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Evaluation of Unmanned Aircraft Systems for Flood Risk Management: Results of Terrain and Structure Assessments

Alexander D. Renaud, Michael F. Forte, Nicholas J. Spore,
Brittany L. Bruder, Katherine L. Brodie, Jessamin A. Straub, and
Jeffrey G. Ruby

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Alexander D. Renaud, Michael F. Forte, Nicholas J. Spore, Brittany L. Bruder,
Katherine L. Brodie, and Jessamin A. Straub

*Coastal and Hydraulics Laboratory
US Army Engineer Research and Development Center
1261 Duck Rd
Duck, NC 27949*

Jeffrey G. Ruby

*Geospatial Research Laboratory
US Army Engineer Research and Development Center
7701 Telegraph Road
Alexandria, VA 22315*

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Abstract

The 2017 Duck Unmanned Aircraft Systems (UAS) Pilot Experiment was conducted by the US Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory, Field Research Facility (FRF), to assess the potential for different UAS to support US Army Corps of Engineers coastal and flood risk management. By involving participants from multiple ERDC laboratories, federal agencies, academia, and private industry, the work unit leads were able to leverage assets, resources, and expertise to assess data from multiple UAS. This report compares datasets from several UAS to assess their potential to survey and observe coastal terrain and structures. In this report, UAS data product accuracy was analyzed within the context of three potential applications: (1) general coastal terrain survey accuracy across the FRF property; (2) small-scale feature detection and observation within the experiment infrastructure area; and (3) accuracy for surveying coastal foredunes. The report concludes by presenting tradeoffs between UAS accuracy and the cost to operate to aid in selection of the best UAS for a particular task. While the technology and exact UAS models vary through time, the lessons learned from this study illustrate that UAS are available at a variety of costs to satisfy varying coastal management data needs.

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Preface

This report was funded by the US Army Corps of Engineers (USACE), Coastal Ocean Data Systems (CODS), program under the “Unmanned Aircraft Systems Support to Coastal Management” work unit; Funding Account Code U4374980; AMSCO Code 190012. Data collection informing the report was also funded by the “UAS Support to Flood Risk Management” work unit, funded by the Flood and Coastal Systems Research and Development (R&D) Program.

The CODS Program is administered at the US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL), with funding from the Headquarters, USACE Navigation Business Line. At the time this effort was conducted, Ms. Tiffany Burroughs was the Navigation business line manager overseeing the CODS Program. Mr. Charles E. Wiggins was the ERDC technical director for Civil Works and Navigation Research Development and Technology. The Flood and Coastal Systems program is administered at ERDC-CHL, under the Flood Risk Management (FRM) business line. Ms. Lisa Kiefel was FRM business line manager overseeing the Flood and Coastal Systems program. Dr. Julie D. Rosati was the technical director of the FRM R&D Programs. Dr. Spicer Bak, Coastal Observations and Analysis Branch, was program manager of CODS. Dr. Brandon Boyd was the program manager of Flood and Coastal Systems R&D.

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Additional work was performed by the Information Generation and Management Branch of the Geospatial Research Division, ERDC Geospatial Research Laboratory. At the time of publication, Mr. Michael F. Mailloux was branch chief, and Mr. Jeffrey B. Murphy was division chief. The acting director was Ms. Valerie L. Carney.

COL Christian Patterson was the commander of ERDC, and the ERDC director was Dr. David W. Pittman.

1 Introduction

1.1 Background

1.1.1 Unmanned Aerial Systems (UAS) platform and processing advancement

The use and utility of UAS for different applications continue to grow alongside advancements in design, component miniaturization, navigation, and sensor resolution (e.g., FAA DronzeZone 2020). As a result, UAS have the potential to fill the gap between ground-based survey techniques and traditional manned aircraft or satellite remote-sensed observations for a number of US Army Corps of Engineers (USACE) mission requirements (Bruder et al. 2018; Padua et al. 2017). The flexibility and cost-effectiveness of UAS have provided potential for generating imagery that supports high-resolution point clouds and digital surface models (DSMs) that compare to lidar-generated point clouds (e.g., Turner et al. 2016; Brodie et al. 2019b). Suir et al. (2018) note the desire by USACE districts to either cost-effectively adopt or improve the utilization of UAS platforms for multiple UAS capabilities, including uses for landscape, structures, and ecology. By mounting sensors onto cost-effective remote airborne platforms, ground survey teams can survey a larger area, with higher-resolution data, over difficult and sensitive terrain, like vegetated dunes.

This study primarily evaluates UAS with lidar scanners and camera sensors nadir-mounted onboard. The coupling of precise Global Navigation Satellite Systems (GNSS) with Inertial Measurement Units (IMU) has been key to the development of all these capabilities but is particularly relevant for lidar-equipped UAS. Similar to airborne lidar systems developed and utilized by the Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) and others for manned aircraft (e.g., Wozencraft and Lillycrop 2003; Wozencraft and Lillycrop 2006; Feygels et al. 2013; Brock et al. 2002; Wehr and Lohr 1999; Imahori et al. 2013; Gutierrez et al. 2001), UAS demand this coupled system to accurately register the lidar returns in geographic space with the UAS flight path and sensors' pitch, roll, and yaw (e.g., LeWinter et al. 2018; Gottfried et al. 2015; Jozkow et al. 2016). High-quality georeferencing is also invaluable to point clouds derived from camera imagery, though the evolution of photogrammetry and Structure from Motion (SfM) algorithms

that can use lower-quality GPS in combination with known ground control points is what initially made UAS imagery attractive for surveying needs.

Image matching has a history of more than 50 yr¹, with the first experiments performed using analogue procedures for mapping purposes (Hobrough 1959). Recent advancements in computer vision (Haala 2013) presently offer additional automated procedures for both image orientation and three-dimensional (3D) reconstruction at different scales. As described by Westoby et al. (2012), SfM was developed in the 1990s and derives 3D structure from multiple overlapping images of the same point/feature rather than the two images used in traditional photogrammetry. While ground control is needed to generate scaled and geo-referenced point clouds, SfM automatically solves for the scene's geometry while simultaneously estimating camera intrinsics (lens calibration parameters) and extrinsics (image position and orientation). Both lidar- and SfM-derived point clouds collected by UAS have demonstrated potential to support surveying of the coastal environment (e.g., Fischer et al. 2019; Seymour et al. 2017; LeWinter et al. 2018; Mancini et al. 2013).

1.1.2 UAS potential support to coastal and FRM

This study focuses on assessing the accuracy of UAS-generated point clouds across (1) general coastal terrain, (2) structural features demanding high resolution, and (3) coastal dune features. Coastal terrain elevations may inform a range of applications in coastal areas, including (but not limited to) local hydrography, habitat suitability, flood risk, and future sea level rise forecasts (e.g., data assimilation of UAS-collected bathymetric data presented by Ghorbanidehno et al. (2019)). As shown later in Table 2-14, data accuracy is critical to deciding how well UAS-generated data can meet USACE standards for multiple activities associated with coastal management, from beach renourishment/hurricane protection plans to flood control and multipurpose project planning. While many UAS platforms advertise accuracies robust enough for these applications, different approaches to ground control and processing can have significant

¹ For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-52, <https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf>.

impacts on data quality (Chapter 2) (Aguera-Vega et al. 2017; Sanz-Ablanedo et al. 2018; Tonkin and Midgley 2016; Jaud et al. 2019; James and Robson 2014) and should be evaluated in practical settings.

Beyond characterizing general elevation and landscape characteristics, UAS can provide critical information on the state of the coastal structures and infrastructure employed by USACE to support coastal management. Detection of changes or movement within small-scale features may be required to detect damage and/or assess overall structural health. UAS have shown potential to identify cracks, other defects, and overall structural displacement issues that may impact similar types of features (Dietz 2019; Yoon et al. 2018; Kersten et al. 2018; Gillins et al. 2016). Coastal environments often present conditions that prevent safe, efficient surveys by ground-based topographic survey methods. For example, structures such as large-scale groins or jetties are dangerous to climb on, especially carrying survey equipment, or may be altogether inaccessible to ground approach. UAS data may be used to efficiently assess the physical condition of coastal structures prior to and following severe events, to enable risk forecasts for the area at large and quantify damage, respectively.

In addition to general terrain and coastal structure physical condition, there has been an increasing interest by USACE districts and other coastal stakeholders to better understand and monitor natural and nature-based features within the context of coastal project construction and management policy across different Civil Works business lines, particularly coastal dunes (Elko et al. 2016; Kress et al. 2016; USACE 2015a). Dunes are considered to be critical elements of shoreline management and have increasingly been valued as resilient natural infrastructure that can reduce coastal inundation and naturally recover (e.g., Bridges et al. 2015; Sutton-Grier et al. 2015). UAS sensors that can capture both spectral imagery and elevation of dunes at the same time over the same spatial extents also considerably improve land classification efforts in coastal environments (Sturdivant et al. 2017). While manned airborne lidar provides point-clouds over large regions, at times detailed surveys at higher spatial and temporal resolution are critical for improving the understanding of dune morphodynamics and needed coastal management actions (Brodie et al. 2019c). Because UAS can require fewer personnel, less time, and less cost to survey small projects (1–10 km long), USACE districts can survey coastal features more often. UAS may provide an opportunity to capture dunes and associated coastal features at

resolutions and/or time scales better associated with dune morphological variability and forcing (Brodie et al. 2019a). In addition to their timely deployment capabilities, UAS surveys may provide high-resolution point clouds without the limitations of ground-based topographic survey methods, such as survey coverage area, sparse measurement density, and line of sight. Given the importance of vegetation and biomass to dune health and resilience (e.g., Bryant et al. 2017; Charboneau et al. 2016, Conery et al. 2019), UAS surveys collect critical data about dunes and vegetation from above, minimizing disturbance to the dunes themselves.

1.2 Objective

The dynamic nature of coastal environments creates interdisciplinary challenges to navigation, flood risk management (FRM), and ecosystem health that demand frequent monitoring and observation. Despite this need, the USACE districts, often lack up-to-date data, leading to significant challenges for effective coastal management due to either (a) costly deployment of significant resources to obtain the data in time or (b) repercussions from making decisions without adequate data. UAS continue to show promise for numerous applications, including those needed for coastal management, ranging from post-storm assessments of USACE projects to mapping marine debris (Brodie et al. 2019; Goncalves et al. 2019). This report presents analyses of data collected during the 2017 Duck UAS Pilot Experiment, which was designed to better inform the use of UAS in the characterization of terrain and structures within coastal environments by the USACE. The collaborative experiment generated a rich collection of UAS data involving multiple platforms and instrument types.

A UAS consists of a platform (vehicle) and a payload (sensor combination). Thus, a given platform can have multiple payload options, or be classified as differing UAS. In this report, various platforms and payloads will be compared. Any specific mention of UAS platform or payload will refer only to that component, not the complete UAS. In addition, due to the focus of this report, payload will be referred to as sensor or sensor combination. Analysis of data from different UAS that surveyed the same coastal features and terrain over similar timeframes allowed for the comparison of the effectiveness of different technologies and approaches. By assessing existing UAS methodology, sensors, and data processing approaches, this report aims to inform selection, costs, and benefits of UAS-associated tools that may be considered by USACE districts as they develop or advance UAS programs for coastal and FRM purposes.

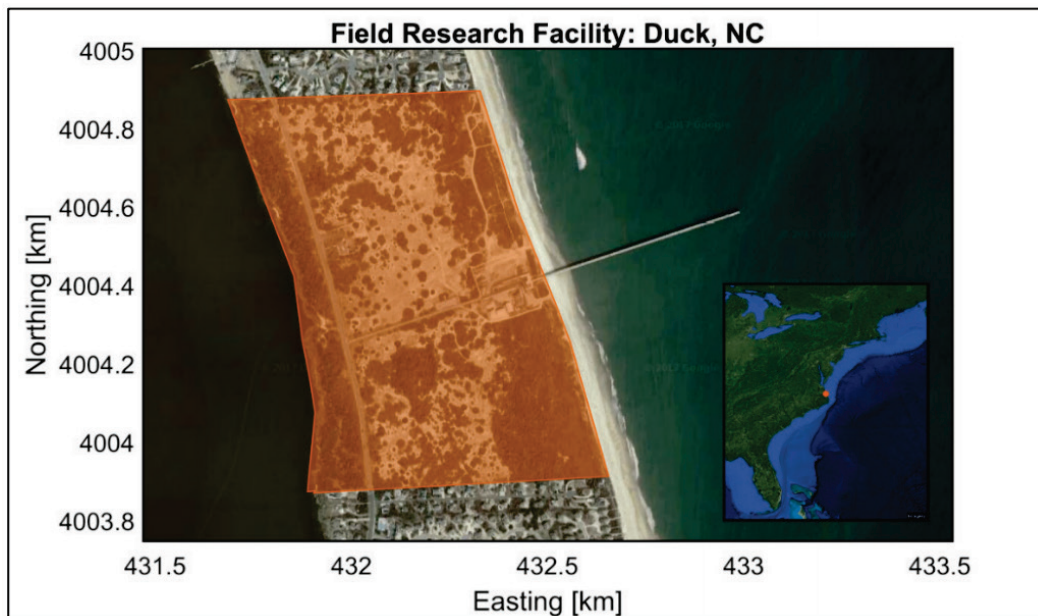
While UAS technology continues to evolve beyond the individual platforms in use at any point in time, examination of UAS side-by-side documents a number of lessons about the applicability and maturity of these technologies to the USACE Civil Works mission along the Nation's coastlines.

1.3 Approach

Given the potential for UAS to support USACE coastal management and flood-risk reduction missions, this study focuses on the quality of UAS data associated with general coastal terrain, small-scale coastal structures/features, and coastal dunes before considering the costs and benefits of UAS applications for coastal management. Chapter 2 assesses the accuracy of digital surface models (DSMs) generated from data collected from four different FW UAS platforms across the entirety of the FRF property and compares the stated accuracies to USACE requirements for different survey needs. In addition to comparing the accuracy of different platforms, sensors and collects, Chapter 2 also briefly examines the differences in SfM processing software and ground control scenarios. Chapter 3 examines object detection and structure disturbance using UAS data, focusing on the UAS-derived point clouds for nine sub-meter (vertical and horizontal) blocks. Chapter 3 then examines the ability of UAS imagery and lidar to detect changes within the deformation of a mock jetty. Chapter 4 characterizes the accuracy of UAS-generated dune profiles and volumes. Chapter 5 explores the costs and benefits of collecting data using a selection of UAS examined in the previous chapters, considering the accuracy of UAS data against USACE standards, costs of establishing and maintaining a UAS program, and other factors one must examine before deploying UAS.

To better assess the potential for UAS technology to support USACE coastal management and FRM, the US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL) hosted the Duck UAS Pilot Experiment at the Field Research Facility (FRF) from 5–24 June 2017. The FRF property consists of 175 acres of coastal terrain between the Atlantic Ocean and Currituck Sound within the town of Duck, NC, on the northern Outer Banks of North Carolina (Figure 1-1). The facility has been monitoring numerous dynamics of the nearshore environment since 1977 (Birkemeier et al. 1985).

Figure 1-1. Map of FRF property (UTM-18N) from Bruder et al. 2018. Orange area denotes property extents.



As described by Bruder et al. (2018), the collaborative experiment invited participants from multiple ERDC laboratories, federal agencies, and private industry. Several multi-rotor UAS, fixed-wing (FW) UAS, and traditional aircraft deployed a variety of sensors across the FRF property, capturing general terrain, beach, dunes, structures, and complex features (e.g., blocks and a mock jetty). These sensors included a range of red-green-blue (RGB), infrared cameras, and multispectral cameras as well as a number of airborne lidar scanners. Ground control points (GCPs) were distributed across the property to allow teams to align their images/point clouds and assess their accuracy. Nearshore surveys and terrestrial lidar scans of key features provided additional ground control references.

While the teams participating in the 2017 Duck UAS Pilot Experiment had their own various objectives and areas of focus, effort was taken to ensure areas of overlap in data coverage for comparison purposes. In return for providing a proving ground for these teams to operate their UAS, ERDC gained access to comparable coastal data from each of the UAS tested during the experiment. This approach allowed ERDC to leverage the teams' combined expertise and resources to generate an unparalleled set of comparison data without the expense of purchasing and training on each of the systems internally. In addition to producing the rich dataset, ERDC personnel were provided a closeup view of different UAS platforms, which helped them select the appropriate UAS for other research and

development work units with coastal management and reduction of flood risk objectives. Using the experience of this experiment and other associated ERDC efforts, CHL has been able to refine the use of UAS technologies for the management of flood risk and coastal projects. These efforts have ranged from the development of proper Concept of Operations (CONOPS) to best allow SfM-generated point clouds of coastal structures and terrain to the use of aerial video to estimate nearshore bathymetry (Brodie et al. 2019b).

2 Coastal Terrain Accuracy Assessment

The primary goal of utilizing UAS in the coastal environment is to expand the USACE survey capabilities, which generally demand high accuracy data across kilometer-scale regions. This chapter presents accuracy results from several coastal terrain datasets collected during the collaborative 2017 Duck UAS field experiment. As described in Bruder et al. (2018), data were collected from multiple platform and sensor combinations and processed using several different commercial off-the-shelf (COTS) applications.

This chapter focuses on data collected by four different FW UAS and a variety of sensors across the majority of the FRF property. Since the focus here is on characterizing large-scale coastal terrain, the decision was made to focus on FW UAS, which have longer flight times that can support collections of this scale (<1 sq km). For the datasets analyzed in this chapter, 18 checkerboard ground control points (GCPs) were used to photogrammetrically control and align aerial data, and 33 checkpoints were used to perform geometric accuracy assessments. The accuracy assessments were compared to each other and then to accuracy standards for a number of user applications published in *Photogrammetric and LiDAR Mapping Engineer Manual*, EM 1110-1-1000 (USACE 2015b).

2.1 Coastal terrain accuracy data sets

This chapter examines nine UAS-generated data sets covering the entire FRF that were collected using four different UAS. Six data sets were collected with a Sensefly eBee, one with a Sensefly eBee RTK, one with a Sky-Watch Cumulus, and one with a BirdsEyeView FireFLY6 PRO. The following sensors were used during collection:

- Canon S110 Red-Green-Blue (RGB)
- Canon S110 Near-Infrared (NIR)
- Sensefly S.O.D.A. RGB
- Sony RX-100 RGB
- Sony a6000 RGB
- thermoMAP thermal
- Sequoia MSI (multispectral imaging).

Table 2-1 lists UAS/sensor combinations as well as approximate flying height above ground level (AGL) and calculated ground sample distance

(GSD) based on data from each collect. Flight mission parameters such as height and primary direction were dictated by each flight team and chosen to optimize sensor performance.

Table 2-1. Summary of data collects that covered entire FRF property.

Date	UAS	Sensor	Height AGL (m)	GSD (cm)	Primary Flight Direction
5 JUN 17	eBee	thermoMAP	75	16	N-S
6 JUN 17	eBee	Canon S110 NIR	110	4.0	E-W
6 JUN 17	eBee	Sequoia MSI	120	16	N-S
6 JUN 17	eBee	Canon S110 RGB	100	3.6	E-W
6 JUN 17	eBee	Canon S110 NIR	100	3.7	N-S
9 JUN 17	eBee	Canon S110 RGB	100	3.6	N-S
13 JUN 17	eBeeRTK	Sensefly S.O.D.A.	100	2.4	N-S
16 JUN 17	Cumulus	Sony RX-100	100	2.7	N-S
20 JUN 17	FireFLY6	Sony a6000	100	2.7	N-S

2.2 Coastal terrain accuracy ground control survey

Eighteen GCPs were used as control during photogrammetric reconstruction, and 33 checkpoints were used to assess geometric accuracy of each data set. GCPs and checkpoints were surveyed using Real-Time-Kinematic (RTK) GPS utilizing the National Geodetic Survey (NGS) Continuously Operating Reference Station (CORS) located at the FRF as the base station. This station identifier is NCurses Disk Usage. Each point was occupied with a Trimble R10 rover on a 1.8 m rod for 180 sec. RTK-GPS survey accuracy for experiment GCPs was ± 0.025 m in the horizontal and vertical directions (Bruder et al. 2018). The final solution was computed as the average position of the 180 sec interval. The original survey was in NAD83 (2011) projected into the North Carolina State Plane coordinate system (meters). Orthometric heights were computed from NAVD88 with Geoid12B corrections applied. The National Oceanic and Atmospheric Administration Vertical Datum Transformation Tool (VDatum) was used for conversion to IGS08/ITRF. IGS08/ITRF Universal Transverse Mercator (UTM) coordinates were used for accuracy analysis of data sets processed with GCPs. NAD83 (2011) coordinates were used for data sets with Post Processed Kinematic (PPK) positions. Figure 2-1 GCPs and checkpoints across entire FRF property shows the locations of the GCPs (red) and checkpoints (orange) in the FRF.

Figure 2-1. GCPs (blue) and checkpoints (orange) across entire FRF property. See Bruder et al. (2018) for more information about ground control point (GCP) distribution.



2.3 Coastal terrain accuracy methodology

The general methodology for assessing accuracy of the data examined within this chapter consisted of the following steps:

1. COTS software processing to generate orthomosaic and DSM
2. Geographic Information System (GIS) processing to compare orthomosaic and DSM to checkpoints
3. Spreadsheet processing to calculate Root Mean Square Error (RMSE) and Horizontal/Vertical Accuracy at 95% confidence levels as described in Chapter 3 of *Photogrammetric and LiDAR Mapping Engineer Manual*, EM 1110-1-1000 (USACE 2015b).

The following sections provide more details on specific processing procedures used.

2.3.1 COTS software processing

Three COTS software packages were used to process the frame data and create orthomosaics and DSMs. These packages were Agisoft PhotoScan Professional (Agisoft 2018), Bentley ContextCapture, and Pix4D Pix4Dmapper.

The general adjustment procedure consisted of the following steps:

1. Import frames into the COTS package. Frame exposure station coordinates were embedded in the Exchangeable Image File Format portion of each image.
2. Convert exposure station coordinates to WGS84/UTM Zone 18N.
3. Perform initial adjustment of the frames without GCPs to get estimated positions and initial camera parameters.
4. Add five GCPs (four corners, one center) and refine adjustment (primarily to facilitate picking the remaining GCPs).
5. Add the remaining GCPs and refine adjustment for final solution.

For the photogrammetric solution, each package was allowed to adjust the following variables:

- Air frame position and orientation
- Sensor focal length (f)
- Sensor principal point offset (c_x , c_y)
- Sensor radial distortion (k_1 , k_2 , k_3)
- Sensor tangential distortion (p_1 , p_2).

Within this chapter, default values were used for most processing settings within each software package for consistency. No fine-tuning of parameters or manual editing of data was performed to refine results with additional optimization steps.

After final adjustment, DSMs and orthomosaic image products were created. Generally, the GSD was full resolution for orthomosaic products. The DSMs had varying GSDs due to differing proprietary smoothing and interpolation algorithms, but they were generally in the 10 – 25 cm range depending on raw GSD of the base imagery and default processing settings of each software package. Orthomosaic images and DSMs were exported in standard GeoTIFF format for accuracy assessment within a GIS package.

2.3.2 GIS processing

The orthomosaics and DSMs were ingested into Quantum GIS (QGIS). Each checkpoint was visually identified in the orthomosaic, and the X-Y coordinates were saved to a GIS data file (an ESRI shapefile). Z values for each checkpoint were interpolated from the DSM using the QGIS Raster Interpolation plugin with bilinear interpolation. Interpolated Z values were saved to the shapefile. Final, measured XYZ checkpoint coordinates were exported to a comma separated value file for calculation of accuracy assessment metrics.

Horizontal positions of a checkpoint identified in the orthophoto and its corresponding vertical value in the DSM were compared to surveyed XYZ checkpoint coordinates for accuracy assessment. This procedure differs from standard DSM accuracy assessments where vertical raster values are extracted at surveyed checkpoint locations. This non-standard approach most likely mirrors how UAS data will be used in practice (looking for a visual feature in the orthophoto and pulling an elevation at that location from the DSM).

