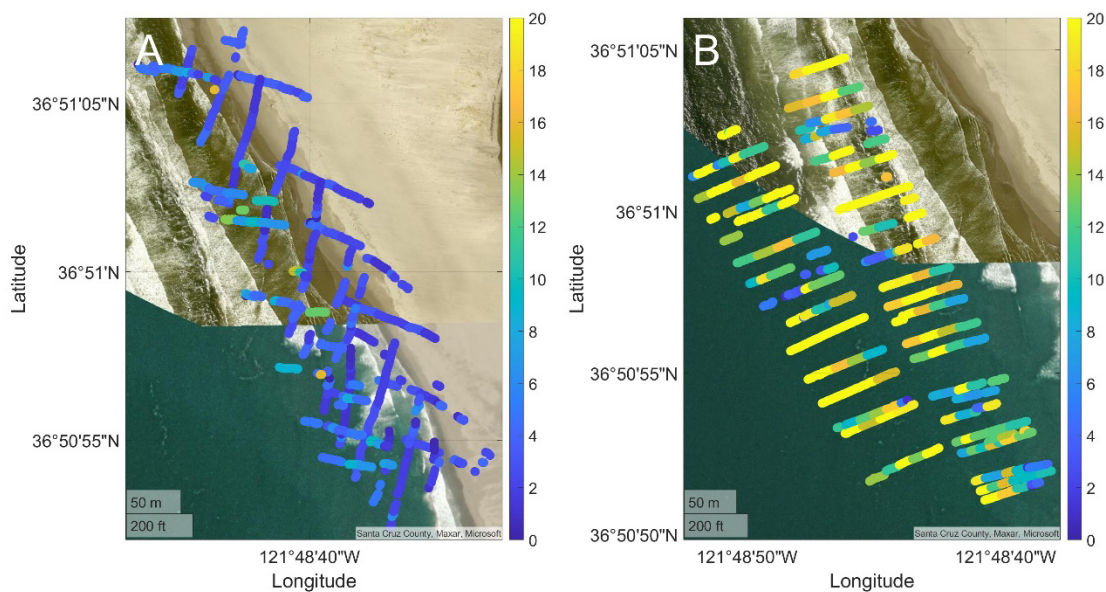


Figure 31. Results comparison for flights at Pajaro Beach at varied velocities. Both collected 01/12/2023. Side A was flown at 5m/s, while side B was flown at 2 m/s.

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V. DISCUSSION AND CONCLUSION

During this research, several factors contributed to errors in the collection and analysis of data. The purpose of this section is to identify these factors and suggest feasible solutions to prevent them. It's important to note that the discussion and recommendations presented are not exhaustive but will assist in future research.

When collecting data with a UAS, the velocity at which it is flown can greatly affect accuracy of bathymetry estimation. The current MATLAB algorithm is particularly sensitive to this factor because a slower velocity can cause the wave crest to become more perpendicular to the viewing angle, as shown in Figure 12. This can lead to undefined slopes and extreme velocity results, as seen in Figures 22 and 23. Furthermore, traveling too fast can lead to a wave crest represented as parallel in the scan, or limit the number of wave crests collected in the scan data. This undoubtedly causes problems in angle and velocity calculation discussed in Chapter III.

To avoid this, it is recommended to fly the UAS at a speed between 4 m/s and 8 m/s. This range will allow for the collection of wave crest data that accurately depicts the gradual slowing of the wave as it moves towards the shore. The resulting wave crest will have a subtle arc towards the UAS trajectory, as seen in most of the wave crest (side A) plots in the results section. Remaining within these velocity limits will ensure that the ordered fit and slope calculation process is reliable. Based on Figures 19 to 21, it appears that a UAS velocity of 5 m/s yields results that are close to expected values.

Determining the precise latitude, longitude, and elevation of the scan data has been a challenge. The relation of elevation data to WGS84 and the North American Vertical Datum 1988 (NAVD88) has been a subject of debate. NAVD88 is a leveling network of sensors across North America, used to establish the vertical datum on the continent. In a perfect world the WGS84 ellipsoid is adjusted locally to the geoid through the NAVD88 vertical datum. To achieve the most accurate position data in the final product, the trajectory of each respective scan needs to be aligned with the WGS84 ellipsoid model during processing. However, during this study, there were inconsistencies in the elevation

data for certain areas, particularly in wave heights, which did not match the expected values for the specific location. It is assumed that a built-in sub-adjustment may exist within the Riprocess or POSPAC proprietary software. Ultimately, causing the processed trajectory to be misaligned with the WGS84 vertical datum. This was evident in many of the Pajaro Beach data sets, raising concerns. There was also a lack of understanding of how the UAS operated with respect to large scale elevation changes, particularly at the MBA research site. It was believed that the UAS would maintain its preprogrammed altitude and adjust itself according to the surrounding terrain, all facilitated by the received GPS signal. However, that was not the case, resulting in the data collected at MBA being recorded from approximately 80 m altitude instead of the programmed 50 m.