Following this procedure, horizontal accuracy assessments are conducted on orthomosaic images, and vertical accuracy assessments are conducted on values interpolated from the DSMs. Horizontal and vertical accuracy of the DSMs were not directly assessed.

2.3.3 Spreadsheet processing

The final measured XYZ coordinates were ingested into a Microsoft Excel spreadsheet and compared to survey coordinates for each checkpoint. The spreadsheet contained formulas to compute RMSE_x, RMSE_y, RMSE_z, RMSE_r, Horizontal Accuracy at 95% Confidence, and Vertical Accuracy at 95% Confidence as described in EM 1110-1-1000 (USACE 2015b). The equations from EM 1110-1-1000 implemented by the spreadsheet are the following:

$$RMSE_x = \sqrt{\frac{\sum_{i=1}^n (Mx_i - Gx_i)^2}{n}}$$

$$RMSE_y = \sqrt{\frac{\sum_{i=1}^n (My_i - Gy_i)^2}{n}}$$

$$RMSE_z = \sqrt{\frac{\sum_{i=1}^n (Mz_i - Gz_i)^2}{n}}$$

$$RMSE_r = \sqrt{(RMSE_x)^2 + (RMSE_y)^2}$$

$$\text{Horizontal Accuracy at 95\% Confidence} = RMSE_r * 1.7308$$

$$\text{Vertical Accuracy at 95\% Confidence} = RMSE_z * 1.96$$

where

Mx_i = x-coordinate of i th ground control point (GCP) measured from orthomosaic

My_i = y-coordinate of i th GCP measured from orthomosaic

Mz_i = z-coordinate of i th GCP interpolated from DSM (based on Mx_i , My_i)

Gx_i = x-coordinate of i th GCP from ground survey

Gy_i = y-coordinate of i th GCP from ground survey

Gz_i = z-coordinate of i th GCP from ground survey

n = number of GCPs.

In photogrammetric/SfM processing, pixel size of the raw imagery drives the accuracy of all processes in the workflow and products derived from processing. It drives the accuracy of the photogrammetric adjustment of the raw frames and the accuracy and density of the passive points cloud derived from those frames. Since all final products (orthomosaics and gridded DEMs/DSMs) are derived from the adjustment and passive point cloud, pixel size drives the accuracy of these products. Pix4D specifically specifies the accuracy of Pix4Dmapper as a function of pixels. If a user knows how a UAS/software combination performs as a function of pixel size, they can easily plan and optimize data collections. For example, if a user has a project with a requirement of 10 cm RMSE_r horizontal accuracy and they know the UAS and software package can reliably collect data with an RMSE_r of two pixels, they know they need to collect data with a 5 cm GSD in the raw frame imagery.

UAS and software accuracy as a function of pixels is also useful for comparing system performance from data sets with different GSDs. If UAS and software system A collected and processed data with 5 cm raw GSD

and an RMSEr of 7.5 cm (1.5 pixels) and system B collected and processed data with 3 cm GSD and an RMSE of 6 cm (2 pixels), system A is actually performing better than system B. System B has a better absolute RMSEr, but only because it has a smaller GSD. If 5 cm data were collected with system B, an RMSEr of 10 cm would be expected.

Results in this chapter are presented in terms of absolute accuracy, but, where appropriate, accuracy numbers have been included as a function of pixels so readers can understand the relative performance between different UAS and software configurations. Accuracy measures in pixels are calculated by dividing the corresponding measure by the GSD of the raw frame imagery:

$$RMSEx_{pixels} = \frac{RMSEx}{GSD}$$

$$RMSEy_{pixels} = \frac{RMSEy}{GSD}$$

$$RMSEz_{pixels} = \frac{RMSEz}{GSD}$$

$$RMSEr_{pixels} = \frac{RMSEr}{GSD}$$

$$\begin{aligned} & \text{Horizontal Accuracy at 95\% Confidence}_{pixels} \\ &= \frac{\text{Horizontal Accuracy at 95\% Confidence}}{GSD} \end{aligned}$$

$$\begin{aligned} & \text{Vertical Accuracy at 95\% Confidence}_{pixels} \\ &= \frac{\text{Vertical Accuracy at 95\% Confidence}}{GSD} \end{aligned}$$

2.4 Coastal terrain accuracy results

Results of the accuracy assessments for the different data sets are presented below in tables and figures organized by processing software. Accuracy numbers are expressed in real world units, but as stated above, some discussion of accuracy in terms of pixels is included as appropriate. As exemplified in the previous section's equations, RMSE accuracy is different from 95% confidence level accuracy defined in EM 1110-1-1000

(USACE 2015b). Users should be aware of this difference when evaluating any accuracy assessment.

RGB and NIR results are presented together. All three COTS software packages were used to process these data. The thermal and MSI data sets were processed in Pix4Dmapper as this is the only evaluated software package that has configurations to process these specific sensors. A brief discussion of these results follows the RGB and NIR results.

Three additional subsections follow that present accuracy results from a few alternate operational scenarios. Section 2.4.4 presents an analysis of the 16 JUN Cumulus/Sony data set processed using a reduced set of GCPs (five points). Section 2.4.5 presents analysis of the 13 JUN eBee Plus/S.O.D.A. data set processed with different resolution DSMs. Section 2.4.6 presents an analysis of the 13 JUN eBee Plus/S.O.D.A. data set using only Post Processed Kinematic (PPK) aircraft positions (Table 2-11). The PPK data set was processed without ground control, using only PPK positions for each frame.

2.4.1 Coastal terrain accuracy RGB and NIR results by processing software

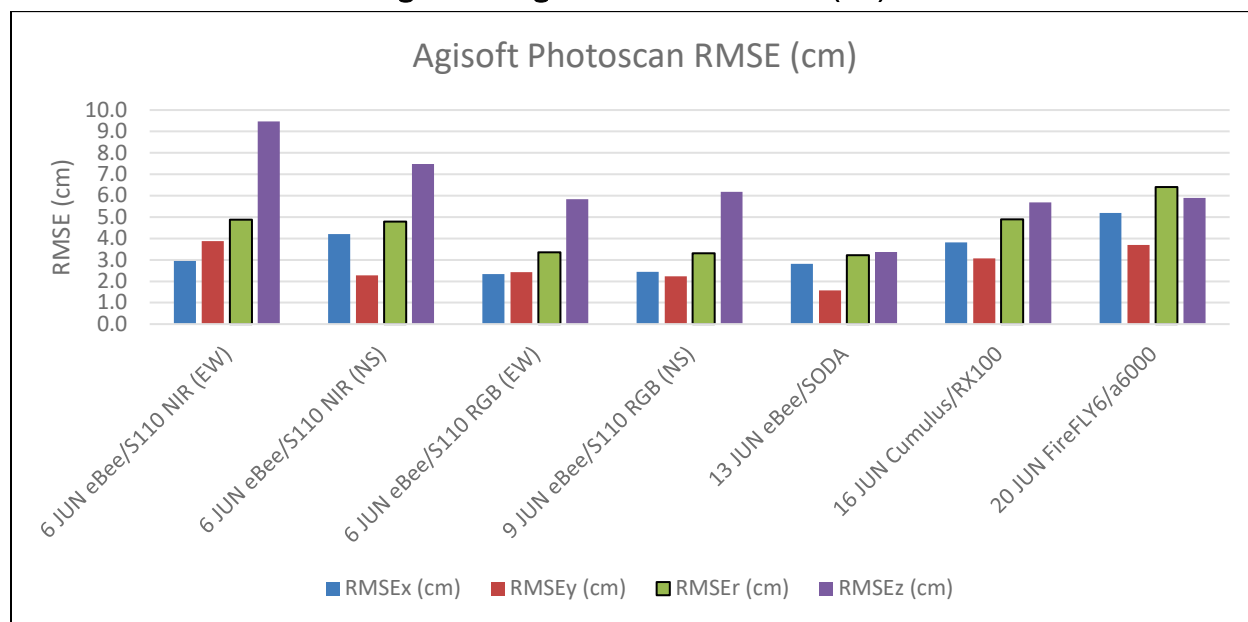
2.4.1.1 Agisoft PhotoScan RGB and NIR

Table 2-2 and Figure 2-2 present accuracies of Agisoft PhotoScan RGB and NIR processing. For these data sets, RMSE_x varied from 2.3 to 5.2 cm. RMSE_y varied from 1.6 to 3.9 cm. RMSE_z varied from 3.4 to 9.5 cm. Horizontal accuracy at the 95% confidence level varied from 5.6 to 11 cm. Vertical accuracy at the 95% confidence level varied from 6.6 to 18.6 cm. This table illustrates the difference between absolute and pixel RMSE. The 6 JUN eBee/S110 NIR (NS) has an RMSE_r of 4.8 cm while the 13 JUN eBee/S.O.D.A. (NS) has an RMSE_r of 3.2 cm. The SODA system is clearly delivering more accurate data, but both systems are performing about the same in terms of photogrammetric processing as they both have an RMSE_r of 1.3 pixels. The improvement in absolute accuracy is due to the smaller pixel size. Photogrammetric RMSE_r varied from 0.9 to 2.4 pixels. Photogrammetric RMSE_z varied from 1.4 to 2.4 pixels.

Table 2-2. Accuracy of Agisoft PhotoScan RGB and NIR processing considered across different flights, instruments, and flight patterns.

Collect	Check Points	Raw GSD (cm)	RMSE (cm)				RMSE (px)		Accuracy 95% (cm)	
			x	y	r	z	r	z	Horiz.	Vert.
6 JUN eBee/S110 NIR (EW)	26	4.0	3.0	3.9	4.9	9.5	1.2	2.4	8.4	18.6
6 JUN eBee/S110 NIR (NS)	32	3.7	4.2	2.3	4.8	7.5	1.3	2.0	8.3	14.7
6 JUN eBee/S110 RGB (EW)	24	3.6	2.3	2.4	3.4	5.8	0.9	1.6	5.8	11.4
9 JUN eBee/S110 RGB (NS)	32	3.6	2.4	2.2	3.3	6.2	0.9	1.7	5.7	12.1
13 JUN eBee/SODA (NS)	32	2.4	2.8	1.6	3.2	3.4	1.3	1.4	5.6	6.6
16 JUN Cumulus/Sony (NS)	32	2.7	3.8	3.1	4.9	5.7	1.8	2.1	8.5	11.2
20 JUN FireFLY6/a6000	26	2.7	5.2	3.7	6.4	5.9	2.4	2.2	11.0	11.6

Figure 2-2. Agisoft PhotoScan RMSE (cm).



2.4.1.2 Bentley ContextCapture RGB and NIR

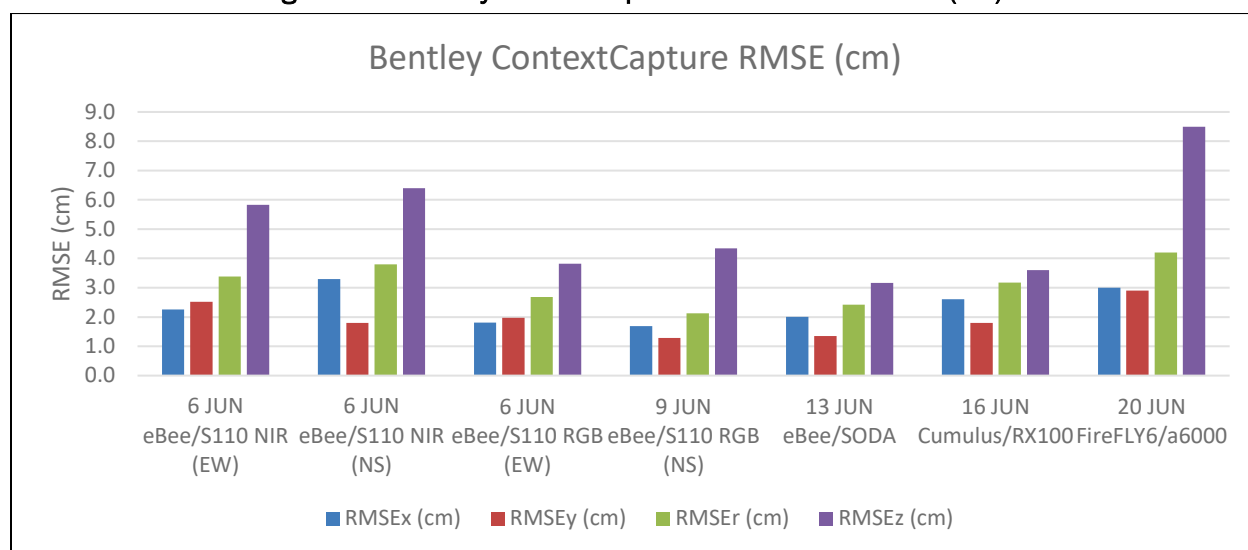
Table 2-3 and Figure 2-3 present accuracies of Bentley ContextCapture RGB and NIR processing. For these data sets, RMSEx varied from 1.7 to 3.3 cm. RMSEy varied from 1.3 to 2.9 cm. RMSEz varied from 3.2 to 8.5 cm. Horizontal accuracy at the 95% confidence level varied from 3.7 to 7.2 cm. Vertical accuracy at the 95% confidence level varied from 6.2

to 16.6 cm. Vertical error for the FireFLY6/a6000 data collect was approximately twice that of the other platforms. Photogrammetric RMSE_r varied from 0.6 to 1.5 pixels. Photogrammetric RMSE_z varied from 1.1 to 3.1 pixels.

Table 2-3. Bentley ContextCapture RGB and NIR accuracy summary.

Collect	GCPs	Raw GSD (cm)	RMSE (cm)				RMSE (px)		Accuracy 95% (cm)	
			x	y	r	z	r	z	Horiz.	Vert.
6 JUN eBee/S110 NIR (EW)	33	4.0	2.3	2.5	3.4	5.8	0.8	1.5	5.9	11.4
6 JUN eBee/S110 NIR (NS)	32	3.7	3.3	1.8	3.8	6.4	1.0	1.7	6.5	12.5
6 JUN eBee/S110 RGB (EW)	33	3.6	1.8	2.0	2.7	3.8	0.7	1.1	4.6	7.5
9 JUN eBee/S110 RGB (NS)	32	3.6	1.7	1.3	2.1	4.3	0.6	1.2	3.7	8.5
13 JUN eBee/SODA (NS)	33	2.4	2.0	1.4	2.4	3.2	1.0	1.3	4.2	6.2
16 JUN Cumulus/RX100	33	2.7	2.6	1.8	3.2	3.6	1.2	1.3	5.5	7.1
20 JUN FireFLY6/a6000	26	2.7	3.0	2.9	4.2	8.5	1.5	3.1	7.2	16.6

Figure 2-3. Bentley ContextCapture RGB and NIR RMSE (cm).



2.4.1.3 Pix4D Pix4Dmapper RGB and NIR

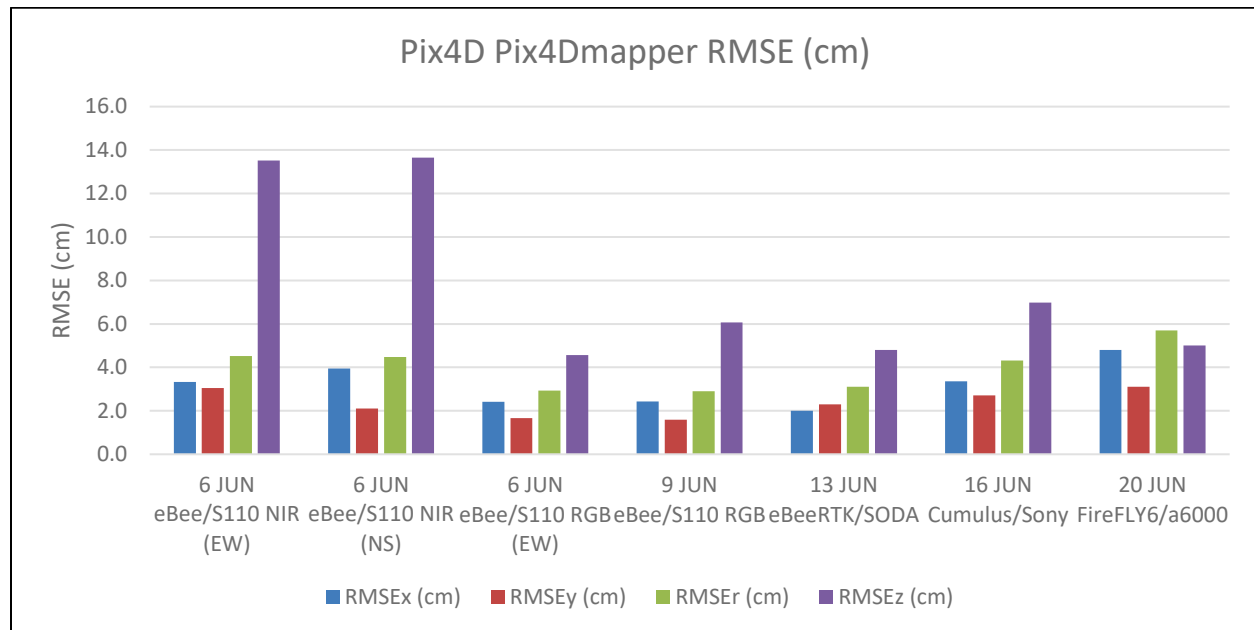
Table 2-4 and Figure 2-4 present accuracies of Pix4D Pix4Dmapper RGB and NIR processing. For these data sets, RMSE_x varied from 2.4 to 4.8 cm. RMSE_y varied from 1.7 to 3.1 cm. RMSE_z varied from 4.6 to 13.7 cm. Horizontal accuracy at the 95% confidence level varied from 5.0 to 9.9 cm. Vertical accuracy at the 95% confidence level varied from 8.9 to 26.8 cm.

Photogrammetric RMSE_r varied from 0.8 to 2.1 pixels. Photogrammetric RMSE_z varied from 1.3 to 3.7 pixels.

Table 2-4. Pix4D Pix4Dmapper RGB and NIR accuracy summary.

Collect	Check Points	Raw GSD (cm)	RMSE (cm)				RMSE (px)		Accuracy 95% (cm)	
			x	y	r	z	r	z	Horiz.	Vert.
6 JUN eBee/S110 NIR (EW)	33	4.0	3.3	3.0	4.5	13.5	1.1	3.4	7.8	26.5
6 JUN eBee/S110 NIR (NS)	33	3.7	4.0	2.1	4.5	13.7	1.2	3.7	7.8	26.8
6 JUN eBee/S110 RGB (EW)	30	3.6	2.4	1.7	2.9	4.6	0.8	1.3	5.1	8.9
9 JUN eBee/S110 RGB (NS)	32	3.6	2.4	1.6	2.9	6.1	0.8	1.7	5.0	11.9
13 JUN eBeeRTK/SODA	34	2.4	2.0	2.3	3.1	4.8	1.3	2.0	5.3	9.4
16 JUN Cumulus/Sony	33	2.7	3.4	2.7	4.3	7.0	1.6	2.6	7.5	13.7
20 JUN FireFLY6/a6000	26	2.7	4.8	3.1	5.7	5.0	2.1	1.8	9.9	9.7

Figure 2-4. Pix4D Pix4Dmapper RGB and NIR RMSE (cm).



2.4.2 Thermal/Multispectral imaging (MSI) processing

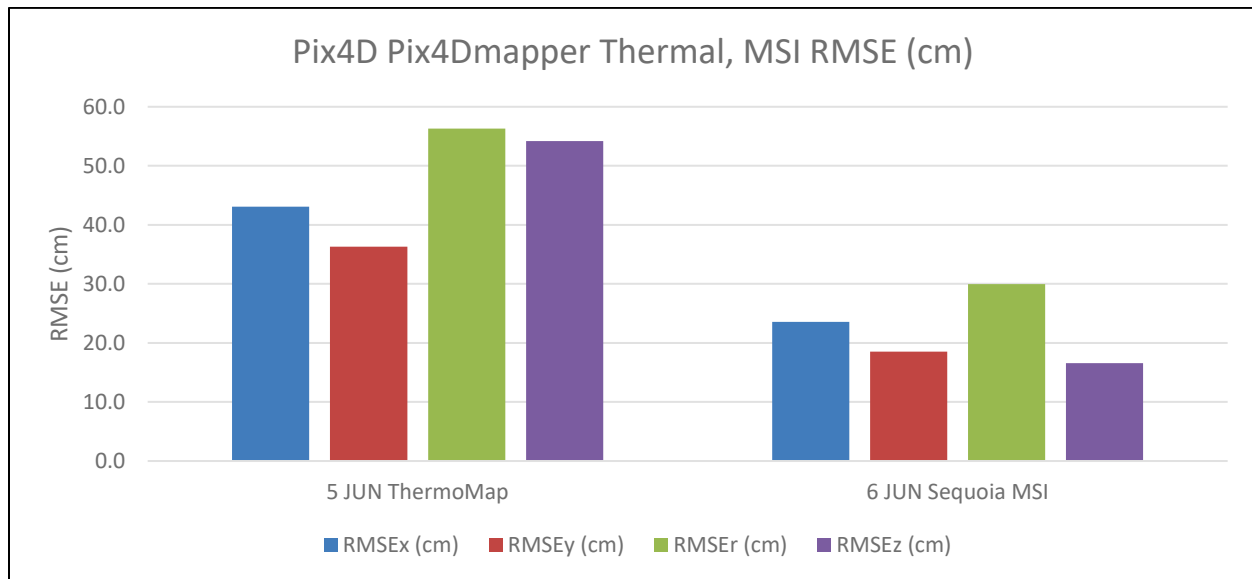
The ThermoMap (5 JUN) and Sequoia (6 JUN) datasets were only processed using Pix4Dmapper. Table 2-5 and Figure 2-5 present accuracies of Pix4Dmapper Thermal/MSI processing in centimeters. For this thermal data set, RMSE_x was 43.1 cm. RMSE_y was 36.3 cm. RMSE_z was 54.2 cm. Horizontal accuracy at the 95% confidence level was 97.5 cm. Vertical accuracy at the 95% confidence level was 106.2 cm. For this MSI

data set, RMSE_x was 23.6 cm. RMSE_y was 18.5 cm. RMSE_z was 16.6 cm. Horizontal accuracy at the 95% confidence level was 51.9 cm. Vertical accuracy at the 95% confidence level was 32.6 cm.

Table 2-5. Pix4D Pix4Dmapper Thermal/Multispectral imaging (MSI) accuracy summary.

Collect	Check Points	Raw GSD (cm)	RMSE (cm)				RMSE (px)		Accuracy 95% (cm)	
			x	y	r	z	r	z	Horiz.	Vert.
5 JUN ThermoMap	28	15.9	43.1	36.3	56.3	54.2	3.5	3.4	97.5	106.2
6 JUN Sequoia MSI	21	16.0	23.6	18.5	30.0	16.6	1.9	1.0	51.9	32.6

Figure 2-5. Pix4D Pix4Dmapper Thermal/MSI RMSE (cm).



2.4.3 Coastal terrain ground control point (GCP) processing discussion

Table 2-6, Table 2-7, Figure 2-6, and Figure 2-7 present a summary of the RGB and NIR accuracy assessment results given above. RMSE_r represents a single number for horizontal accuracy, and RMSE_z represents vertical accuracy. Agisoft, Bentley, and Pix4D all performed well for the given datasets. All three packages generated results with RMSE_r values under 6.5 cm. RMSE_z for these packages varied from 3.2 to 13.7 cm.

Bentley had the best absolute horizontal accuracy with RMSE_r varying between 2.1 and 4.2 cm and RMSE_z varying between 3.2 and 8.5 cm. This is another instance where results in terms of raw imagery pixels can provide more insight into the performance of the different software packages. As stated above, Bentley had the best absolute RMSE_z numbers,

but when examining Table 2-7, it is evident that Agisoft actually performed better photogrammetrically. RMSEz for Agisoft varied between 1.4 and 2.4 pixels while Bentley varied between 1.1 and 3.1 pixels.

Table 2-6. Summary of RGB and NIR results (cm).

Collect	Raw GSD (cm)	RMSEr (cm)			RMSEz (cm)		
		Agisoft	Bentley	Pix4D	Agisoft	Bentley	Pix4D
6 JUN eBee/S110 NIR (EW)	4.9	4.9	3.4	4.5	9.5	5.8	13.5
6 JUN eBee/S110 NIR (NS)	4.8	4.8	3.8	4.5	7.5	6.4	13.7
6 JUN eBee/S110 RGB (EW)	3.4	3.4	2.7	2.9	5.8	3.8	4.6
9 JUN eBee/S110 RGB (NS)	3.3	3.3	2.1	2.9	6.2	4.3	6.1
13 JUN eBee/SODA	3.2	3.2	2.4	3.1	3.4	3.2	4.8
16 JUN Cumulus/RX100	4.9	4.9	3.2	4.3	5.7	3.6	7.0
20 JUN FireFLY6/a6000	6.4	6.4	4.2	5.7	5.9	8.5	5.0
Minimum		3.2	2.1	2.9	3.4	3.2	4.6
Maximum		6.4	4.2	5.7	9.5	8.5	13.7

Table 2-7. Summary of RGB and NIR results (pixels).

Collect	Raw GSD (cm)	RMSEr (px)			RMSEz (px)		
		Agisoft	Bentley	Pix4D	Agisoft	Bentley	Pix4D
6 JUN eBee/S110 NIR (EW)	4.0	1.2	0.8	1.1	2.4	1.5	3.4
6 JUN eBee/S110 NIR (NS)	3.7	1.3	1.0	1.2	2.0	1.7	3.7
6 JUN eBee/S110 RGB (EW)	3.6	0.9	0.7	0.8	1.6	1.1	1.3
9 JUN eBee/S110 RGB (NS)	3.6	0.9	0.6	0.8	1.7	1.2	1.7
13 JUN eBee/SODA	2.4	1.3	1.0	1.3	1.4	1.3	2.0
16 JUN Cumulus/RX100	2.7	1.8	1.2	1.6	2.1	1.3	2.6
20 JUN FireFLY6/a6000	2.7	2.4	1.5	2.1	2.2	3.1	1.8
Minimum		0.9	0.6	0.8	1.4	1.1	1.3
Maximum		2.4	1.5	2.1	2.4	3.1	3.7

Figure 2-6. Summary of RGB and NIR horizontal accuracy results (cm).

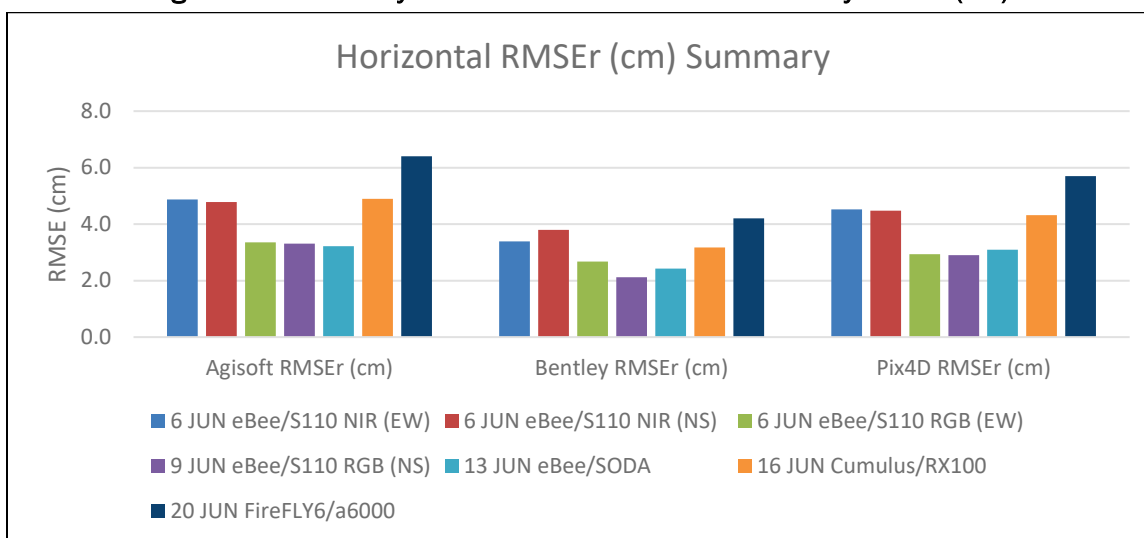


Figure 2-7. Summary of vertical accuracy results (cm).

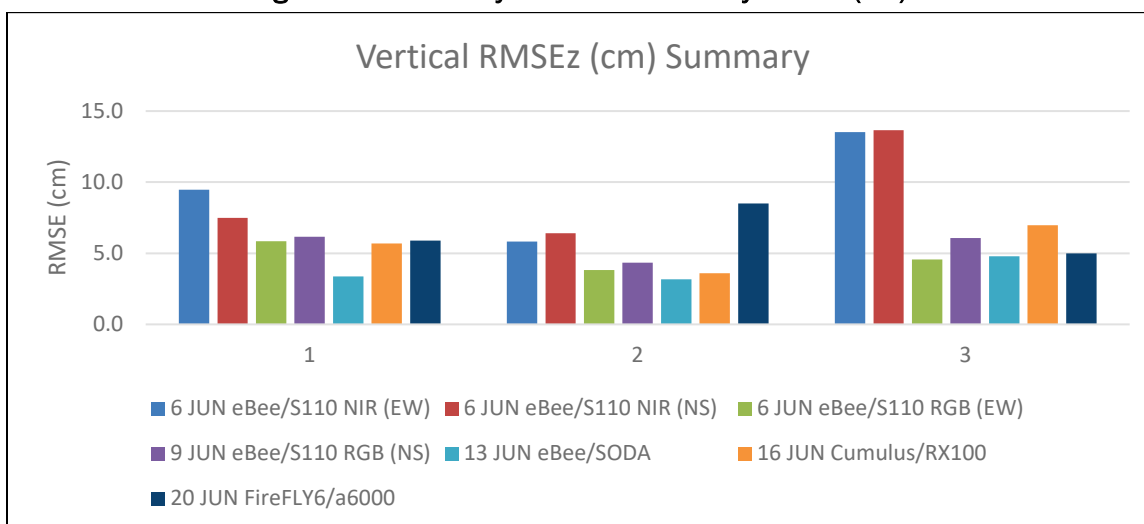


Table 2-8 presents a concise summary of the Pix4Dmapper Thermal/MSI given above. Photogrammetrically, the MSI data set has similar results to the RGB and NIR with RMSEr of 1.9 pixels and RMSEz of 1.0 pixels. The thermal has approximately twice the RMSEr error that the RGB and NIR data do, but, photogrammetrically, still within the ranges of the RGB and NIR data.

Table 2-8. Thermal/MSI results.

Data Set	Raw GSD (cm)	RMSEr (cm)	RMSEz (cm)	RMSEr (px)	RMSEz (px)
Thermal	15.9	56.3	54.2	3.5	3.4
MSI	16.0	30.0	16.6	1.9	1.0

2.4.4 Cumulus/Sony data set with five GCPs

The datasets above use a substantial amount of ground control, with 18 GCPs over a 0.6 km² area. Surveying GCPs is labor intensive. If users can get similar results with fewer GCPs, districts and offices can save time and money during UAS collections. To demonstrate the effect of a reduced number of GCPs, the 16 JUN Cumulus/Sony data set was reprocessed using only five GCPs, as this data set had slightly better coverage at the bounding corners than the other data sets. This configuration represents a minimum baseline configuration for photogrammetric work. GCPs in each of the four corners of the site and one in the center were used (point 101, 113, 205, 212, and 240 from Figure 2-1). This configuration was chosen as suggested by Campbell and Katz (2019). The imagery was processed with the reduced GCP data set in Agisoft PhotoScan, Bentley ContextCapture, and Pix4D Pix4Dmapper.

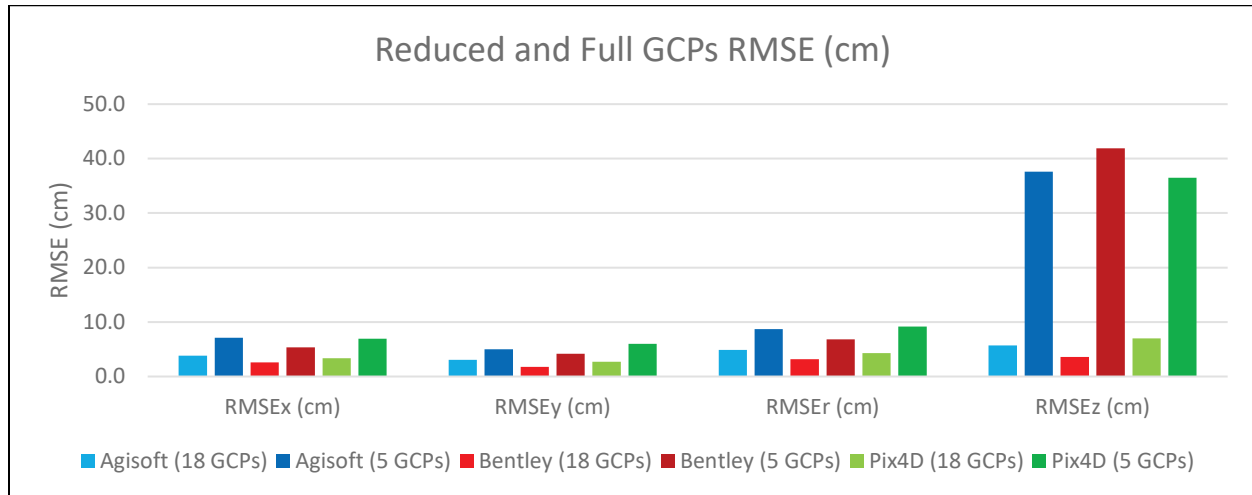
Table 2-9 presents accuracies of reduced GCPs processing in pixels. Figure 2-8 graphically presents RMSE results in pixels for both the 18 GCP data set and the 5 GCP data set. For the five GCP data sets, RMSE_x varied from 5.4 to 7.1 cm. RMSE_y varied from 4.2 to 6.0 cm. RMSE_z varied from 36.5 to 41.9 cm. Horizontal accuracy at the 95% confidence level varied from 11.8 to 15.9 cm. Vertical accuracy at the 95% confidence level varied from 71.5 to 82.1 cm.

Comparing the 5 GCP results to the 18 GCP results presented in Section 2.4.1, it is evident that RMSE_x and RMSE_y approximately doubled. RMSE_z, however, increased by 6 to 10 times the RMSE_z of the 18 GCP data. Reducing the number of GCPs as described has some effect on horizontal accuracy, but it has a significant effect on vertical accuracy, which is critical for informing numerous coastal management activities and forecasting risk. These two layouts (5 GCPs and 18 GCPs) represent bounding cases accuracy analysis based on the number of GCPs. The addition of more GCPs above five should help improve the accuracy of the data.

Table 2-9. Reduced GCP processing results.

Package	Check Points	Raw GSD (cm)	RMSE (cm)				RMSE (px)		Accuracy 95% (cm)	
			x	y	r	z	r	z	Horiz.	Vert.
Agisoft	35	2.7	7.1	5.0	8.7	37.6	3.2	13.9	15.0	73.7
Bentley	35	2.7	5.4	4.2	6.8	41.9	2.5	15.5	11.8	82.1
Pix4D	35	2.7	6.9	6.0	9.2	36.5	3.4	13.5	15.9	71.5

Figure 2-8. Reduced and full GCPs RMSE (cm).



2.4.5 DSM density analysis

To show an example of how point cloud density can affect accuracy, data from the 13 JUN collect (eBee Plus/S.O.D.A.) was processed with different point cloud densities to determine how point density affected DSM accuracy. Agisoft PhotoScan was used for this analysis. Agisoft has five quality options when creating a dense point cloud: Ultra-High, High, Medium, Low, and Lowest. Other packages have similar output parameters. Ultra-High quality was not used in this analysis due to extended processing times (and crashes on several attempts), but the other four options were. Agisoft can also create a DSM from the sparse point cloud data (the data used to perform the initial alignment, prior to densification of the point cloud). A DSM and orthomosaic were also created from sparse point cloud data.

Table 2-10 presents summary statistics for each of the different data sets for the 13 JUN eBee Plus/S.O.D.A. data collect due to the low vertical RMSE. Using the High-Quality Point Cloud as an example, it is evident that the dense point cloud had 474.5 million points, at a density of 519.3 points per square meter. The output DSM for this data set had a GSD of 4.9 cm, which was approximately double the native resolution of the raw frames.

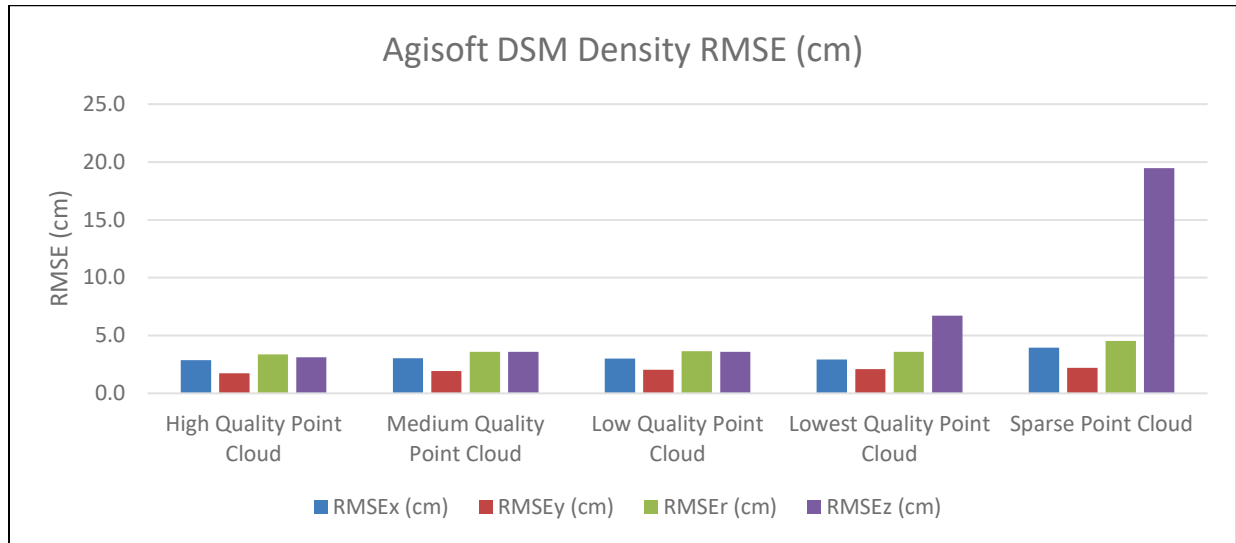
Table 2-10 presents accuracy summaries of DSMs derived from point clouds with different densities. As in the accuracy analyses presented in Section 2-4, horizontal accuracy is assessed on the orthomosaic product, and vertical accuracy is assessed on interpolated values from the DSMs. Figure 2-9 graphically presents RMSE results in cm. The tables and figures show that horizontal accuracy was relatively unchanged for the High, Medium, Low, and Lowest point cloud densities. RMSE_x was approximately 3 cm and RMSE_y was approximately 2 cm. There was a slight degradation in horizontal accuracy for the sparse cloud data set. RMSE_x dropped to 3.9 cm, though RMSE_y was still 2.2 cm. Vertical accuracy was consistent for High, Medium, and Low quality point cloud data RMSE varying between 3.1 and 3.6 cm. RMSE_z dropped to 6.7 cm for the Lowest quality data set and to 19.5 cm for the sparse data set. As lower resolution point clouds require less time to process, these results suggest that lower intensity processing may be adequate for quick field assessments to determine whether any area of interest (AOI) merits a further assessment at a higher resolution.

This analysis presents results for positional accuracy of the data only. As expected, the higher density data sets will have much more detail in the data and will allow users to observe/analyze smaller-scale features as in Section 3.

Table 2-10. DSM density analysis results.

Point Cloud	Check Points	GSD (cm)		RMSE (cm)				RMSE (px)		Accuracy 95% (cm)	
		DSM	Ortho	x	y	r	z	r	z	Horiz.	Vert.
High Quality	32	4.9	2.4	2.9	1.7	3.4	3.1	1.4	1.3	5.8	6.1
Medium Quality	32	9.7	2.4	3.0	1.9	3.6	3.6	1.5	1.5	6.2	7.0
Low Quality	32	19.4	2.4	3.0	2.0	3.6	3.6	1.5	1.5	6.3	7.0
Lowest Quality	32	38.9	2.4	2.9	2.1	3.6	6.7	1.5	2.8	6.2	13.2
Sparse	32	64.3	2.4	3.9	2.2	4.5	19.5	1.9	8.0	7.8	38.1

Figure 2-9. DSM density analysis RMSE (cm).



2.4.6 Post-Processed kinematic (PPK) data set for coastal terrain

All datasets discussed to this point were positioned using SfM processing and ground control points. The 13 JUN eBee Plus/S.O.D.A. data set was collected with RTK/PPK processing enabled (Table 2-11). GPS position data were post-processed on the ground. Frame and PPK position data were processed through three software packages without ground control, and an accuracy assessment was performed on the output products.

Table 2-11. Agisoft point cloud density statistics for 13 JUN eBee Plus/S.O.D.A. data set.

Data Set	Raw GSD (cm)	Points (millions)	Points per m ²	DSM GSD (cm)	DSM/Ortho GSD Ratio
High Quality Point Cloud	2.4	474.5	519.3	4.9	2:1
Medium Quality Point Cloud	2.4	120.0	129.9	9.7	4:1
Low Quality Point Cloud	2.4	30.0	32.3	19.4	8:1
Lowest Quality Point Cloud	2.4	7.3	7.9	38.9	16:1
Sparse Point Cloud	2.4	0.6	1.4	64.3	25:1

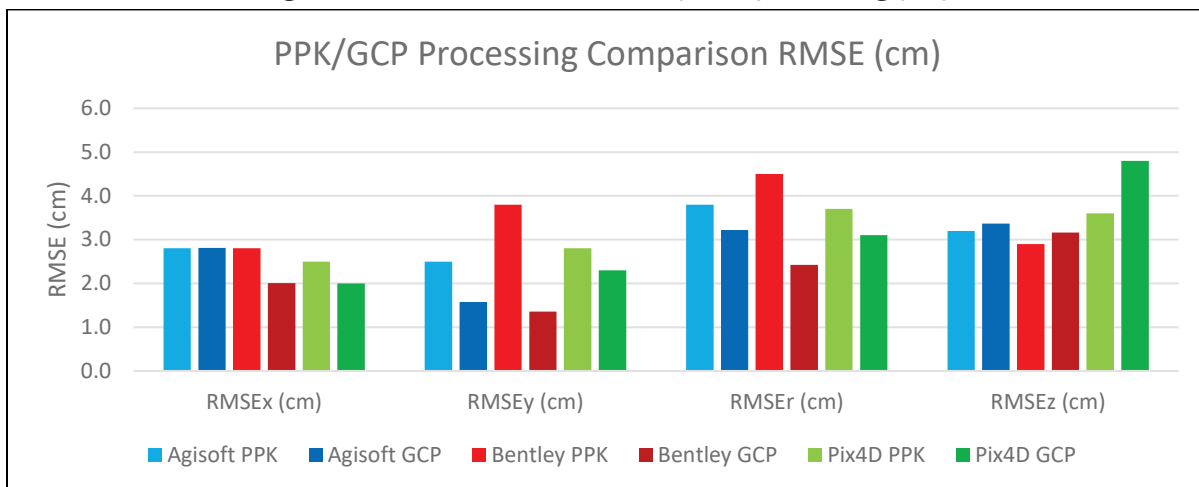
A Topcon HiPer V GPS receiver was stationed on a 2 m range pole over NGS benchmark FW0683 located on the FRF property. This receiver was used to broadcast corrections to the drone in real time. After landing, the GPS positions were updated using Sensefly Flight Data Manager BBX tool. The published NGS coordinates for FW0683 were used to produce final drone coordinates for each frame. These coordinates alone were used in the COTS software packages to generate output products.

Table 2-12 and Figure 2-10 present a comparison of the accuracies of PPK and GCP processing. Accuracies were determined via orthophoto and DSM interpolation as outlined in Section 2.3. These results show that PPK processing without ground control compares very favorably to processing with substantial ground control. RMSE_x was between 2.0 and 2.8 cm for both PPK and GCP processing in all three packages. RMSE_y for GCP processing was greater with PPK processing (1.4 to 3.8 cm), but still low. RMSE_z varied from 2.9 to 3.6 cm for PPK processing and from 3.2 to 4.8 cm for GCP processing. Vertical accuracy values generated with PPK processing were slightly more accurate than with GCP processing for all three software packages. Horizontal accuracy at 95% confidence was slightly reduced with the PPK processing relative to the GCP processing. Vertical accuracy at 95% confidence again shows similar results between both types of processing and software package with PPK processing results slightly better than GCP processing results.

Table 2-12. RMSE results in pixels for PPK/GCP processing.

Processing	GCPs	Raw GSD (cm)	RMSE (cm)				RMSE (px)		Accuracy 95% (cm)	
			x	y	r	z	r	z	Horiz.	Vert.
Agisoft PPK	37	2.4	2.8	2.5	3.8	3.2	1.5	1.4	6.5	6.2
Agisoft GCP	32	2.4	2.8	1.6	3.2	3.4	1.3	1.4	5.6	6.6
Bentley PPK	37	2.4	2.8	3.8	4.5	2.9	1.7	1.1	7.7	5.6
Bentley GCP	33	2.4	2.0	1.4	2.4	3.2	1.0	1.3	4.2	6.2
Pix4D PPK	37	2.4	2.5	2.8	3.7	3.6	1.5	1.5	6.4	7.1
Pix4D GCP	33	2.4	2.0	2.3	3.1	4.8	1.3	2.0	4.3	9.4

Figure 2-10. RMSE results for PPK/GCP processing (cm).



2.5 USACE data applicability example

The following examination of the eBee/Canon S110 RGB, 18 GCP collect data illustrates the applicability of these UAS SfM-generated data to common USACE Civil Works activities, which include those associated with coastal management (Table 2-13). eBee/Canon S110 RGB data were collected on 6 June and 9 June. Both datasets were processed through PhotoScan, ContextCapture, and Pix4Dmapper. RMSE_x varied from 1.7 cm to 2.4 cm. RMSE_y varied from 2.3 to 2.4 cm. RMSE_z varied from 3.8 cm to 6.2 cm.

Table 2-13. eBee/Canon S110 RGB results (cm).

Collect	Package	GSD (cm)	RMSE _x (cm)	RMSE _y (cm)	RMSE _z (cm)
6 JUN EW	Agisoft	3.6	2.3	2.4	5.8
6 JUN EW	Bentley	3.6	1.8	2.0	3.8
6 JUN EW	Pix4D	3.6	2.4	1.7	4.6
9 JUN NS	Agisoft	3.6	2.4	2.2	6.2
9 JUN NS	Bentley	3.6	1.7	1.3	4.3
9 JUN NS	Pix4D	3.6	2.4	1.6	6.1

Table 2-14 and Table 2-15 are excerpted directly from EM 1110-1-1000 (USACE 2015b) and show horizontal RMSE_x and vertical RMSE_z requirements for many different USACE Civil Works activities. RMSE_x indicates the minimum accuracy requirement for both RMSE_x and RMSE_y. For illustration, each activity has been highlighted by color indicating whether the eBee/Canon S110 RGB data presented above meets the desired accuracy. Green indicates that all data sets met the requirement. Yellow indicates some of the eBee/Canon S110 RGB data sets met the requirement. Red indicates none of the data sets met the requirement.

The tables show that this dataset meets accuracy requirements for all the given Site Plan for Design Memoranda, Contract Plans and Specifications, and all of the River and Harbor Navigation Projects activities.