To mitigate any errors that may have been introduced during the scanning process, it is important to ensure a thorough understanding of each piece of equipment being used. Additionally, conducting a GPS walking survey on the beach directly adjacent to the scanned areas of the surf zone can provide an accurate representation of local elevation. This can be compared to the scanned wave heights for a more accurate final product. Another option is to use GPS-based ground control points placed on the beach at both ends of the shore adjacent to the scanned area to mitigate any elevation errors that may have been introduced.

During the research, it was expected that the angle between the UAS and waves would introduce error, given the nature of their estimation. The wave scans look like curved lines because of the assumption that the waves move straight towards the shore, and the UAS moves parallel to the wave crests. However, this is not the case in the real world as there is always some inherent angle between the two. To address this, the angle between the UAS and waves was adjusted early in the MATLAB algorithm using land features, UAS's orientation, and swash zone, which is the zone where the wave surge runs up the beach. Unfortunately, this introduced many errors, skewing the results. Additionally, the mounting angle between the UAS and the LiDAR was inconsistent in earlier scans, which is the second reason for the shallow bathymetry estimates seen in Figures 16 and 17.

To ensure accurate angle measurements, it's important to follow a strict and detailed procedure when mounting the LiDAR to the UAS. Visual alignment marks should

also be present and utilized during the mounting process. To further mitigate any errors in angle approximation, it's recommended to use imagery taken simultaneously with LiDAR. While the Mini-VUX 2 has a built-in camera system that can be used for this purpose as was originally intended, the cable was destroyed and could not be used for this research. Another option to consider is placing reflective surfaces in the swash zone that are aligned and parallel to the waves. These structures must be visible in the initial scan data so they can be referenced later for accurate angle estimation.

During the research, one of the challenges was obtaining accurate reference data. It was necessary to verify the proposed methodologies and resulting estimates with real world quality-controlled data. However, due to the dynamic nature and constant change of the surf zone, it was difficult to collect reliable ground truth bathymetry data. The collection of large-scale surf zone bathymetry is done on a strict schedule that is not easily changed.

Therefore, it is important to collect bathymetry ground truth data on the same day as LiDAR collection, or at the latest, within the same week. This will ensure an accurate reference (ground truth) during process verification and provide data necessary for understanding the constant change occurring in the surf zone as well as quantitative error assessments. In addition, it is recommended to monitor offshore wave characteristics through deployed buoys or monitoring stations, as this data may prove valuable in interpreting the estimated bathymetry results.

During the data collection process, the focus was mainly on establishing effective protocols. Crucial aspects of the atmosphere, such as air clarity, wave characteristics, and their effects on air and water conditions, were found to affect flight success. This sensitivity resulted in many datasets being rendered useless due to issues like specular and diffuse reflectance.

To avoid such problems in the future, it is essential to maintain a catalogue of surf zone characteristics and air quality. This will not only increase the efficiency of pre-collection operations but also help identify post-processing anomalies. Additionally, incorporating imagery of the surf zone from the shore may provide insights into the reasons why LiDAR scans are not usable.

Implementing these changes in future works will enhance the efficiency of data collection and the accuracy of bathymetric estimations. It will also pave the way for further research into the implementation of the “Full Theory” via equation (8), the surface gravity wave dispersion relation.

As an aside, Figure 32 has been provided to highlight a proof of concept. It displays the interpolated wave crest data nestled between LiDAR land coverage and offshore echo sounder bathymetry data, all located offshore of Pajaro Beach. The figure displays a traditional method to acquire bathymetry via the lawn mower style pattern driven by the echo sounder. As expected, this pattern stops just short of the surf zone, which poses a challenge for larger vessels or small jet skis to traverse. Therefore, three wave scans from January 12, 2023, were used to estimate bathymetry. This data was subsequently placed in between the echo sounder and land data to fill in the missing sections of coverage. Figure 32 intends to show the viability of the initial estimates of this research, thus warranting further examination.