The data did not meet requirements of Archeological/Structural Site Plans and Details. The data also did not meet the accuracy requirements for any of the Structural Deformation Monitoring Studies/Surveys. The data met the requirements for many other USACE Civil Works coastal activities including General Planning and Feasibility Studies, Reconnaissance Reports, Permit Applications, Flood Control and Multipurpose Project Planning, Floodplain

Mapping, Water Quality Analysis, Flood Control Studies, and Federal Emergency Management Agency Flood Insurance Studies.

As noted in EM 1110-1-1000 (USACE 2015b), RMSE_{xy} and RMSE_z in these tables pertain to the absolute horizontal and vertical accuracy of digital geospatial data produced from aerial mapping technologies. Relative accuracies may be more demanding than the absolute accuracies of those features. Refer to EM 1110-1-1000 (USACE 2015b), pages 3–50 and 3–51, for more details.

Table 2-14. Standards for suitability of UAS data to various Civil Works activities. Shaded according to whether data from eBee/Canon S110 RGB meet standards. Green indicates that all data sets met the requirement. Yellow indicates some of the eBee/Canon S110 RGB data sets met the requirement. Red indicates none of the data sets met the requirement.

Civil Works Design, Construction, Operations and Maintenance Activities	Feature Horizontal Accuracy RMSE _{xy}	Feature Vertical Accuracy RMSE _z
Site Plan for Design Memoranda, Contract Plans and Specifications, etc., for Input to CADD 2D/3D Design Files		
- Locks, Dams, Flood Control Structures; Detail Design Plans	2.5 cm	10 cm
- Grading/Excavation Plans	30 cm	20 cm
- Spillways, Concrete Channels, Upland Disposal Areas	10 cm	40 cm
- Construction In-place Volume Measurement	30 cm	20 cm
River and Harbor Navigation Projects: Site Plans, Design, Operation, or Maintenance of Flood Control Structures, Canals, Channels, etc., for Contract Plans or Reports.		
- Levees and Groins (New Work or Maintenance Design Drawings)	30 cm	20 cm
- Beach Renourishment/Hurricane Protection Projects	60 cm	20 cm
- Project Condition Reports (Base Mapping for Plotting Hydrographic Surveys: line maps or air photo plans)	240 cm	20 cm
- Revetment Clearing, Grading, and As-built Protection	180 cm	20 cm

Table 2-15. Standards for suitability of UAS data to various USACE Civil Works activities, continued. Shaded according to whether data from eBee/Canon S110 RGB collected and processed as described herein meet standards. Green indicates that all data sets met the requirement. Yellow indicates some of the eBee/Canon S110 RGB data sets met the requirement. Red indicates none of the data sets met the requirement.

Civil Works Design, Construction, Operations and Maintenance Activities	Feature Horizontal Accuracy RMSE _{xy}	Feature Vertical Accuracy RMSE _z
GIS Feature Planning		
Archeological or Structure Site Plans and Details (Including Non-topographic, Close Range, Photogrammetric Mapping)	0.625 cm	2.5 cm
Structural Deformation Monitoring Studies/Surveys		
- Reinforced Concrete Structures (Locks, Dams, Gates, Intake Structures, Tunnels, Penstocks, Spillways, Bridges, etc.)	1 cm	1 cm
- Earth/Rock Fill Structures (Dams, Floodwalls, Levees, etc.) (slope/crest stability and alignment)	3 cm	1 cm
- Crack/joint and deflection measurements (precision micrometer)	0.2 mm	NA
Other Activities		
General Planning and Feasibility Studies, Reconnaissance Reports, Permit Applications, etc.	120 cm	50 cm
Flood Control and Multipurpose Project Planning, Floodplain Mapping, Water Quality Analysis, and Flood Control Studies	240 cm	20 cm
Federal Emergency Management Agency Flood Insurance Studies	240 cm	20 cm

2.6 Coastal terrain accuracy discussion

The analysis provided in this chapter shows that UAS are capable of collecting data with sufficient accuracy to meet requirements for many USACE Civil Works design, construction, operations, and maintenance activities that may be associated with coastal management and FRM. With sufficient control and basic operation of the appropriate software (Agisoft, Bentley, or Pix4D), users can expect RMSE_r accuracies from 2.16 to 9.6 cm and RMSE_z values from 3.96 to 13.69 cm.

Agisoft PhotoScan, Bentley ContextCapture, and Pix4D Pix4Dmapper all produced data with similar positional accuracy, though Bentley ContextCapture had the best overall results by a slight margin over the other two packages. All three packages are capable of producing data suitable for use in many common USACE Civil Works projects.

This analysis also shows that a reduction of control from 18 to 5 GCPs had some effect on horizontal accuracy, but a significant effect on vertical accuracy within the coastal environment. Horizontal error doubled when reducing control from 18 to 5 GCPs. Vertical error for the data set controlled with 5 GCPs was 6 to 10 times that of the data set controlled with 18 GCPs. Given the importance of vertical accuracy in the coastal environment (e.g., dissipation of wave runup, overtopping of structures or dunes), these values stress that surveys relying on GCPs must deploy adequate numbers of them. The results also build on the findings of Fisher et al. (2019), that find that the assessment of UAS-produced coastal terrain data should be improved by uniform GCP distribution and additional checkpoints.

All the above data collection did take place in idealized conditions at a location that operators were familiar with (Fischer et al. 2019). Whereas this collect had fairly square coverage over the <1 km² AOI that included different land cover types, other coastal terrain collects may demand narrower collects that can lead to SfM issues, due to *bowl* effects (e.g., James and Robson 2014; Jaud et al. 2019; Renaud et al. 2019) or additional homogeneity in sandy areas (Seymour et al. 2017). As a result, there may be reduced accuracy with GCP dismissal. The dismissal of GCPs should be continually evaluated in other environments/collect types.

The performance of the RTK/PPK system also provided encouraging results for future development of UAS and associated coastal CONOPS. The accuracy of the data produced from this system is comparable to that of data produced using substantial ground control (18 GCPs) and is significantly greater than data produced using minimal ground control (5 GCPs). RTK/PPK systems are generally more expensive than non-RTK/PPK systems (see Chapter 5), but it appears that they should allow users to collect quality data with a single base station under ideal conditions rather than an extensive array of GCPs. In addition to UAS PPK developments, efforts have been made to conduct SfM from manned aircraft flights for large stretches of coastline without GCPs but with PPK (e.g., Warrick et al. 2019; Sherwood et al. 2018). This development likely would result in savings in labor and time during field collects.

3 Object Detection and Structure Disturbance

3.1 Objective

USACE utilizes various engineering structures to facilitate navigation, mitigate flood risk, provide recreational space, and assist in emergency management in coastal environments. To monitor the condition of the structures, a variety of techniques are used including visual site inspection, traditional surveying, and remote sensing. Recent advances in UAS and photogrammetric algorithms have provided a potentially cost-effective measurement option. As part of the UAS Duck experiment, analysis was performed for a variety of UAS and sensors (Bruder et al. 2018) to determine the smallest objects that UAS could efficiently be used to accurately measure and identify, as well as evaluate the ability of UAS to assess disturbances to structures like jetties.

This chapter compares and evaluates the quality of 3D point clouds for measuring structural features. To this end, this chapter specifically focuses on analysis of point clouds over two main areas within the infrastructure area (IA) of the experiment: the block targets and the mock jetty (see Bruder et al. [2018] for a description of targets). Following the site and data descriptions (Sections 3.2–3.3), this chapter analyzes UAS characterization of the block targets (Section 3.4), qualitatively and quantitatively assessing the point cloud resolution of the features, including calculations of point density, Root Mean Square Difference (RMSD) (i.e., comparison to control terrestrial lidar scan [TLS] data), and block volumes from each survey. Note, RMSD is used here and other locations in the report rather than RMSE since results are compared against other remotely measured lidar point clouds with similar accuracy, rather than well-established/precise ground survey measurements with an accuracy at least an order of magnitude greater than the test data. The analysis objectives of the mock jetty (Section 3.5) were to characterize coastal structures and assess measurable changes due to deformation and other changes driven by coastal forces.

3.2 Infrastructure area datasets

3.2.1 Imagery

Imagery from nine UAS were processed using SfM techniques and compared to terrestrial lidar over two target areas within the experiment's IA as shown in Figure 3-1. The UAS, GSD, flight altitude, aligned images, and approximate view angle are listed in Table 3-1. Two lidar-equipped UAS were also evaluated. The following sections describe the processing methodology, analysis, results, and conclusions.

Figure 3-1. Site overview. Blocks and jetty analysis areas are contained within red rectangles within the IA inside the FRF inner compound. GCPs are designated by green circles – note targets 502 and 511 were not used.



Table 3-1. Photogrammetry datasets and flight parameters. Note: AGL levels as reported and may have slightly differed based on take-off location.

UAS	Sensor	GSD (cm)	AGL (m)	Aligned Images	View Angle
eBee	Sequoia RGB	4.18	150	24	Nadir
Phantom4Pro	Stock 1" CMOS*	3.04	80	53	Nadir
eBee	S110RGB	2.72	100	28	Nadir
eBeeRTK	S.O.D.A.	1.2	100	28	Nadir
X8+	GoProH4	2.55	100	51	Nadir
Cumulus	RX100	2.06	100	81	Nadir
eBee	S.O.D.A.	1.82	100	72	Nadir
FireFly6 PRO	a7R	1.2	120	70	Nadir
FireFly6 PRO	a7R/Ultra High Quality	1.2	120	70	Nadir

*complementary metal-oxide-semiconductor

3.2.2 Block targets

Nine block objects of various sizes were set up during the experiment and were surveyed by all the UAS. The blocks ranged in size from 10 × 10 cm up to 50 × 50 cm and are shown in Figure 3-2 with Table 3-2 containing their dimensions (blocks are square, length = width) and volumes.

Co-registered scans from a Riegl VZ-200 terrestrial lidar scanner from multiple locations were used to provide ground control to compare the UAS data sets to (Bruder et al. 2018).

Figure 3-2. Block objects.

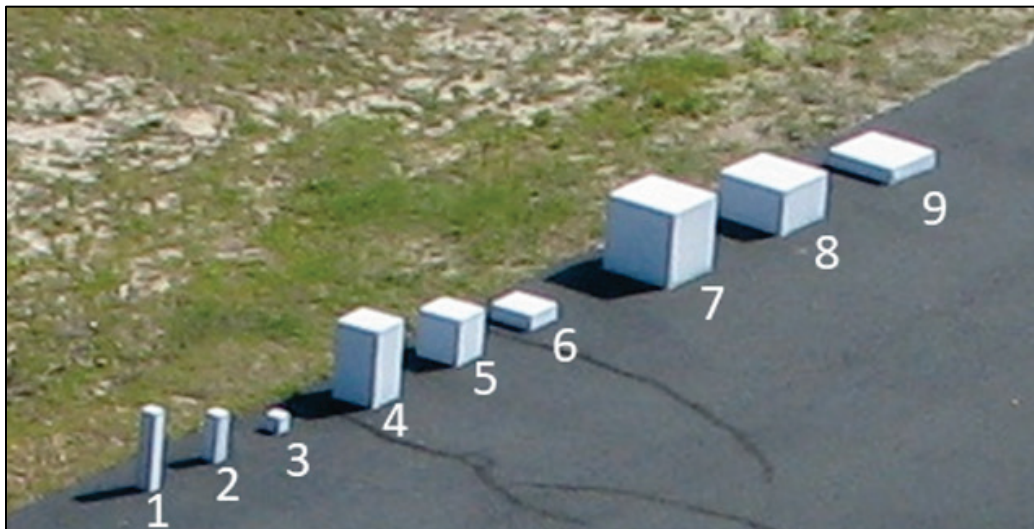


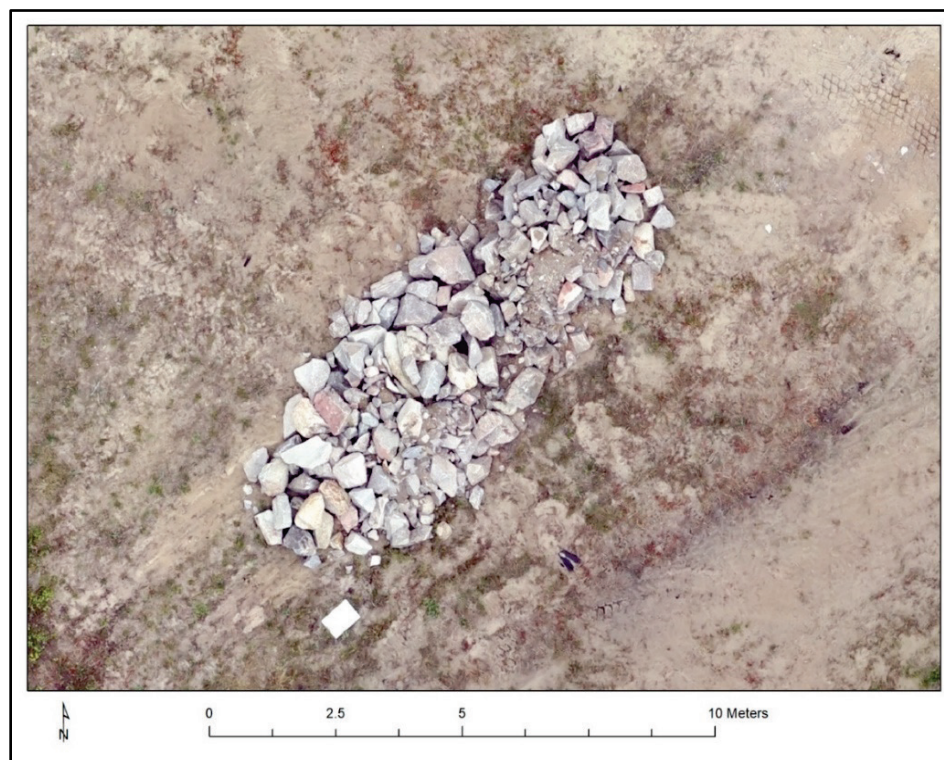
Table 3-2. Block dimensions.

Block	Height [m]	Width [m]	Volume m ³
1	0.5	0.1	0.005
2	0.3	0.1	0.003
3	0.1	0.1	0.001
4	0.5	0.3	0.045
5	0.3	0.3	0.027
6	0.1	0.3	0.009
7	0.5	0.5	0.125
8	0.3	0.5	0.075
9	0.1	0.5	0.025

3.2.3 Mock jetty

A mock jetty (3×10 m) was constructed from Class 2 rip-rap (0.4–0.55 m diameter) and is shown in Figure 3-3. Each week of the 2017 Duck Pilot experiment, the CHL-FRF operations team disturbed/redistributed the rocks to simulate storm changes that might occur on real structures.

Figure 3-3. Mock Jetty showing Class 2 riprap.



3.3 Data processing

3.3.1 Structure from Motion (SfM) processing

The imagery data from nine UAS-generated datasets were processed using Agisoft PhotoScan (Version 1.4.1, 2018) since this was the software most familiar to the author at the time.

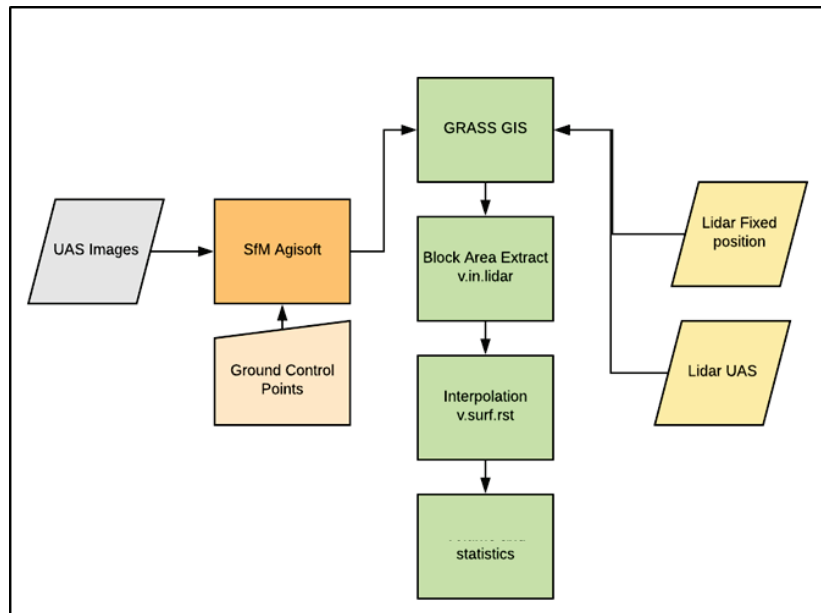
The Agisoft workflow generally consisted of generating initial key points, matching tie points, matching and aligning photos, identifying and selecting GCP markers, gradual filtering, and bundle optimization and reconstruction of the final dense point cloud. These steps approximately follow the workflow described by Sloan (2017). GCPs, pictured in Figure 3-1 were imported in the NAD83 (EPSG:3358) reference system. To optimize processing time and accuracy of point clouds, the dense point cloud was constructed with the high-quality setting. The point clouds were then exported as .las files, an industry standard format for point cloud data.

3.3.2 Geographic Resources Analysis Support System (GRASS) processing and analysis

The point clouds were then imported into the GRASS GIS (GRASS Development Team 2012) using the `v.in.lidar` function. The block and jetty areas were isolated using `v.clip`, which clips points relative to a polygon shape. Due to the size of point clouds (>1 GB), the Windows version of GRASS failed. As an alternative, the Linux version was used for pre-processing all datasets. The point clouds for both feature areas were then interpolated using regularized spline with tension (RST) to develop a continuous surface at 0.02 m resolution (note: this is higher resolution than some of the UAS datasets – Table 3-1 contains the ground resolution). RST is a type of interpolation function that minimizes the deviations from the measured points and the smoothness seminorm. The RST smoothness seminorm includes derivatives of all orders with their weights decreasing with the increasing derivative order. The method has both geostatistical and physical interpretation (Mitas and Mitasova 1999). The intuitive physical interpretation of this method is a thin surface that can be tuned via the tension parameter. The tension works as a rescaling parameter (high tension increases the distances between the points and reduces the range of impact of each point; low tension decreases the distance, and the points influence each other over longer range). High tension (~2000) behaves like a membrane (rubber sheet stretched over

the data points). Low tension (~ 10) behaves like a stiff plate, and overshoots can appear in areas with rapid change of gradient. The smoothing parameter controls the deviation between the given points and the resulting surface. The parameters used for this study were tension equals 2000 to effectively resolve the block shapes and smoothing = 0, which allowed the surface to pass exactly through the data points. The generalized workflow diagram is included as Figure 3-4.

Figure 3-4. Data processing and analysis generalized workflow.



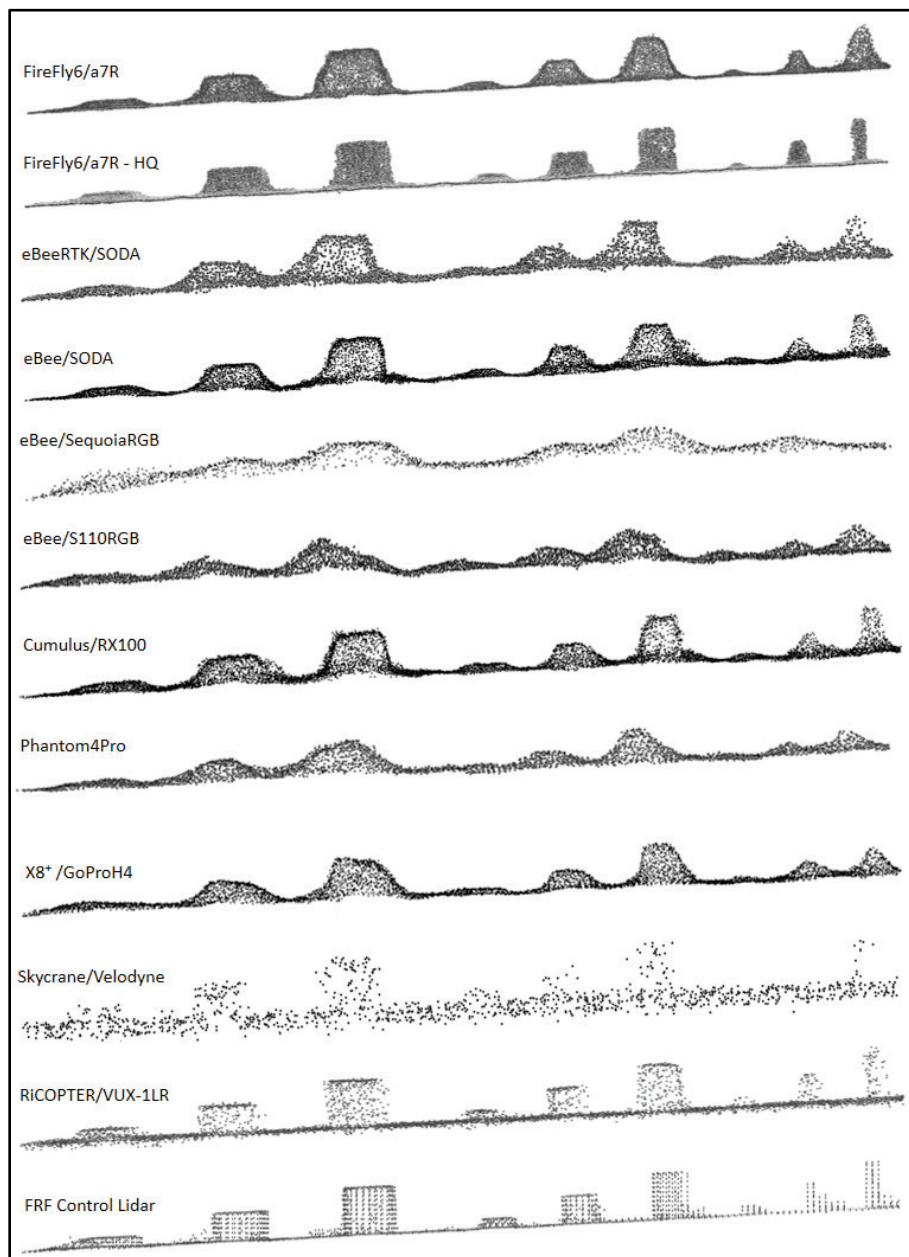
3.4 Block target analysis and results

The following analysis of the IA target blocks includes a qualitative review of the point clouds and a quantitative analysis of point density, RMSD (comparison to control lidar), and block volumes from each survey. Each calculation is further described below with results displayed in a series of figures and tables.

A profile view of the point clouds from each UAS along with the control lidar are shown in Figure 3-5. The blocks shapes are generally well resolved by most of the UAS-derived SfM point clouds. Apart from the one data set processed on the Ultra-High-Quality setting (FireFly6/a7R-HQ), the block edges in the SfM point clouds appeared sloped instead of vertical. Most SfM point clouds resolved the 20 and 30 cm tall blocks, but the 10 cm high block were poorly resolved in all but the FireFly6 and eBee S.O.D.A. datasets (the cameras with higher resolution).

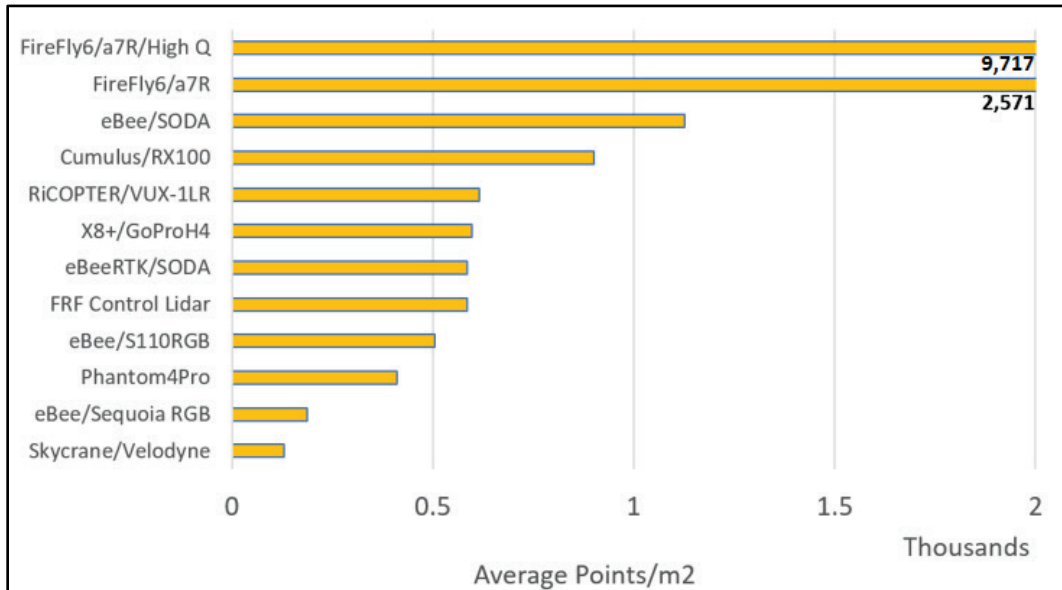
Relative to all of the photogrammetric data sets, the point clouds derived from the UAS-mounted lidars resolved the block edges more crisply, but the Velodyne data display some noise where the block meets the ground and did not adequately resolve the 10 cm block targets. In contrast, the RICOPTER/VUX-1LR lidar demonstrated a high ability to resolve all the blocks with the resultant point cloud visually most similar to the terrestrial control lidar. Other UAS including eBee/SequoiaRGB and Skycrane/Velodyne demonstrated a lower ability to resolve the blocks.

Figure 3-5. Point clouds of block area from UAS platforms and FRF TLS control lidar (black dots). Note: angle is natural due to block placement on ramp.



The mean point density was calculated for each UAS in the block area by summing the points and then dividing by the area (9.7 m²). The FireFly6/a7R-HQ had the highest (9,717/m²), Skycrane/Velodyne the lowest (129/ m²), and the control lidar reporting (585/m²). The results for all UAS are shown in Figure 3-6.

Figure 3-6. Point density for each UAS.



The interpolated surface elevations (z) at a 0.02m resolution were subtracted from the control lidar elevations for each of the point clouds. The results are shown in Figure 3-7 with cooler (blue) colors representing lower values and warm (red) colors representing higher values. Histograms are shown to the left of the scalebar and highlight the distribution of values. RMSD was calculated for each UAS using the following equation

$$RMSD_z = \sqrt{\frac{\sum_{i=1}^n (X_{obs,i} - X_{lidar,i})^2}{n}}$$

where X_{obs} is the UAS observations and X_{lidar} is terrestrial lidar (Figure 3-8).

Figure 3-7. Surface difference of UAS/aircraft data against TLS control, showing histogram (left of scalebar). White, red, and blue areas respectively represent no change, positive, and negative change.

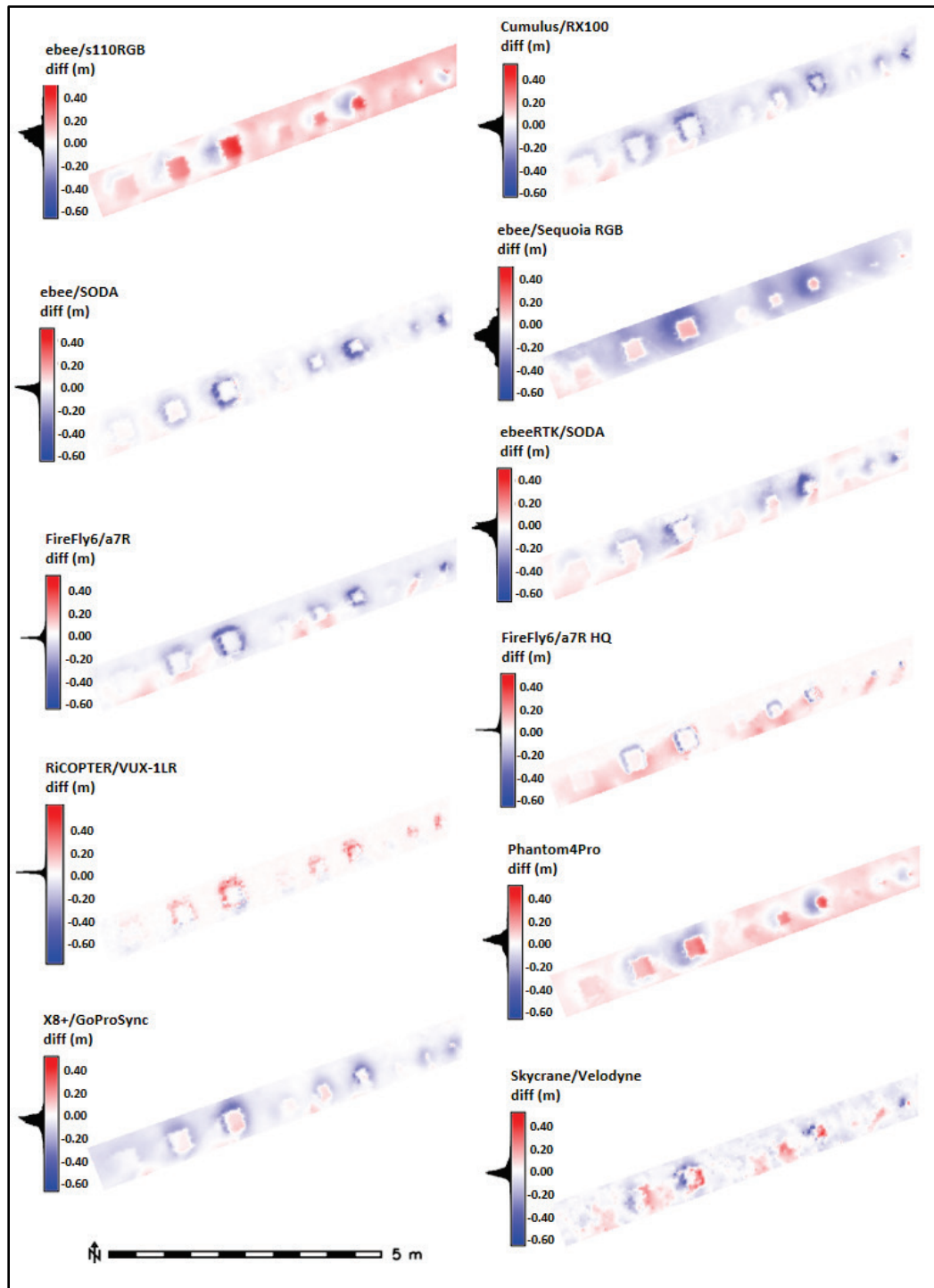


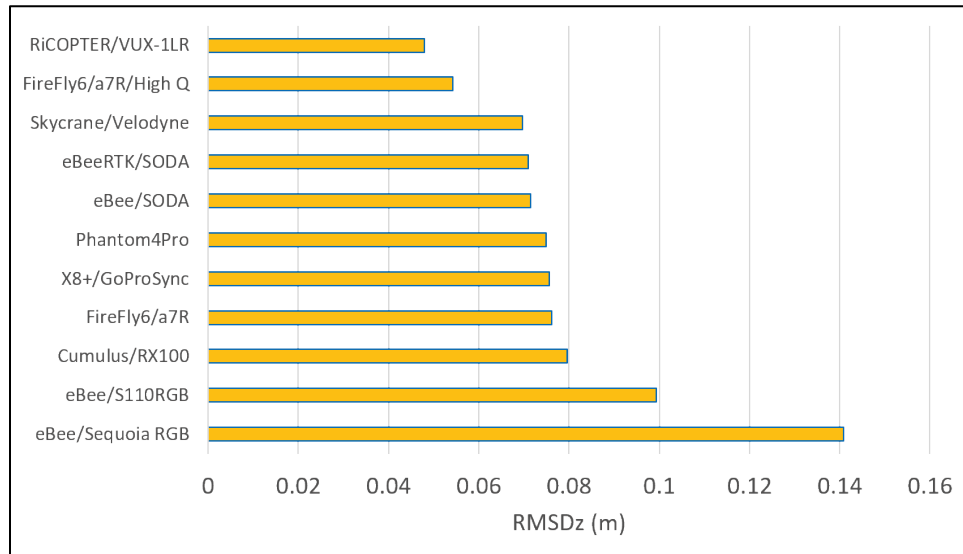
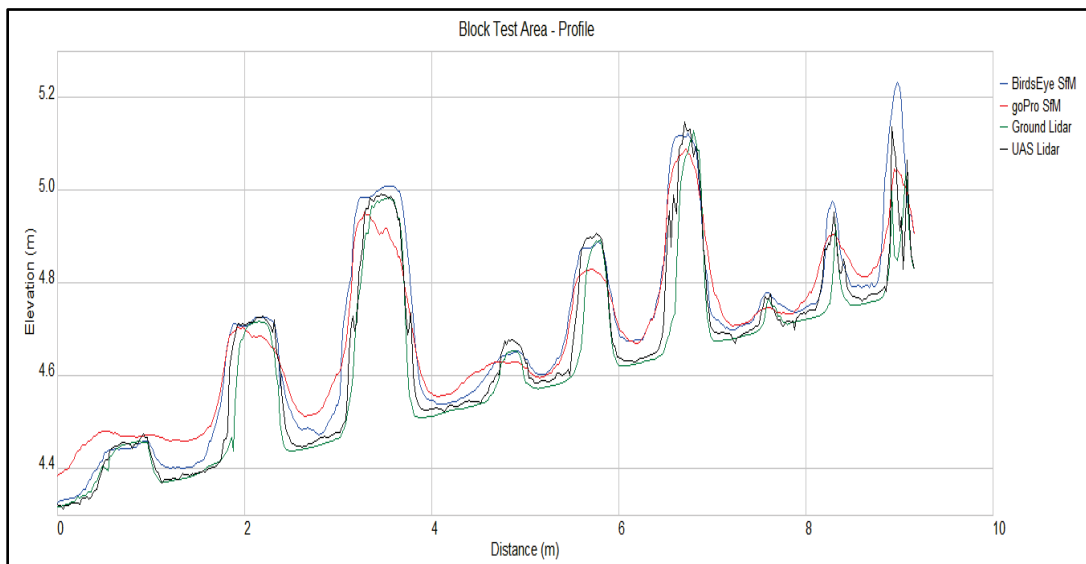
Figure 3-8. RMSDz (elevation) for data of block area for all UAS.

Figure 3-9 displays a transect over the approximate center of all nine blocks for four select datasets including the highest quality SfM (FireFly6/a7R [blue], low quality Phantom4Pro [red], UAS lidar RiCOPTER/VUX-1L [black], and FRF TLS control [green]) to bound conditions on the data. Note the differences of block corners and ground elevations between blocks.

Figure 3-9. Profile view over blocks within IA from three UAS along with control lidar.

Volumes for individual blocks were also computed for each UAS survey by first subtracting the surface (control lidar) from each of the UAS surveys. Polygons were digitized for each block object, which were slightly larger than the footprint of each block to allow for the sloping areas (over-predicted) found in many of the UAS datasets. The volume was then computed for each block with the GRASS function *r.volume*, which sums the cell values in each block polygon (elevations), which are then multiplied by the east-west and north-south resolutions (0.02 m).

The percentage error between UAS-measured and actual block volumes was computed by

$$\% \text{ error} = \frac{sUAS \text{ Volume} - \text{Block Volume}}{\text{Block Volume}} \times 100$$

The results for UAS are shown in Figure 3-11. The smaller block objects (1–3) demonstrated the largest differences while smaller percentages were found on the larger blocks (7–9). Most of the UAS overestimated the volumes (i.e., the dimensions) of all the blocks although there were some that underestimated. The overestimation appeared particularly significant for the smaller narrower blocks, which is also related to the block footprint polygon where volume was computed (blue rectangle in Figure 3-10) being slightly larger than the block size and capturing the unresolved blocks found in the Phantom 4 Pro dataset.

Figure 3-10. Comparison of two UAS datasets over block area showing example polygon used for volume computation (blue rectangle). Note the larger footprint of polygon and volume differences between the Phantom4Pro (poorly resolving) and the FireFly6/a7R-HQ (highly resolving) the blocks.

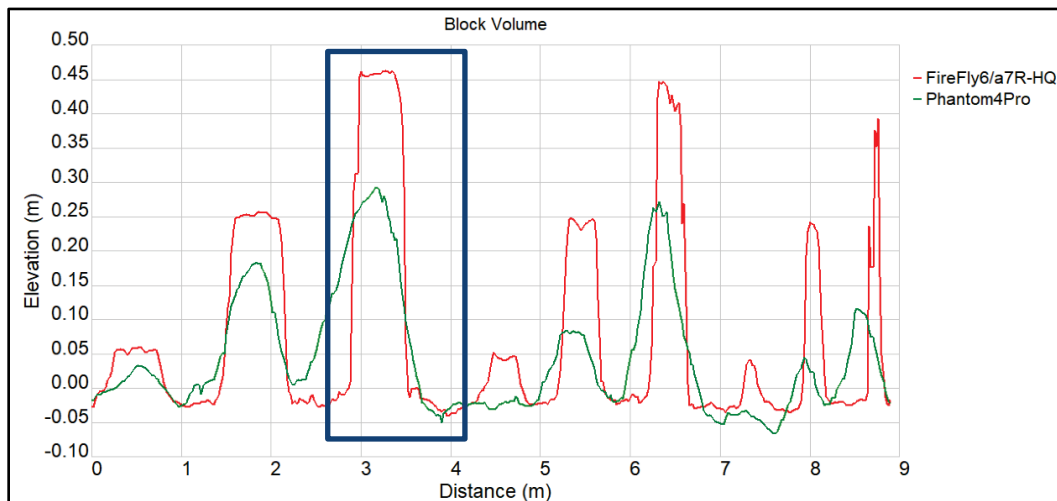
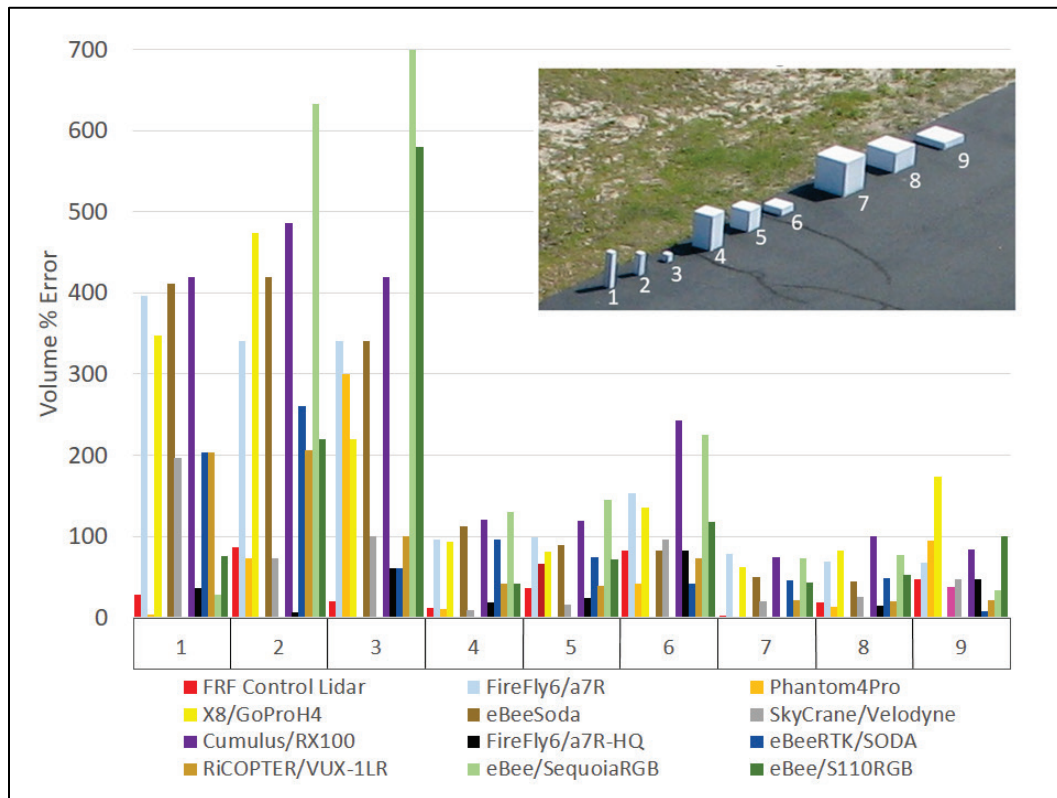


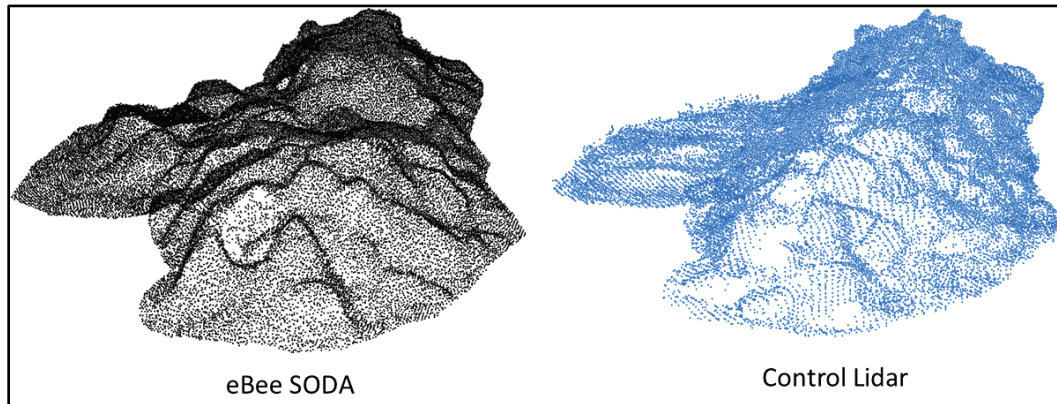
Figure 3-11. Error in UAS block volumes measured by each UAS as compared to actual measured volume of control blocks. Note actual volume provided by block measurements. FRF control lidar included for reference.



3.5 Mock jetty deformation assessment

Building on the characterization of the blocks, the mock jetty was examined for detection of similar volume changes via SfM and the control lidar over the same period. For analysis of the mock jetty point clouds, the point clouds were first qualitatively assessed, with an example shown in Figure 3-12 comparing the eBee S.O.D.A. with the control lidar. Jetty point cloud qualities were similar to the point clouds produced over the block targets; therefore, only an example SfM point cloud is shown here (Figure 3-12). In this example, the eBee S.O.D.A. SfM point cloud resolves the individual rocks well and provides a high point density, similar to the control lidar data, but the SfM point cloud tends to smooth the rock edges like it did the block edges in the preceding section.

Figure 3-12. Point clouds from both UAS (SfM) and the TLS control lidar.



A volume comparison was made between three UAS platforms and the control lidar conducted on the same day or within 1 day to identify changes within the structure. The region was isolated by a polygon to capture only the rocks and not the surrounding topography. The eBee/S.O.D.A. was the closest reporting -0.73 m^3 within the control lidar, the FireFly6/a7R - 2.74 m^3 , and the X8+/GoProH4 with -3.97 m^3 . Table 3-3 presents the results from the volume comparison.

Table 3-3. Select UAS platforms jetty volume comparison.

Dataset & Date of Collection	Volume m^3	Volume % Error
X8+/GoProH4 2017-06-14	205.48	-1.9
FRF Control Lidar 2017-06-14	209.45	
FireFly6/a7R 2017-06-20	210.99	1.3
FRF Control Lidar 2017-06-20	208.25	
eBee/S.O.D.A. 2017-06-13	209.72	0.3
FRF Control Lidar 2017-06-12	208.99	

Given that one of the main goals of this test was to determine if the SfM point cloud data were of high enough quality to detect changes to structures such as jetties, two UAS surveys over the jetty and two lidar control surveys were analyzed to detect changes. Figure 3-13 shows the elevation surface from the TLS control data ([A] and [B]) and UAS (FireFly6/a7R [D] and eBee/S.O.D.A. [E]). The surveys were conducted 7 days apart and captured the jetty pre- and post-disturbance. The two surfaces were subtracted from one another, and areas of change greater and less than 0.10m (Figure 3-13 [C and F]) were isolated. The volume for

each area was then computed by summing the areas of positive and areas of negative change and are listed in Table 3-4. A westward shift in the center of mass of the jetty was detected in both the control lidar (1.96 m³) and the UAS (1.05 m³).

Figure 3-13. Change detection over mock jetty for Control Lidar (A,B,C) and UAS (D,E,F). Areas of negative change are highlighted in orange/red and positive in blue (C,F).

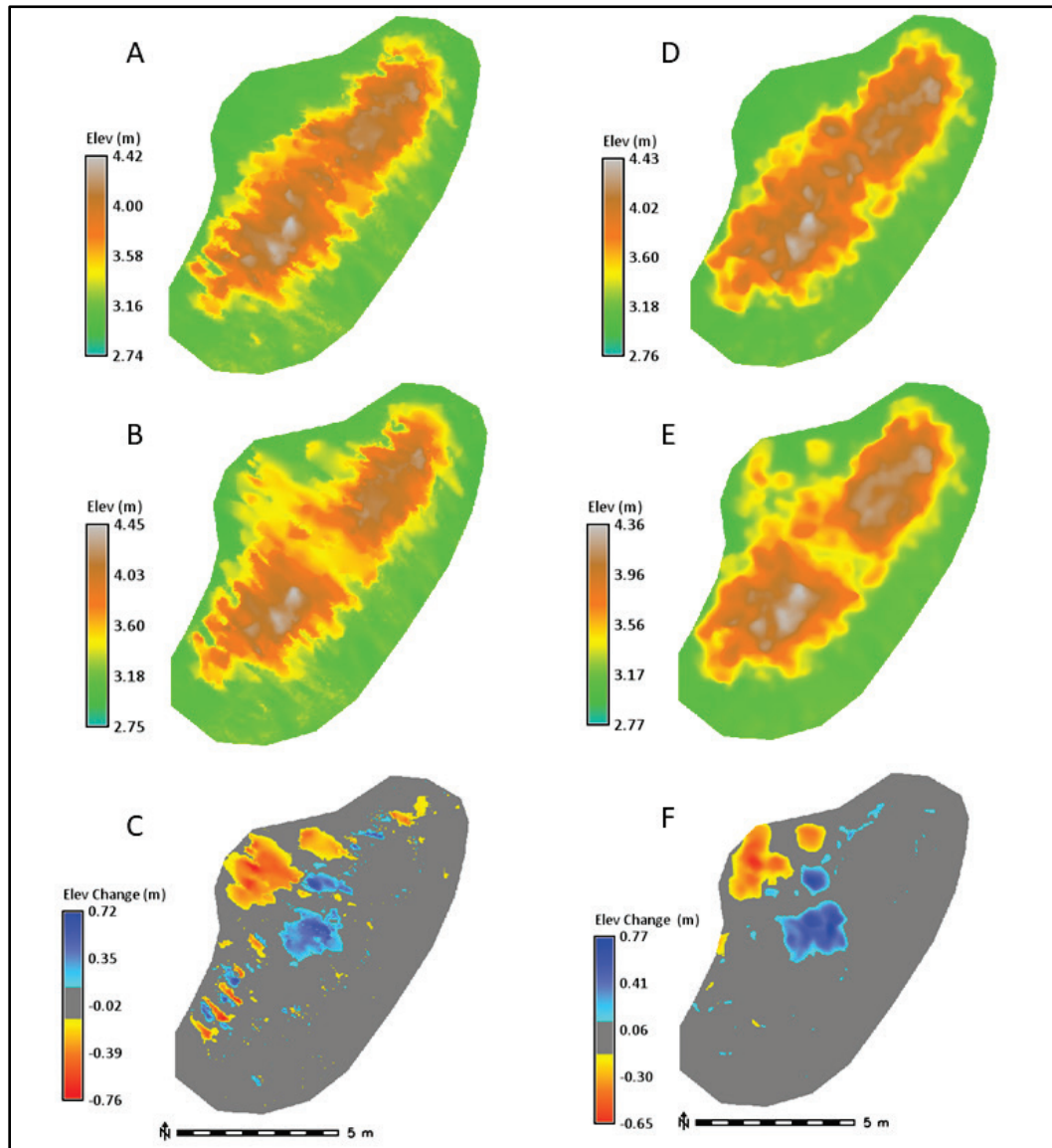


Table 3-4. Volume change from disturbed jetty for control TRS lidar (Figure 3-13 [C]) and UAS (Figure 3-13 [F]).