The use of LiDAR technology for estimating surf zone bathymetry will undoubtedly be a significant advancement in oceanography. This innovative approach offers a remote sensing approach to estimating bathymetric data in the dynamic and often challenging environment of the surf zone. LiDAR’s ability to capture high-resolution elevation information, particularly in the presence of breaking waves, provides researchers with valuable insights into coastal processes, sediment transport, and wave dynamics. Additionally, its efficiency and cost-effectiveness make it a promising tool for ongoing monitoring and research efforts in the study of coastal zones and their vital role on the impact on military ship to shore operations. As LiDAR technology continues to be refined and its application expanded, we can expect to enhance our understanding of surf zone dynamics and improve upon littoral ship to shore operations and the acquisition of data needed to ensure the success of these movements.

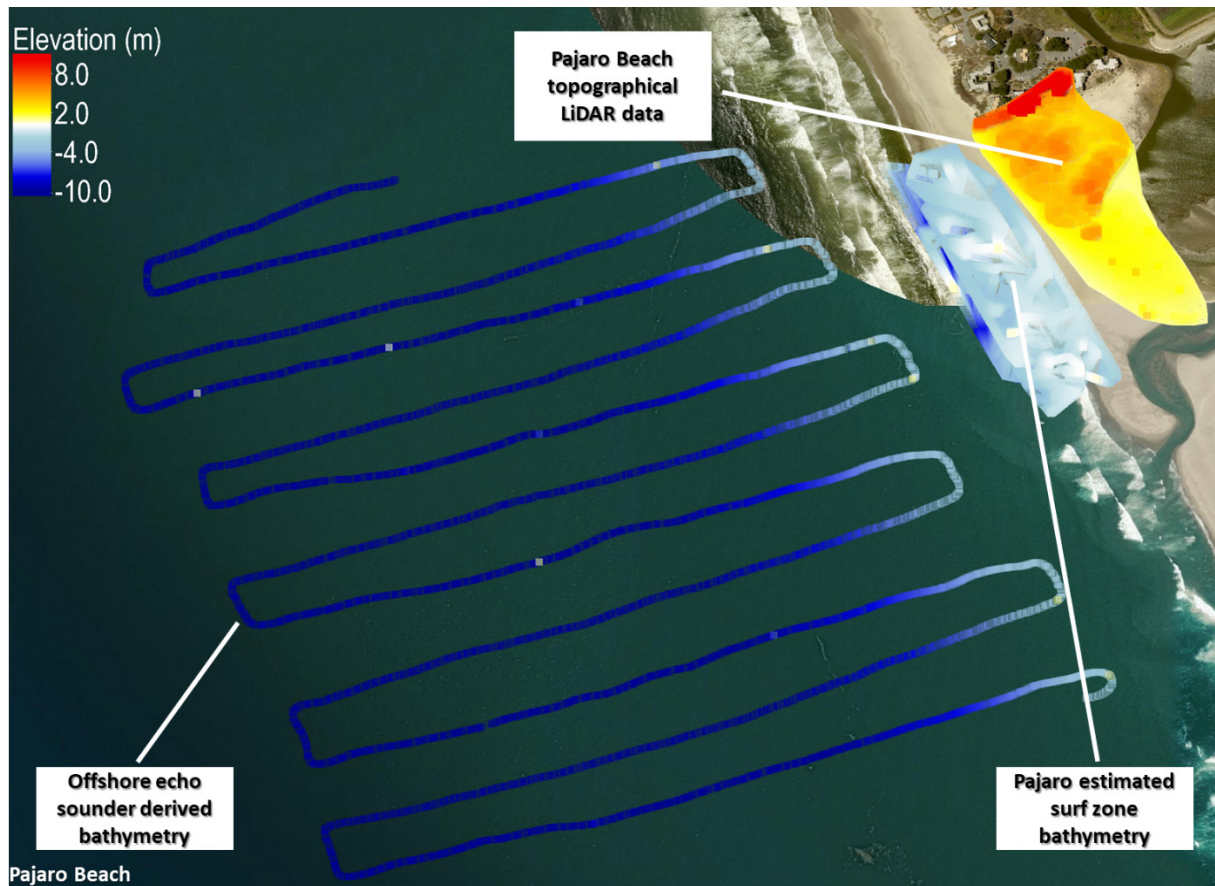


Figure 32. Pajaro Beach surf zone bathymetry estimates for 12 January 2023. In addition to bathymetry estimates, the figure includes offshore echo sounder bathymetry and onshore LiDAR derived elevation data.

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