Sensor	Positive Volume Change m ³	Negative Volume Change m ³
Control Lidar	1.25	1.96
UAS	1.45	1.05

3.6 Discussion – Object detection and structure disturbance

Imagery from eight UAS platforms were processed using SfM techniques and compared to terrestrial lidar over two target areas. In addition, two lidar-equipped UAS were evaluated within the IA. The majority of data collected by UAS platforms at the experiment elevations met the RMSEz standards acceptable for USACE Civil Works activities (Figure 3-8; Table 2-14, Table 2-15). Note, acceptable USACE RMSE values have been compared against RMSD values in this chapter, given the comparison of UAS data against terrestrial lidar point clouds for ground truth rather than individual GCPs or surfaces. However, the accuracies reported in this chapter indicate these approaches are not necessarily accurate enough for structural deformation monitoring studies/surveys of reinforced concrete structures or earth/rock fill structures, which require sub 1 cm level vertical accuracy. These thresholds may limit UAS use in those applications. However, UAS data may be able to augment or replace visual inspection or traditional survey of coastal structures.

The blocks shapes are generally captured by the SfM point clouds, although errors do exist around the block edges. Similar to Marčič (2013), while the lidar generally capture the edges well, SfM errors arose from points below edges gradually sloping towards the ground. The UAS platforms with higher-resolution cameras outperformed the lower-resolution sensors, although both displayed some error when compared to the control lidar. Theoni et al. (2014) also noted SfM improvement due to higher resolution but saw a threshold where increases in resolution did not lead to significant improvements in accuracy. Among their subset of cameras, a charge-couple device sensor appeared to outperform the active-pixel sensor complementary metal-oxide-semiconductor (CMOS) sensors despite resolution.

The Agisoft SfM processing quality level also contributed to improved results for both resolving the block corners and improving the RMSD. Similar results were found in Slocum and Parrish (2017) who simulated

SfM workflows to assess reconstruction accuracy (i.e., the accuracy defined by tie-point matching and stereo reconstruction equations [not GCPs]). The differences between lidar and SfM decreased as the block size increased. The largest errors were observed in the areas immediately adjacent to the blocks and were likely due to shadowing effects sometimes found on object edges. More noise between the blocks was also present in the lower-resolution cameras. The narrowest blocks (10 cm widths vs. GSD of 1.2–4.5 cm) were the least resolved. On these blocks, the tops presented as only a few scattered points instead of planes while the largest blocks (0.5 m widths vs. GSD of 1.2–4.5 cm) were well resolved.

As might be expected given the UAS platform technical specifications and costs, the RiCOPTER/VUX-1LR had the lowest RMSDz of all the lidar-equipped UAS platforms and all the datasets examined within this chapter. These results reinforce the capability that the RiCOPTER brings to those applications requiring the most precise data on small objects. However, many SfM-generated products fell within 5 cm of these results and may be perfectly acceptable to district applications where sub-5 cm RMSDz accuracy is not required.

Though results were not exactly equivalent, the UAS SfM demonstrated the ability to resolve individual rocks of the mock jetty and measure total volumes to within 1 m³ of the control lidar. While likely not to the standards required for structural deformation monitoring studies, the level of detection may be enough to identify areas of concern that may justify further investigation by USACE. The LeWinter et al. (2018) breakwater survey in Hawaii shows that UAS-based lidar shows promise for improved coastal structural monitoring data compared to other collection methods and that further assessment of these capabilities is therefore merited, particularly when coupled with bathymetric lidar. While the rip-rap structure was used in this experiment for convenience, future studies may look to assess changes within individual surfaces within a point cloud, such as those that might be required for dolos or other larger armored material used in jetties or groins.

4 UAS Extraction of Dune Features

4.1 Background

The presence of healthy dunes has been correlated with reduced storm damage to coastal assets (Sigren et al. 2018; USACE 2013; Walling et al. 2014). Dune height, width, volume, and vegetation health are critical metrics to properly quantify the vulnerability of the coastal communities and ecosystems that reside behind them. Dune shape and volume can change rapidly during coastal storms and recover at different rates depending on the severity of the storm. Subsequent events that follow may limit the quantification of event-specific impacts to dunes and the sub-aerial beach (e.g., Brodie and Spore 2015; Brodie et al. 2019c; Houser et al. 2015). UAS have proven practical for assessments of coastal beaches, structures, and dunes, allowing for rapid, flexible, and cost-effective surveys of coastal dunes to adequately quantify their condition and dynamics (e.g., Sherwood et al. 2018; Turner et al. 2016; Brodie et al. 2019b).

Various studies have often reported differences in accuracy between beaches and dunes, usually attributed to differences in vegetation, slope, and surface texture between dunes and the beach below them (Conlin et al. 2018; Studivant et al. 2017; Mancini et al. 2013). UAS SfM-generated point clouds do face limitations based on a number of factors, including impacts by vegetation, terrain *smoothness*, sun-angle and shadows, camera misalignment, imperfections in camera lenses, or motion blur (e.g., Sherwood et al. 2018; Seymour et al. 2017; Mancini et al. 2013; Westoby et al. 2012). Given the importance of dunes to coastal beach project assessments, this chapter assesses the capability of data collected by five different UAS to support the extraction of dunes and similar coastal features. Using data collected during the 2017 Duck UAS Pilot Project Experiment, the imagery was used to generate 3D point clouds and DSMs of coastal foredunes at the FRF.

Section 4.2 briefly summarizes the dune area of the FRF and the conditions present at the time of the 2017 Duck Pilot experiment. Sections 4.3 and 4.4 describe the UAS platforms and imagery data sets, as well as the control data. Section 4.5 details the general data processing methodology, and section 4.6 includes the final data products and compares the accuracy within different sections along the dune features.

Section 4.7 concludes the chapter with a discussion of the findings and their implications for future use of UAS to extract natural coastal features.

4.2 Study site

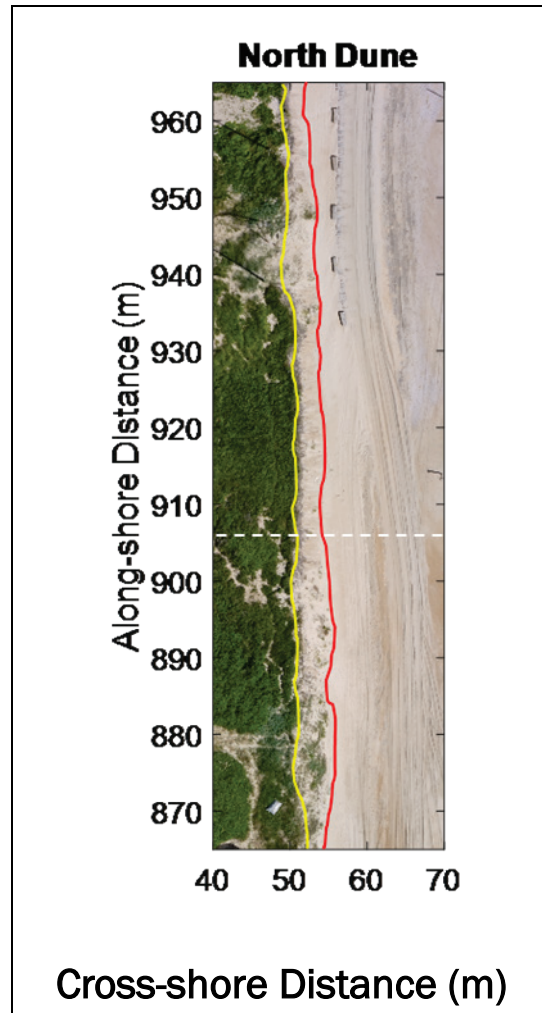
The oceanside of the FRF property is approximately 1 km long and is lined by coastal foredunes that had an average crest elevation of approximately 7.36 m north of the pier that bisects the property and 6.15 m south of the pier during the experiment in June 2017 (Figures 1-1 and 2-1). These dunes are generally parallel to the shoreline, facing north-northeast.

The foredune crest line has discontinuities at the 560 m pier, at one beach access approximately 75 m north of the pier and at one access ramp approximately 50 m south of the pier. Through time, the dunes north and south of the FRF pier have often seen different behavior and trends in erosion and growth. In recent years, the dunes along the northern half of the property have experienced greater erosion than dunes along the southern area south of the FRF pier (Brodie et al. 2019c).

The beach at the FRF has a bimodal grain size distribution, historically ranging from 0.25 to 0.45 mm (Birkemeier 1985). The mean grain size continues to decrease towards the dune and beyond. Historically, the dunes along the FRF property have not been managed since the 1930s and 1940s, following an extensive depression-era public works foredune stabilization effort via dune fencing and plantings (Birkemeier et al. 1984). While management has remained limited, during June 2017, a beach renourishment project was being constructed immediately to the north of the property, with sediment placed up to the northern FRF property line. Note that the dredging contractor's equipment was mobilized out of the FRF property; therefore, large trucks often passed along the subaerial foreshore during the course of the experiment, generating tracks across the subaerial beach. Wooden board-roads were also positioned along parts of the beach as well. As summarized by Bruder et al. (2018), precipitation and storms were limited during the experiment time period, though high winds occurred near the beginning (5, 7–9 June 2017) and end (19–20, 23 June 2017). In addition to limiting UAS operations during these windows, high winds may have contributed to sediment mobility along the dunes, especially given the disturbance of the subaerial foreshore by passing vehicles. A local coordinate system was utilized to orient the data in the FRF local coordinate system, which has an origin located near the south-eastern corner of the property with the x-axis extending offshore and the y-axis

extending along the dune line to the NNW (Figure 4-1). Alongshore values increase towards the north, and cross-shore values increase seaward.

Figure 4-1. Example aerial view of the FRF north dune site with the cross-shore, along-shore system defined. Note the lines at 50 m and 55 m define the dune compartment.



As visible in Figure 4-1, significant vegetation is present behind the foredune crest, consisting of a variety of coastal species, particularly dune grass, vines, and coastal shrub species (Birkemeier et al. 1985; Levy 1976). Seaward of the dune crest, the distribution of vegetation shows significant variation along the face of the foredunes. Coverage primarily consists of bare sand, dune grasses, or overhanging shrub or vine species where the foredune eroded below them. The presence of dead vegetation existing seaward of the foredune crest was particularly evident in the northern section of dune analyzed, whereas the southern part of the

property often has fewer eroded dunes with more dune grasses (e.g., Sea Oats, *U.paniculata*).

4.3 UAS and data characterization

As detailed in Bruder et al. (2018), there were 10 different UAS flown during the course of the 2017 Duck Pilot Experiment. Data from one of these UAS were processed with PPK rather than depending solely on GCPs. This chapter's assessment focuses on a subset of five UAS to compare characteristics. These data were compared against control data collected with mobile, terrestrial lidar scanning system.

While the overall Duck Pilot UAS experiment was designed for different UAS to contemporaneously capture data from the same features, UAS were still operated by different teams with different coastal data collection goals in mind (Table 4-1) (Bruder et al. 2018). As a result, UAS imagery is not always directly comparable, as exact flight paths, flight elevations, and CONOPS differed in addition to the instrumentation. Table 4-1 summarizes the UAS platforms and associated differences in instrumentation and CONOPS for this chapter's assessment.

Table 4-1. Characteristics of UAS and instruments examined in this chapter.

Airframe	Primary Instrument	Instrument View	Flight Altitude (m AGL)	GSD (cm)	Approximate Flight Pattern
3DR Solo	Ricoh GR11 RGB Camera	Oblique at 30°	70	1.8	Beach Transect
3DR X8+	Single GoPro	Side Oblique at 40° Off Nadir	50	3.5	Beach Transect
BirdsEyeView Aerobotics LLC	Sony a6000	Nadir	120	2.9	Canvas
Sensefly eBeeRTK (w/o GCPs)	S.O.D.A. Camera	Nadir	100	2.4	Canvas
Riegl RiCOPTER	Riegl VUX-1LR scanner, Sony a6000	Nadir	60	NA	Canvas

Note: approximate flight path describes the trajectory of the UAS during the image acquisition. Beach transect refers to shore-parallel flight lines restricted to sub-aerial beach whereas canvas refers to the more traditional combination of shore-parallel and shore-perpendicular flight lines that span the exposed sub-aerial beach as well as the back dune.

4.4 Control data

4.4.1 Ground control points (GCPs)

GCPs were distributed across the FRF property according to Bruder et al. (2018), of which 13 were visible near or within the foredune. These targets were occupied with an RTK-GPS rover for at least 180 epochs following Section 3.4 in Bruder et al. (2018). Four temporary GCPs were deployed on the dry beach during flights that only encompassed the beach and foredunes areas of the property, and these were surveyed via the same method.

4.4.2 Mobile terrestrial lidar (MTLS) control

The entirety of the FRF beach-dune system was scanned with the Coastal Lidar and Radar Imaging System (CLARIS), a van-mounted Riegl VZ-2000 terrestrial lidar scanner coupled to an IX-Blue ATLANS-C inertial navigation system on 15 June 2017. The system and its operation are described in Spore and Brodie (2017), Spore et al. (2019), and Conery et al. (2020). The system was capable of collecting elevation data from the approximate location of the dune crest to the shoreline utilizing a mobile 3D scanning pattern (radar mode) with similar accuracies described in Conery et. al. (2020) for radar mode scanning with a 300 kHz pulse repetition rate. Once the data were globally rectified, it was transformed into the local FRF coordinate system and nearest-neighbor interpolated at 0.5 m cell size using the mean elevation within each cell. Cells that did not contain data were not included in the interpolation to minimize smoothing of the control surface. Vegetation and structural artifacts were also included in the interpolation to create the DSM to remain consistent with the other datasets. The resulting DSM was used as the control surface for all further calculations and error assessment and is referred to as “CLARIS.” It is understood that using a coarse resolution grid as a control surface may introduce uncertainty/artifacts into the difference analysis. However, this CLARIS DSM is a documented data product, and the authors chose to compare data product to data product rather than treat the CLARIS data as *truth* such as a ground survey.

4.5 Data processing

4.5.1 Point cloud generation

Imagery from the 3DR X8+ GoPro, 3DR Solo Ricoh GR11, eBeeRTK S.O.D.A., were processed through Agisoft PhotoScan v1.4.4 as in Section

3.3.1 and described by Sloan (2017). In the case of the eBee S.O.D.A. data, imagery was geotagged via PPK processing (see Chapter 2.10). For the FireFLY6 PRO imagery analyzed in this chapter, SfM was generated using Pix4D, the native software associated with the UAS platform and employed by the BirdsEyeView Aerobotics firm.

As described in LeWinter et al. (2018), the Riegl VUX-1LR captures up to 1000s of direct measurement points/m². The RiCOPTER's Applanix IMU data and associated ApplanixPOSPac UAV software then assist in point cloud processing by providing better measurements of UAS position and trajectory before Riegl RiPROCESS software is used to enhance point cloud registration using control points.

4.5.2 Model generation

The point clouds were rotated into the local FRF coordinate system and gridded at 0.5 m cell size with a nearest neighbor interpolation utilizing the mean elevation of all the points residing within a cell. This approach was chosen due to the unconventional environment used for assessing accuracy within a steeply sloped, vegetated dune field. Obtaining stable control points on a continuously modulating surface without any static features necessitates a more holistic approach by comparing the surface morphology directly through DSM surface differencing. Due to the lack of robust bare-earth filtering for the SfM point clouds, DSMs were generated that include the bare earth, vegetation, and other surface artifacts. The lidar point clouds were processed similarly, and DSMs were generated at the same 0.5 m cell size and gridded similarly with the mean elevation of all points within a cell.

4.5.3 Dune volume

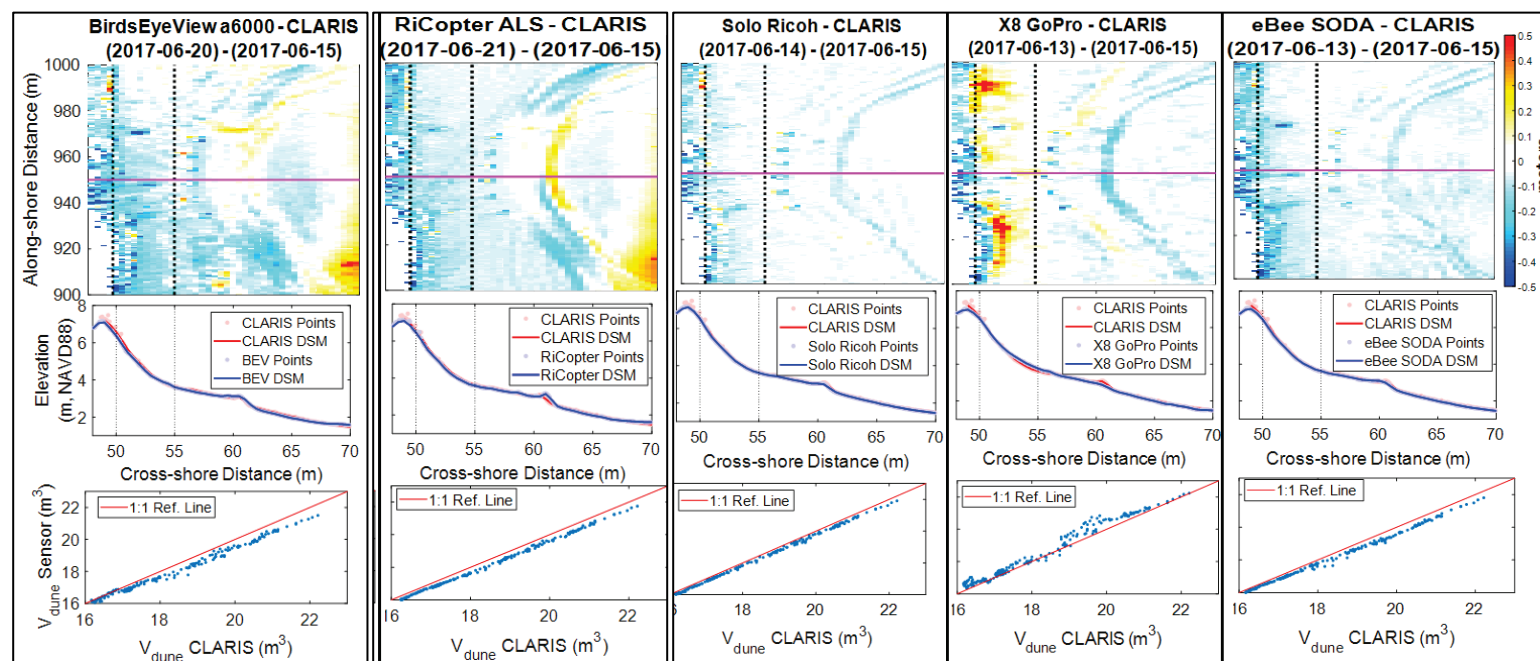
Dune volume was calculated for each 0.5 m wide transect as the area under the foredune curve between the cross-shore positions 50 m and 55 m. These bounds were chosen to ensure data continuity along the entire 100 m reach while attempting to minimize the shadowing effect of vegetation near the dune crest, while also mitigating any physical disturbances near the base of the dune such as pedestrian and vehicular traffic that occurred throughout the 3-week experiment.

4.6 Data summary

To compare their relative potential to inform coastal dune assessment and management, data from the different UAS have been evaluated by comparing their characterization of dune elevation in two dimensions (dune profiles) and three dimensions (dune volume). A 100 m section of coincident dune data north of the pier was selected to highlight relative performance of these different approaches for dunes with different morphology and vegetation density.

Figure 4-2 provides a synopsis for how each system performed relative to the CLARIS MTLs control data. The top row of plots in these figures display a DSM surface difference between the sensor and the MTLs control data, with warmer colors denoting areas where the sensors' derived elevations reside above (overpredict) the control surface and cooler colors corresponding to areas where the sensors' derived elevations reside below (underpredict) the control surface. The middle row of plots displays a representative cross-shore elevation profile denoted by the magenta line (location 950 m along-shore). The third row of plots displays each 0.5 m along-shore transect volume relative to the control volume. This volume is limited between the two dashed lines in the above elevation profile plots at cross-shore locations 50 m and 55 m, respectively.

Figure 4-2. Each vertical column represents each sensor compared to the CLARIS MTLs control dataset. The top row is the result of DSM surface difference between the sensor and the CLARIS MTLs. The middle row presents an example cross-shore elevation transect noted by the magenta line in the surface difference plots at $y=950$ m. The dashed vertical lines at $x=50$ m and $x=55$ m represent the dune compartment region where volume was calculated. The third row presents the dune volume at each alongshore transect compared to the dune volume at each transect measured by CLARIS MTLs with a 1:1 line for reference.



4.6.1 Digital surface model (DSM) differences

Intertidal changes and vehicular and pedestrian traffic between 60 and 70 m cross-shore resulted in significant elevation differences among the systems within this region, given the 3-week duration of the experiment and the timing of the MTLS control survey relative to the airborne surveys. Along the dune face, elevation differences from the various UAS are particularly evident towards the dune crest as seen in the first row of plots in Figure 4-2. Many of the aerial UAS are challenged by the thick vegetation in this area as well as the steep slope that may amplify any subtle horizontal error in the vertical dimension. The X8 GoPro had the largest positive error near the dune crest, and the BirdsEyeView a6000, RiCopter ALS, Solo Ricoh, and eBee SODA DSMs contained less negative error in this region.

4.6.2 Elevation profiles

The second row of plots in Figure 4-2 highlights an example cross-shore elevation profile at 950 m alongshore. All UAS were capable of resolving the dune and beach morphology including the approximate dune toe and dune crest locations as well as the subtle scarp feature near cross-shore coordinate 61 m. The points used in the creation of the DSMs were also included to highlight point density and interpolation effects on the resulting DSMs used for analysis.

4.6.3 Volume

The third row of plots in Figure 4-2 accounts for the third dimension and compares each sensor's measured dune volume with the MTLS measurements between 50 m and 55 m in the cross-shore. These boundaries were used as the volume compartment as they remain static in space and are not subject to the irregularities presented by defining a dune crest or toe amongst the various datasets. The volume plots follow the same trend as the surface difference plots, where the X8 GoPro overpredicts the volume with some scatter within 19–21 m³, and the BirdsEyeView a6000, RiCopter ALS, and eBee SODA DSMs slightly underpredict the volume in this region. The Solo Ricoh performed well with the most consistent measurements relative to the MTLS control across the distribution of datapoints.

4.6.4 Root Mean Square Differences (RMSD)

An RMSD was used in this chapter to assess dune DSM accuracy as calculations were referenced from a control surface determined from a point cloud (CLARIS MTLs) rather than from individual GPS-surveyed GCPs (as in Chapter 3). The sensor and control datasets had similar orders of magnitude with respect to global accuracy; hence, the RMSD_z was chosen as the comparison metric. RMSD_z was calculated with the following approach:

$$RMSD_z = \sqrt{\frac{\sum_{i=1}^n (Z_{plat,i} - Z_{lidar,i})^2}{n}}$$

where

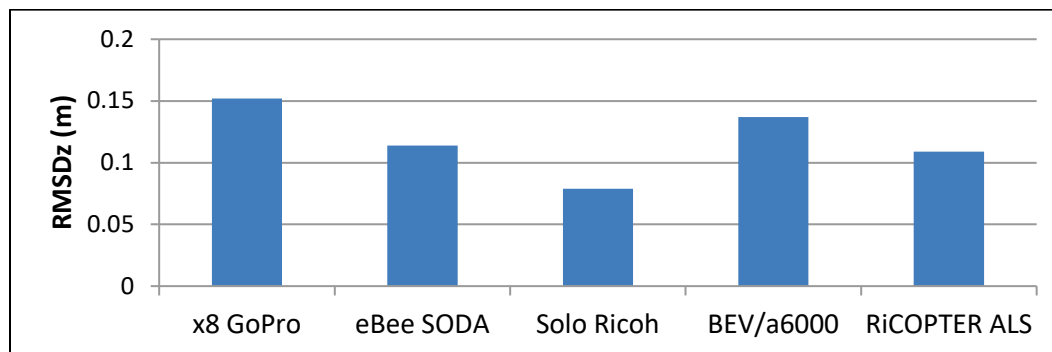
Z_{lidar} = the elevation measured with the CLARIS MTLs between the cross-shore locations 50 m and 55 m for all cells in each cross-shore dune transect

Z_{plat} = the elevation measured with the UAS between the cross-shore locations 50 m and 55 m for all cells in each cross-shore dune transect

n = the number of observations.

The RMSD_z of the dune elevation profiles was calculated for all transects within the north dune site for each sensor relative to the CLARIS MTLs survey and is shown in Figure 4-3.

Figure 4-3. RMSD_z calculations for the various UAS sensors relative to the CLARIS MTLs data.



4.7 Discussion – UAS coastal dune data

The analyses described here compare surfaces generated from point clouds captured of the FRF primary dune by five UAS against MTLs (CLARIS). As illustrated in Section 4.6, the different UAS generated relatively similar point clouds within the example FRF foredune, despite collection from a variety of different UAS and instruments flown on different flight paths and altitudes. The maximum RMSD_z values among all UAS datasets considered and the terrestrial lidar control data of 15.2 cm suggest that these UAS may provide acceptable options to surveyors and coastal managers looking to assess the condition of coastal foredune faces, depending on the objective (Table 2-14).

As expected, the general agreement within the point clouds extended to informing similar dune feature extraction statistics. The consistent dune volume calculations suggest that under correct flight planning, operation, and data processing for these UAS all might be considered viable options for various dune management applications. The relative consistency hints that while exact positional accuracy of dune crest may differ in steep and/or vegetated dunes, when used to assess dune volume, these limitations are minimized (Figure 4-2). In cases where volume estimates are particularly biased in one direction, airborne imagery still may allow for the identification of extreme trends in overall dune volume change at a given alongshore location or an overall coastal site.

The maximum difference between all the UAS and control is within the vertical accuracy limits demanded by numerous Civil Works design, construction, and maintenance activities pertinent to coastal management activities. These surface RMSD_z values fall within the 20 cm feature vertical accuracy demanded by projects likely involving dunes, such as site plans, design, operation, and maintenance reports for beach renourishment projects or the 50 cm vertical RMSE_z required flood control and multipurpose project planning, floodplain mapping, and flood control studies (Table 2-14) (EM 1110-1-1000 [USACE 2010b]). Note, USACE EM 1110-1-1000 RMSE_z values have been compared against RMSD_z values here due to the DSMs derived from point clouds being compared against DSMs derived from MTLs point clouds rather than exact GCPs on the dunes and gridded products of similar order accuracies were compared. Federal Emergency Management Agency (FEMA) Flood Insurance studies also demand 20 cm vertical accuracy. Though these data meet USACE Civil Works requirements, they might not be acceptable for other dune surveys,

such as studies of aeolian transport. For example, while RMSDz values fall below the 50 to 75 cm accretion values observed within dunes by Conery et al. (2019) over 21 months, the RMSDz likely are too high for considering smaller changes taking place over shorter periods of time.

These data often exceeded requirements for USACE coastal management purposes (Table 2-14) (EM 1110-1-1000 [USACE 2015b]). Sturdivant et al. (2017) have commented on the importance of high point densities to support narrow swaths for extraction of dune feature positions (such as dune crest and dune toe). Their study suggests that effects of point density differences were more pronounced for dune positions than the subaerial foreshore. Fine-resolution dune dynamics studies may therefore suggest the uses of UAS-based lidar (e.g., RiCOPTER) or high-resolution cameras over lower-resolution instrumentation for focused dune assessments.

SfM does face limits in more heavily vegetated areas. Within the data examined in this chapter, vegetation may have led to the observed differences in sensor performance, due to differences in flight paths and corresponding camera view angles. Vegetation along parts of the northern dune site may have compounded issues of dune steepness, as vegetation overhangs sections of the dune crest there. While semi-sparse vegetation in certain areas may provide regions for keypoint generation, UAS-generated SfM data may have limited accuracy when producing DSMs in more heavily vegetated areas (Westoby et al. 2012; Seymour et al. 2017). This vegetation limit may also pose challenges to other surveying techniques (e.g., shadowing and occlusion of data due to structure or vegetation), as obtaining a true bare-earth measurement may require significant disturbance to vegetation and the surrounding earth. At these points, the CLARIS MTLs data collected from lower elevations and angles may have penetrated materials differently than the airborne UAS.

Overall, this chapter illustrates that multiple UAS-collected data on the seaward side of dunes that meet USACE requirements for various USACE Civil Works activities. This success occurred despite some smaller-scale differences in data and differences in UAS type and exact collection approaches. Despite the high-quality of these datasets, there remain limitations and further room for improvement, especially at the dune crest and on the backside of dunes, where dense vegetation may optically limit not only UAS data but may also limit the collection of adequate ground control data.

5 UAS Platform Costs and Benefits

5.1 Overview

This report has detailed the performance of a variety of UAS evaluated during the 2017 Duck UAS Pilot experiment with respect to their potential to provide data that can inform coastal management. Numerous studies have stressed the ability of UAS to provide effective and flexible solutions for coastal mapping and surveying (e.g., Fischer et al. 2019; Sturdivant et al. 2017; Holman et al. 2017; Seymour et al. 2017; Turner et al. 2016; Mancini et al. 2013; Brodie et al. 2019a,b). The analyses here show that multiple UAS and associated data products are fully capable of delivering high-quality 3D data of coastal terrain and infrastructure.

Each previous chapter assessed UAS performance in different scenarios, thereby laying the groundwork to better inform USACE decisions for developing capabilities to utilize and operate UAS platforms. The relative performance of the UAS varies in cost as well as relative accuracy in characterizing coastal features. As exemplified in accuracy standards in USACE Engineering Manual on Photogrammetric and LiDAR Mapping (EM 1110-1-1000 [USACE 2015b]), coastal survey and mapping tasks have different levels of acceptable error (Tables 2-4 and 2-5). These data accuracy standards should be considered alongside each UAS relative cost as well as those provided by other technologies employed by USACE for the proposed UAS coastal data acquisition.

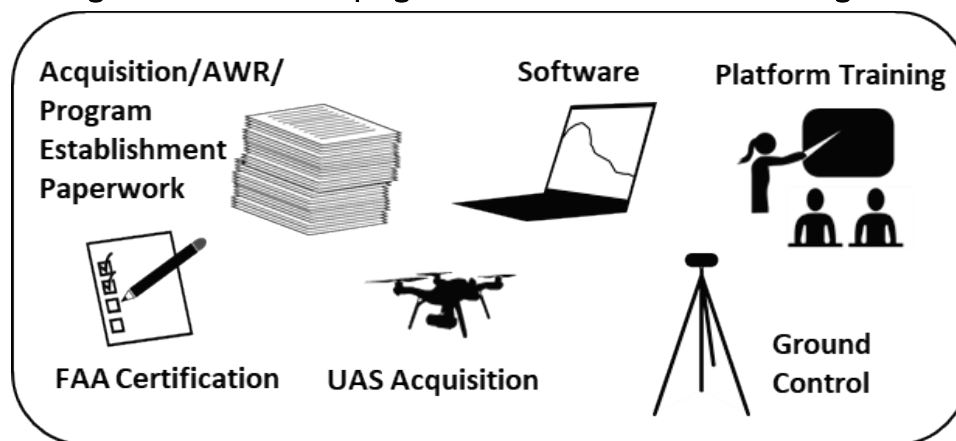
This chapter addresses the overall costs and benefits of different UAS platforms by summarizing UAS acquisition factors such as cost-effectiveness, possible missions/need, annualized system costs, maintenance, system descriptions, and training. Section 5.2 presents the overall costs to establishing a UAS program at any command, summarizing required start-up costs, including pilot training and costs associated with acquiring UAS platforms, instrumentation, and associated software and equipment. Sections 5.3–5.5 then proceed to summarize common operation costs specific to typical coastal data acquisition and processing via UAS. Section 5.6 considers these costs alongside the relative UAS performance for each coastal infrastructure/terrain application presented in the previous chapters and associated UAS platforms. The chapter concludes with a brief synopsis of these discussions and additional

considerations on UAS operation use that may change costs with UAS operation in the future.

5.2 UAS programmatic costs

Prior to any data collection, any USACE UAS operations require establishment of a UAS program and fleet. Within USACE, the Civil Works UAS program has been established under the management of the Aviation Program Manager under Section 1124 of the Water Resources and Development Act of 2016 . Locally, a UAS Aircrew Training Program Manager (ATPM) and Mission Briefing Officer (MBO) must also be authorized by local command. The following sections document costs associated with a selection of UAS that were utilized during the Duck 2017 UAS experiment and that ERDC teams have additional working operational knowledge of. These costs are summarized in Figure 5-1 and Sections 5.2.1 – 5.2.4. USACE regulations associated with UAS acquisition and operation have evolved since the 2017 Duck Experiment as the USACE Aviation and Remote Systems Program has been established, refined, and implemented. The following costs and requirements represent the authors' best understanding of UAS Community of Practice (CoP) guidance and UAS associated policy at the time of the experiment for operations with these UAS. At the time of the experiment, EC 110-1-106 was in place. The finalized Aviation Policy Letter 19-08 (USACE 2020) may be viewed for more in-depth guidance on current operation requirements.

Figure 5-1. USACE UAS program-establishment factors affecting cost.



5.2.1 Pilot training

Pilot training for any district must be coordinated through the establishment of a UAS ATPM that is responsible for USACE element UAS

program management, standardization, and subordinate UAS operator training. (EC 1110-1-109, Appendix A [DOA 2018]). All UAS pilots involved in operating UAS for USACE require proper certification, primarily a Remote Pilot Certification certificate issued by the Federal Aviation Administration (FAA), Small Unmanned Aircraft Rule, Part 107 of Title 14 Code of Federal Regulations (Title 14 Code of Federal Regulations 2017). The \$150 registration cost for the FAA remote pilot exam did not differ amongst UAS pilots. While more extensive study preparation is available, pilots involved in the experiment primarily prepared with freely available materials on the internet, or other low-cost materials (e.g., study prep book costing under \$15). The certification requires several hours to take, and several hours may be required for each staff member to prepare and travel to their exam location. While not required, ensuring that visual observers (VOs) are trained may enhance mission efficiency and safety.

While FAA certification costs did not differ amongst pilots, training requirements for the technical operation of the different UAS did somewhat vary with the complexity of the UAS. While operation of more consumer level COTS UAS such as 3DR Solo or DJI UAS is fairly self-explanatory and mainly improves with flight experience (Table 5-1), other more complicated platforms such as the FireFLY6PRO or RiCOPTER require more significant training to ensure UAS safety and quality data collection.

Table 5-1. Approximate training costs and duration by UAS employed by USACE officials during the experiment or other times close in date. Selected UAS include the BirdsEyeView FireFLY6 PRO, the Riegl RiCOPTER, the Multirotor G4 Skycrane, the Sensefly eBee RTK, the Sky-watch Cumulus, the Sensefly eBEE, the 3DR Solo, the DJI PhantomPro 4, and the 3DR Solo. Grouped by large multicopter UAS supporting lidar, FW UAS equipped with RTK-GPS, a hybrid RTK-GPS fixed-wing/Vertical Take Off Landing (VTOL) UAS, and traditional non-RTK and FW and quadcopter UAS.

	Lidar multicopter		RTK-FW		RTK-FW-VTOL	FW	Quadcopters	
	RiCOPTER	Skycrane	eBeeRTK	Cumulus	FireFLY6PRO	eBee	Phantom4 pro	Solo
Training Level	High	High	Moderate	Moderate	High	Moderate	Low	Low
Reported Training Cost (USD)	\$5,000	\$7,000	Free w/ purchase	Free w/ purchase	\$6,000	Free w/ purchase	In-house	In-house
Training Duration (Hours)	32	32	16	8	32	16	8	8

5.2.2 UAS platforms and instrumentation

The most significant difference in cost among various UAS operated by ERDC personnel and equivalent agency and industry partners during the Duck experiment was the cost of the UAS themselves, consisting of the

airframe and onboard sensors. The approximate prices of UAS referenced in this chapter are shown below (after Bruder et al. 2018), conservatively referencing price to the next highest increment of \$5,000 as reported by the operator of that UAS during the experiment or the price as acquired by USACE. The rounded price allows for potential instrumentation package upgrades or even future security adjustments, as guidance has called for increased use of encrypted datalinks and additional secure link steps. RTK-GPS capabilities that provide precise data on UAS position increase UAS price.

The majority of UAS discussed here have sensor package options that greatly improve the overall versatility of the UAS. Of those UAS listed in Table 5-2, all but the DJI Phantom 4 Pro allow for some level of interchangeable sensors. The miniaturized lidar scanners (RiCOPTER VUX-1LR scanner and Skycrane Velodyne HDL 32E) even allow for lidar capabilities while still operating as small UAS rather than airframes requiring more regulation and operational oversight (the weight of small UAS limit is 25 kg (FAA DroneZone 2020)).

Table 5-2. Approximate costs of selection of UAS rounded up to next increment of \$5,000 USD. Grouped by large multicopter UAS supporting lidar, FW UAS equipped with RTK-GPS, an RTK-GPS Vertical Take Off Landing (VTOL) UAS, and traditional non-RTK and FW and quadcopter UAS.

	Lidar multicopter			RTK-FW		RTK-FW-VTOL	FW	Quadcopters
	RiCOPTER	Skycrane	eBeeRTK/SODA	Cumulus/R10	FireFLY6PRO	eBee	Phantom4 Pro	Solo/Rico h
Approximate Price	\$345,000	\$250,000	\$25,000	\$25,000	\$15,000	\$15,000	\$5,000	\$5,000
Primary Instrument	Lidar	Lidar	Camera	Camera	Camera	Camera	Camera	Camera
RTK-GPS/GNSS Enabled	Yes	Yes	Yes	Yes	Yes	No	No	No

As expected, camera quality and the integration of precise UAS positioning technology drives the cost of camera-equipped UAS (e.g., Mosbrucker et al. 2017; Westoby et al. 2012). Cheaper cameras have less image resolution, increased distortion due to rolling shutter effects, and other artifacts in final data products. As SfM is enhanced by precise camera position and orientation information, it is ideal for position information and camera triggering cues to be perfectly aligned.

In addition to acquiring the UAS, USACE operators must also work with Army aviation engineers to obtain an Airworthiness Release (AWR) for their UAS (US Army 2016). The labor required for this paperwork is

conservatively estimated approximately 8 hr for most of the COTS UAS, though more complicated platforms towards the upper limit of UAS weight ranges (25 kg), such as the Riegl RiCOPTER, may demand additional labor (up to 40 hr) to fully obtain approval. Fees accounting for the reimbursable work by the Army Aviation Engineering Directorate are charged back to the AWR submitters as well. At the time of this report, these fees have been estimated at approximately \$3000 to \$5000 per UAS.

Policies and procedures for meeting USACE approval for UAS acquisition and operation have evolved since the 2017 Duck experiment during the publishing of this report. While the AWR is still required for non-standard UAS, the AWR fees and labor have been translated to costs charged by the USACE Aviation Program Management Office (APMO) for properly acquiring and operating UAS within USACE. These fees have evolved and are equated with UAS associated with each flight team. AWR development labor costs have been translated to labor associated with meeting fleet development requirements for USACE users. Note, not all the UAS referenced in this analysis here are still operable under USACE UAS regulations; however, they have still been included to provide examples of different UAS types, as similar UAS with encrypted communications links and other security updates may correlate to UAS used in Duck.

5.2.3 Software procurement and training

In addition to the UAS and instruments themselves, any USACE UAS team requires the appropriate software. Among the USACE UAS CoP, Agisoft PhotoScan¹ and Pix4Dmapper are frequently utilized platforms within USACE, with permanent licenses costing approximately \$3,500 and \$5,000 as of the writing of this report. All software packages are capable of producing results within acceptable accuracy value ranges for most survey activities supporting potential Civil Works design and operations activities (Table 2-14 and Table 2-15).

For districts considering the two cheaper options, the Chapter 2 analysis illustrates the relative statistical similarity of PhotoScan and Pix4D processing and aligns with the findings of Gross and Heumann (2016). That study does credit Pix4D with enhanced visual quality. Certain UAS

¹ Note: since this processing, newer versions of Agisoft PhotoScan have been renamed as Agisoft Metashape.

equipped with dual-frequency GPS (L1/L2) may also include software to further improve camera rectification (e.g., PPK via Sensefly eBee eMotion software). Positional survey data may also make use of the National Geodetic Survey (NGS), Online Positioning User Service (OPUS), which aligns positions with the National Spatial Reference System, thereby improving spatial position accuracy. Working with these additional spatial considerations may demand additional labor time, though NGS does provide trainings at no cost related to OPUS. These requirements may also influence the training required for USACE UAS operation.

Software managing the UAS position information is even more critical to UAS instrumented with lidar, as it is critical to processing their returns and aligning the point clouds in space and filtering noise. Both lidar-equipped UAS discussed in this chapter utilize Applanix POSPac software to georeference the UAS trajectory before importing the paths into software suites for post-processing of the results and refinement of lidar point clouds and export of .las files. LeWinter et al. (2018) provide an overview of collection and a walkthrough of general processing for this type of system of topographic lidar data for the subaerial portion of a jetty. These software packages, RiPROCESS and SpatialFuser, were both included with the RiCOPTER and Skycrane lidar systems, respectively. Therefore, the packages do not contribute to additional post-processing software costs. The POSPac software for georeferencing returns was also included but does require annual updates at over \$3,000 per year.

While processing can be learned through trial-and-error and nominal experience, achieving ideal processing results in SfM software suites may involve complex, non-intuitive steps. Within USACE, internal training through colleagues and the UAS CoP has provided software training and approaches that can guide most standard SfM analyses through approximately 4–8 hr of instruction. As suggested by more advanced hardware, lidar processing may demand further levels of training in addition to further experience. The ERDC Environmental Laboratory personnel in charge of analyzing Skycrane data received 40 hr of associated training with the lidar and its processing suite. Once point clouds are generated, they may be exported to a number of other typical programs for further analysis or data exploration (e.g., ArcGIS, Microstation, or MATLAB).

5.2.4 Additional operational equipment

While ground control was set up and provided for the 2017 Duck Pilot UAS experiment (Bruder et al. 2018), GCP deployment currently remains an important aspect of UAS operations. In most cases, ground stations and control demand certain survey equipment. These costs generally consist of GNSS receivers or base stations and associated networks to survey ground control and/or UAS operations stations. Additional GCPs can range from ~\$15 painted PVC targets to \$600/target self-surveying Aeropoints. Field laptops also are usually required for mission planning and/or flight operational monitoring for the vast majority of UAS. For UAS discussed in this chapter, UAS operating teams consistently cited these resource costs as ranging between \$25,000 and \$35,000 in total (Table 5-3). However, some of these items are standard equipment for USACE survey teams (e.g., Trimble R10 unit or laptops) and may already be available to the team at little to no cost to the UAS operator.

Table 5-3. Estimation of minimum overall establishment costs for procurement of a UAS and associated operation. Costs and labor DO NOT include burdens, administrative costs of purchasing, etc. Instrumented UAS platform costs were rounded to the next greatest \$5,000 increment to allow instrumentation package upgrades or even future security adjustments. For ease, labor overhead rates were considered at \$50/hr. FW refers to *fixed-wing*. VTOL refers to *vertical take off and landing*.

	Lidar multicopter			RTK-FW		RTK-FW-VTOL	FW	Quadcopters
	RICOPTER	Skycrane	eBeeRTK	Cumulus	FireFLY6PRO	eBee	Phantom4 Pro	Solo
FAA Exam Fee (x2)	\$300							
Practice/Cert Exam Labor (x2)	\$800							
Training Cost	\$5,000	\$7,000	Free w/ purchase	Free w/ purchase	\$6,000	Free w/ purchase	In-house	In-house
Training Labor (x2)	\$1,600	\$1,600	\$800	\$400	\$1,600	\$800	\$400	\$400
Instrumented UAS Price	\$345,000	\$250,000	\$45,000	\$25,000	\$15,000	\$15,000	\$5,000	\$5,000
AWR Prep Labor	\$2,000	\$400	\$400	\$400	\$400	\$400	\$400	\$400
AWR AED Reimbursable (per UAS)	← \$5,000 →							
Additional Software	\$0	\$0	\$5,000	\$5,000	\$5,000	\$5,000	\$5,000	\$5,000
Addit. Software Training Labor (x2)	\$4,000	\$4,000	\$3,200	\$3,200	\$1,600	\$1,600	\$1,600	\$1,600
Operational Equipment	\$25,000	\$30,000	\$30,000	\$30,000	\$35,000	\$30,000	\$35,000	\$35,000
Total UAS Capability Establishment	\$388,700	\$299,100	\$90,500	\$70,100	\$64,700	\$58,900	\$53,500	\$53,500
Per Flight UAS Sunk Cost*	\$7,774	\$5,982	\$1,810	\$1,402	\$1,294	\$1,178	\$1,070	\$1,070

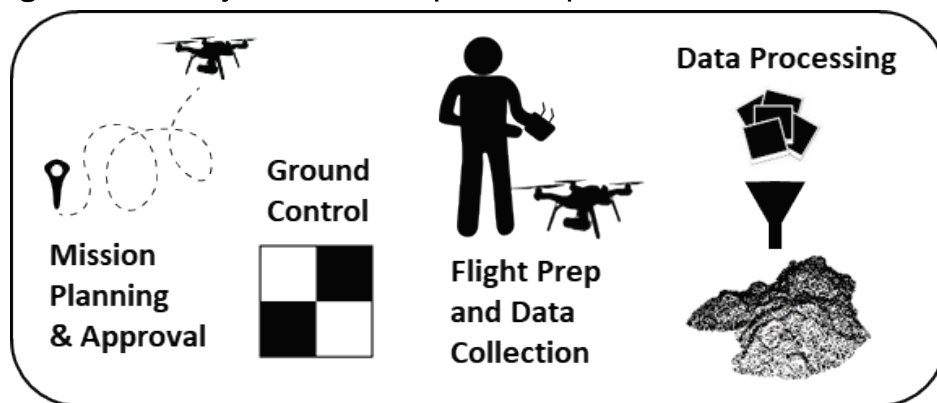
*Per flight cost assuming an average of 10 missions per year for a 5 year platform lifespan

**All costs are reported estimates of minimum unburdened costs of setting up operation of a UAS platform with 2 trained pilots @ OH rate of \$50/hr

5.3 Data collection costs

Bruder et al. (2018) and Chapters 2 through 4 provide numerous details on the collection and processing of UAS data from the pilot 2017 Duck UAS Support to Coastal Management Experiment. To better inform cost-benefit considerations, the following Section 5.3 subsections attempt to extend the general costs of collection with these UAS to typical USACE costs associated with UAS coastal mapping (Figure 5-2). UAS surveys informing these estimates have generally been R&D in nature; however, actual data collection and processing costs may vary significantly. As with any other survey type, travel and equipment transport demand additional resources as well; those are considered to be similar to other traditional survey efforts and therefore have not been considered here.

Figure 5-2. Primary USACE data acquisition aspects to consider in overall cost.



5.3.1 Mission planning

Prior to any deployment, USACE regulations require that an aviation mission plan be submitted, as characterized in EC 1110-1-109 (DoA 2018) and subsequent policy updates. This work requires the Pilot in Charge (PIC) or Aviation Mission Planner to become familiar with the survey area's terrain and airspace and assess risk to the flight crew and others as well as necessary steps to mitigate such risk. The plan is reviewed by the MBO for completeness and authorization prior to the mission approval authority level corresponding with the level of risk (as of this report, currently up to the USACE Aviation Program). In the case where ideal flight lines conflict with other classified airspace (often near airports), further coordination with the FAA may be required. USACE teams report that typical flight plan development requires 4 hr. Following operations an additional hour is generally required to confirm mission approval by USACE APMO. Once approved, flight teams may review the targeted

survey terrain and plan the exact flight lines (those that are programmed into the UAS and account for the latest conditions) and ground control for approximately 2 to 3 hr the day before a mission as well as on the ground the day of.

5.3.2 Data collection

Once approved, most flights generally require a team of two for UAS operations reported here as, the Pilot in Command (PIC) and the VO; some more complicated missions or CONOPS (e.g., missions in more heavily trafficked areas or involving larger UAS with greater safety risk associated with a crash UAS, may require a crew of three). UAS data collection often consists of ground control deployment, any final mission and flight planning modifications, pre-flight checks and base-station establishment prior to each flight, UAS flights, downloads of data (and geotagging of imagery if needed) from the UAS, transition between take-off areas, and ground control collection (as required) (Figure 5-2). As expected, target coastal survey area size is a driver in the required labor (and therefore cost) to UAS operations. Larger areas require additional flights, flight planning, preparation, and significantly more ground control. As explained previously and in Bruder et al. (2018), ground control was already established for the 2017 Duck Experiment. In real-world deployments USACE UAS teams have reported requiring 3 hr of survey time for larger stretches of coastline. RTK-GPS or PPK-based solutions can eliminate some of these considerations, as long as the base station has adequate time (sensor and threshold dependent) to secure its precise position and communicate the exact position to the UAS in real time and/or collect enough information to inform post processing of the position information. While GCPs currently are integral to achieving the maximum accuracy for many COTS UAS, the potential for any UAS to effectively capture data without them may lead to significant savings.

Once at the coastal survey site and ground control is deployed, several factors may affect data collection rates, especially maximum flight time, and the maintenance of visual line of sight (VLOS). 14 CFR § 107.31 (Title 14 Code of Federal Regulations 2017) authorizes pilots to operate their UAS only within VLOS. As VLOS distance has generally been reported as 1 – 2 km by USACE PICs, the range in flight area for UAS teams in one flight has generally been between 1 and 13.5 km² for square canvas-type flights, or 2 to 4 km² linear coastal corridor-type flights (with maximum coverage dependent on altitude and camera field of view). Therefore, ease of UAS

deployment and redeployment must be considered for those applications where significant amounts of ground must be covered. Moving flight ground control stations with more complicated UAS may demand a minimum of 15 to 30 min to move and reestablish the control center (accuracy generally improves with longer time on the station). A simpler UAS (e.g., a 3DR Solo or DJI Phantom) may be quickly launched back into the air with minimal downtime.

UAS flight duration can be a significant factor for data collection. During the 2017 Duck Experiment, the maximum area was under 1 km², and the corresponding longest flight was under 45 min (Bruder et al. 2018). Many teams canvassing the whole property surveyed the north or south half of the property rather than surveying the entire property in one flight. The limited flight time of certain quadcopters, such as the 3DR Solo or the Multirotor G4 Skycrane, would require multiple flights to cover the same area that can be covered by the eBee or FireFLY6 PRO.

As documented in Chapter 2 – 4 and Bruder et al. (2018), the vast majority of flights during the experiment operated between 50 and 120 m altitude. UAS capable of providing high-resolution data from high altitudes could theoretically reduce collection times as well as the number of flight lines, but Part 107 (Title 14 Code of Federal Regulations 2017) limits UAS flight altitudes to 400 ft (121.9 m) AGL, and once again, PICs must maintain VLOS (14 CFR § 107.51, § 107.53 2017). While these regulatory constraints increase flight time for UAS capable of supporting high-resolution data from higher altitude flights on any given survey area, through time they may also reduce costs by demanding fewer batteries for any given missions and reducing battery replacement costs through time.

Overall, imagery or lidar covering the FRF property was generally covered by any given airframe within 2 hr by any team (multiple flights were flown for further evaluation purposes and are documented in Bruder et al. [2018]). Operational deployments with similar UAS reported in literature or by USACE UAS operators have reported coastal surveys taking approximately half a day for smaller areas (>1 km² area or 2 km alongshore) (Seymour et al. 2018; Brodie et al. 2019a), but for extended areas (5 to 10 km long by a few hundred meters wide), USACE UAS teams have reported typical UAS coastal data collections taking closer to 8 hr on site. As reported at the beginning of this section, GCP deployment can increase labor costs. At the same time, collection of adequate data without

GCPs requires more complex instrumentation and expertise. If a CORS network station is not available, UAS not utilizing GCPs at all may demand at least 2 hr for a base station to survey itself adequately (e.g., the RiCOPTER) to support enhanced accuracy of OPUS-provided National Spatial Reference System positions (OPUS 2018).

5.4 Processing costs

As noted in Section 5.2.3, most costs of available UAS SfM processing software options fall into a similar price range whereas lidar processing software was included with the purchase of lidar-based UAS. Processing labor requirements and turnaround time generally increase with the relative complexity of the instrumentation as much as the processing software itself. The two lidar-equipped UAS deployed in the experiment, the Riegl RiCOPTER and Multirotor G4 Skycrane, respectively required 1 to 3 days of processing per mission for an area similar to the FRF property (0.7 km²). A larger area collect might require significantly more (estimated at 4 to 8 times the collection times). These times encapsulate the complexity of lidar point cloud geo-referencing and processing (Section 5.2.3).

The turnaround time for UAS data processed with the two most common SfM programs, Agisoft PhotoScan and Pix4D, is dependent on the size and richness (i.e., number of images) of the dataset. As described in previous chapters, the general processing SfM workflow requires importing and aligning the imagery, importing GCP information, tagging the GCPs in photographs, gradually refining, adjusting, and optimizing the point cloud, and generating a DSM. The software processing times are heavily dependent on the computer processing power (e.g., processor, RAM, and graphics card) and is therefore variable, but also depends on the quality of point clouds desired.

For example, in Agisoft PhotoScan these options can range from “Lowest” to “Ultra High.” An exemplary difference in processing times of eBeeRTK/S.O.D.A. data of the FRF property was provided in association with Chapter 2 analysis performed on an ASUS GL702V laptop with an Intel i7-7700HQ CPU@ 2.80 GHz (four cores), 32 GB memory, an NVIDIA GeForce GTX 1080 graphics card, and 64-bit OS. Whereas processing the data at “Lowest” required just over 1 hr in processing time, processing the data at “High” took over 4 hr. On this machine for this data case, Ultra-High ran for over 24 hr prior to crashing. The Chapter 3 analysis of blocks did generate higher accuracy values with Ultra-High but

required running 8–10 hr for an area of only 0.02 km² on a 2 GHz processor with 16 GB RAM. As detailed in Table 2.10, these point cloud quality values and extra processing time did lead to significantly lower GSD values within the generated DEMs for the FRF property, and “High” processing led to vertical accuracy values under half of those produced under “Lowest” and 10% lower than “Medium.” PIX4D guidance¹ discusses similar constraints for processing, reporting “Lw” point density as processing four times faster than “Optimal” point density as well.

Data preparation prior to SfM processing may also be a consideration. Even though the UAS might be cheaper to acquire, the need to properly extract frames from video data may actually increase costs associated with each data collect. The SfM processing time estimates did not include the marking of GCPs as they had been completed previously. For analysis of the entire FRF property, GCP selection within SfM software was estimated as having taken up to 1–2 min per GCP. RTK-GPS tagged images may improve this processing, but results still generally improve with GCP incorporation. The SfM software packages can proceed without GCPs; however, properly scaled and georeferenced point clouds cannot be developed unless additional GPS data for each image are incorporated into processing. RTK/PPK-enabled UAS can remove the additional step of tagging GCPs but may require some additional time and expertise to download OPUS results and ensure that images are properly geotagged for accurate processing.

Overall, in an ideal, efficient processing workflow, SfM could require closer to 4 hr if the processing steps were immediately started back-to-back or lower-quality accuracy is acceptable (this time requirement of course likely to decrease with increased computing power, particularly powerful graphics processing units). As processing may not always proceed perfectly the first iteration, additional work is generally required, including adequate quality assurance/quality control. UAS teams using Agisoft have reported on average requiring 8–16 hr of turnaround time per survey. These times assume only point cloud and DSM generation and do not include advanced processes like bare ground classification.

¹ Pix4D online guidance at <https://support.pix4d.com/hc/en-us/articles/204191535> and <https://support.pix4d.com/hc/en-us/articles/202557799#label1>.

5.5 Overall UAS operating costs

To assess the benefits relative to cost in the next section, this segment briefly summarizes the overall costs broadly summarized in Sections 5.2–5.4 in the forms of Table 5-4. These reported cost estimates are informed by *typical* ERDC missions and are by no means exact or inclusive, especially given the continual evolution of the technologies involved. They attempt to provide relative estimates for informing potential USACE UAS operations as experienced by ERDC R&D operations with these UAS at the Duck experiment and other deployments. Smaller, simpler AOIs may consider significantly less collection and processing time.

Table 5-4. General estimates of UAS operating costs for a typical mission area. Labor rates were considered at a base rate of \$50/hr. eBeeRTK includes cost with and without GCPs. Cumulus and FireFLY6PRO would have similar \$300 decreases in cost if no GCPs were used.

Est. Data Collection for Multi-Km ² AOI	Lidar multicopter		RTK-FW		RTK-FW-VTOL	FW	Quadcopters	
	RICOPTER	Skycrane	eBeeRTK	Cumulus	FireFLY6PRO	eBee	phantom4 Pro	Solo
Mission Plan/Approval/Prep Work	\$700							
GCP Deploy/Collect Labor (x2)	\$0	\$0	\$0	\$300	\$300*	\$300	\$300	\$300
Flight Prep/Collection on Site Labor (x2)	\$800	\$800	\$500	\$500	\$500	\$500	\$600	\$500
Processing Labor	\$2,000	\$1,600	\$700	\$800	\$800*	\$800	\$900	\$800
TOTAL COLLECT ESTIMATE	\$3,500	\$3,100	\$1,900	\$2,300	\$2300*	\$2,300	\$2,500	\$2,300
TOTAL INCLUSIVE COST PER FLIGHT	\$11,274	\$9,082	\$3,710	\$4,110	\$3702*	\$3,478	\$3,570	\$3,370

*Per flight cost assuming an average of 10 missions per year for a 5 year platform lifespan

**All costs are reported estimates of minimum unburdened costs of setting up operation of a UAS platform with 2 trained pilots @ OH rate of \$50/hr

5.6 Cost-benefit by application

The relative accuracy of different UAS have been thoroughly explored through the preceding four chapters of this report. The following sections briefly tie several of these accuracy assessments to the approximate costs of collecting and processing data. While other considerations may inform UAS acquisition (Section 5.7), price and data quality are the two most critical factors that inform UAS selection. Although additional UAS were assessed within each chapter, the comparisons continue to refer only to a representative handful of UAS that USACE-ERDC teams have operational knowledge of, as of the writing of this report. As noted in Section 5.2.2, procurement prices for UAS and instrumentation were rounded and can vary depending on the year acquired and purchaser; therefore, any trends apparent due to small differences in cost must be considered with some appreciation for the cost estimates used above. UAS and technology

continue to evolve over time with technological advancements and USACE policy constraints (e.g., updated security), but these assessments exemplify the relative differences in UAS while also illustrating the proven effectiveness or baseline to evaluate next-generation UAS against.

5.6.1 Overall coastal terrain

Chapter 2 documents multiple assessments of UAS data across the entirety of the FRF property. Chapter 2, Figure 5-3–Figure 5-5 and Figure 5-8 illustrate that despite differences in relative accuracy, the selected UAS were able to deliver results with horizontal/vertical RMSE values required for numerous coastal USACE Civil Works Design, Construction, Operations, and Maintenance Activities (Tables 2-4 and 2-5). These applications include surveys informing project condition reports (240 cm/20 cm, respectively) or beach nourishment/hurricane protection (240 cm/20 cm), general planning and feasibility studies (120 cm/50 cm), flood control and multipurpose project planning (240 cm/20 cm), or FEMA Flood Insurance Studies (240 cm/20 cm) (Tables 2-4 and 2-5). As detailed in Chapter 2, these thresholds were met for multiple datasets processed with Agisoft PhotoScan, Bentley ContextCapture, and Pix4D Pix4Dmapper.

5.6.1.1 Relative GCP-aided accuracy against UAS cost

Trends varied by software, but of UAS compared for terrain assessment, data collected by the eBee RTK UAS with the S.O.D.A camera (the most expensive cost per flight) generally provided the most accurate point survey data. Vertical accuracy of data processed with Agisoft PhotoScan generally improved with increased UAS cost; however, this trend was not necessarily as clear for data processed with Pix4D or Context Capture.

RMSEr values improved regardless of software as UAS cost increased for the top-three most expensive UAS, but the eBee/S110 UAS (the estimated least expensive UAS to set up and operate within this selection of UAS) had the lowest RMSEr for overall coastal terrain (Figure 5-3). This performance was achieved despite the advantage of RTK-GPS capabilities available to the other UAS.

Figure 5-3. Comparison of vertical RMSE against approximate cost per flight for selected UAS data for entire UAS property processed using GCPs.

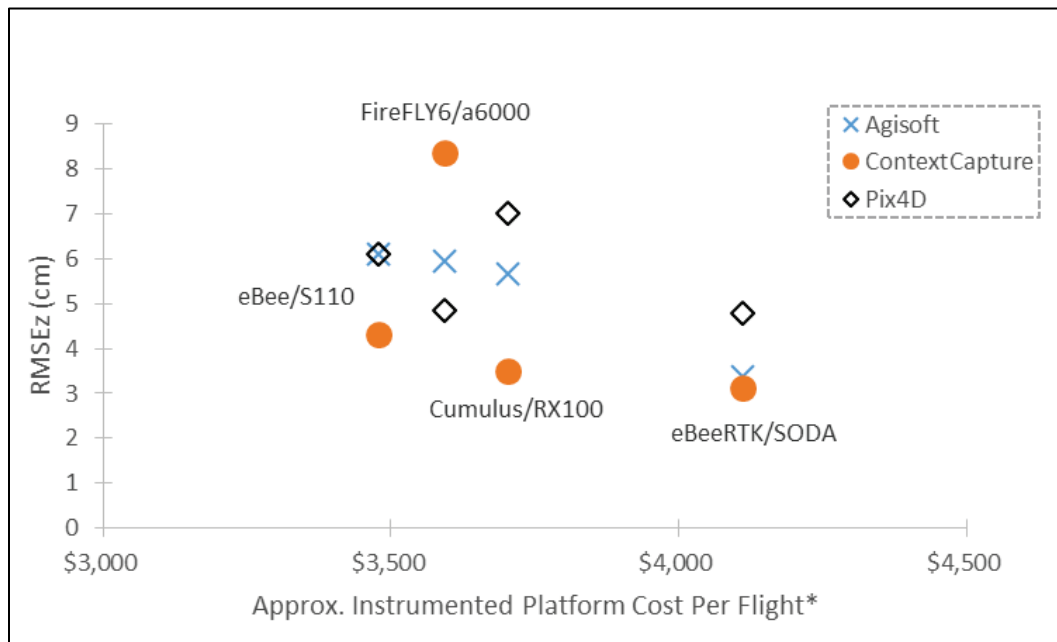
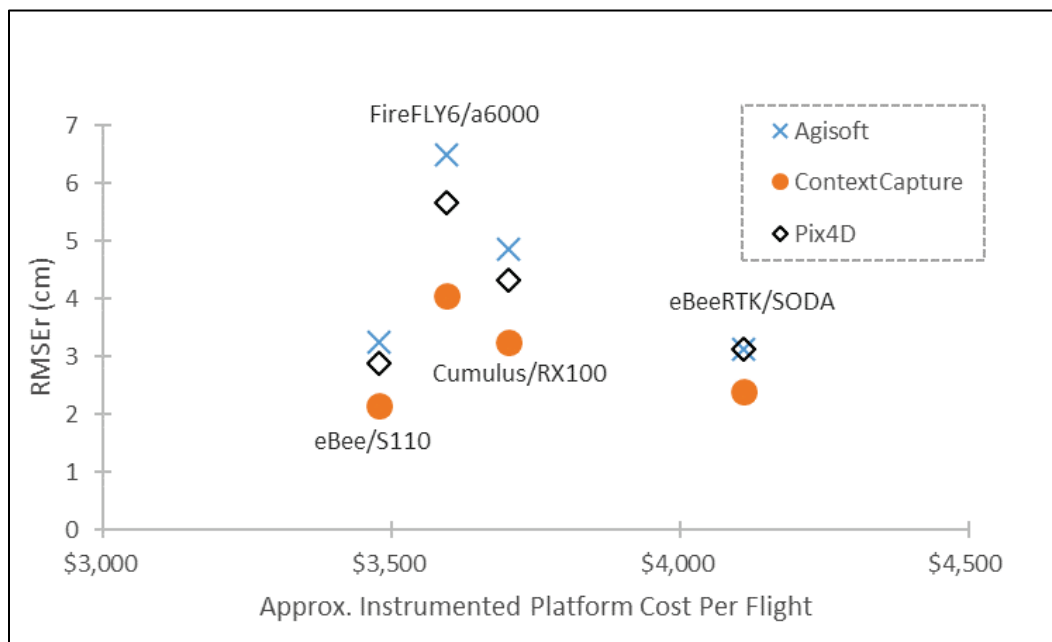


Figure 5-3 and Figure 5-4 show the Chapter 2 overall results that with basic processing workflows, Bentley ContextCapture does generate data with higher level of accuracy for more cases than Agisoft PhotoScan and Pix4D's Pix4Dmapper. As referenced in Section 5.2.3, PhotoScan and Pix4Dmapper have a similar one-time purchase cost. ContextCapture costs twice that amount on an annual basis, which means that improved accuracy comes at a cost 5 to 10 times the cost of the other two software packages over the course of 5 yr. Chapter 2 notes that basic approaches were used with the software processing of the UAS data. Advanced adjustments of processing approaches may also be used to further improve point cloud generations and overall DSM accuracies.

Figure 5-4. Comparison of horizontal RMSE against approximate cost per flight for selected UAS data for entire FRF property processed with GCPs.



5.6.1.2 Cost-benefit of reduced or no GCPs

The Chapter 2 results (Table 2-9) reinforce the importance of dedicating time towards deploying adequate ground control. Decreasing the number of GCPs used in UAS processing decreases the accuracy of the final data product. While horizontal RMSE maintained values within acceptable USACE photogrammetric accuracy standards, the reduction increased RMSEz values beyond acceptable limits. While these data result from one UAS, the data caution against any argument for saving time by utilizing only a handful of ground control targets and support the need for further review.

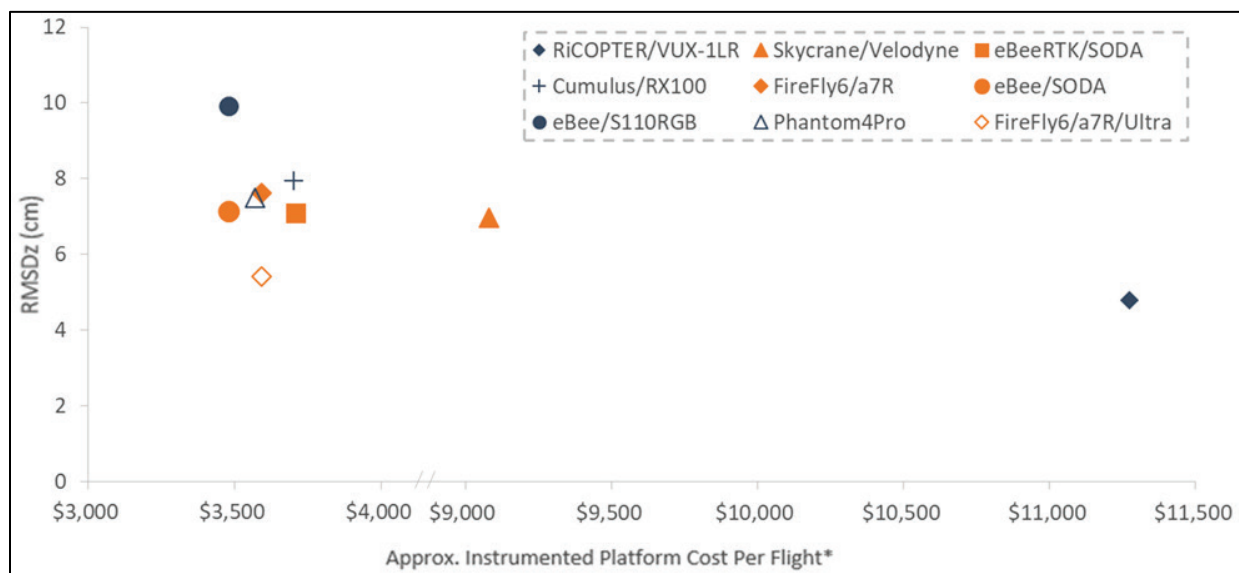
As deploying a full suite of GCPs is often difficult in certain coastal terrain, there is benefit to be gained by reducing dependence on the need for GCPs. The Chapter 2 presentation of the similarity in accuracy between PPK and GCP processing of eBeeRTK/S.O.D.A. data suggests that the RTK/PPK capability could justify the initial difference in UAS costs when compared against the GCP deployment cost per collect. As shown in Table 2-12, PPK-based processing provided better vertical accuracy than the GCP-based processing while maintaining similar horizontal RMSE values as the GCP-processed eBeeRTK data. This data collection approach would thereby provide the most accurate data at a cost similar to the other UAS summarized in Figure 5-3.

5.6.2 Detailed feature characterization

Whereas Chapter 2 allows for assessing accuracy of UAS data for coastal terrain in general, the Chapter 3 analysis of the experiment's IA features allows for consideration of the costs of fine-scale data collection at Duck 2017 experiment altitudes. All the UAS assessed in Chapter 3 met accuracy requirements of 20 cm specified for many coastal planning, design, and monitoring purposes when processed with Agisoft or lidar scanner specific software. Note that they do not meet the strict accuracy limits for certain purposes (e.g., the 1 cm error limit required of construction deformation studies).

Of the UAS considered in this chapter, a basic assessment shows that UAS with higher overall purchase and/or operational costs did generate data products with lower RMSDz values, with the Riegl RiCOPTER providing the lowest overall vertical error values (Figure 5-5). The principal exception to this overall trend was for the data processed using the "Ultra High" option in Agisoft, which decreased mean RMSDz by over 2 cm. As noted in Chapter 3, this "Ultra High" setting demanded more than twice the processing time than Agisoft's "High" setting, despite the limited size of the processed AOI. Note also that the RiCOPTER, Skycrane, and eBeeRTK S.O.D.A. data here did not rely on GCP processing.

Figure 5-5. Comparison of RMSDz values against approximate cost per flight for selected UAS data for the block volumes in the IA (Chapter 3).



As shown in Chapter 3, the lidar-equipped UAS did provide more accurate volumes of several blocks as well, but the FireFLY6PRO equipped with the Sony a7R generated the least average difference between UAS data-informed block volumes and the blocks' true volumes of those point clouds generated via SfM (Figure 5-6). The DJI Phantom PRO 4 also outperformed a number of UAS with similar costs and matched the block estimates. Figure 5-7 suggests that the FireFLY6PRO processed on Ultra High provides a higher density point cloud overall. The lidar-equipped UAS point clouds do provide limited point density on these small block features given their additional costs. Each of these points is a direct measurement, unlike the SfM-generated point clouds. The methodology in Chapter 3 explains how some of these volume differences may have appeared despite better capture of true block form (Figure 3-4).

Figure 5-6. Comparison of cumulative difference between volume of actual blocks and point-cloud calculated volume against approximate cost per flight for selected UAS data for the blocks in the infrastructure area (Chapter 3).

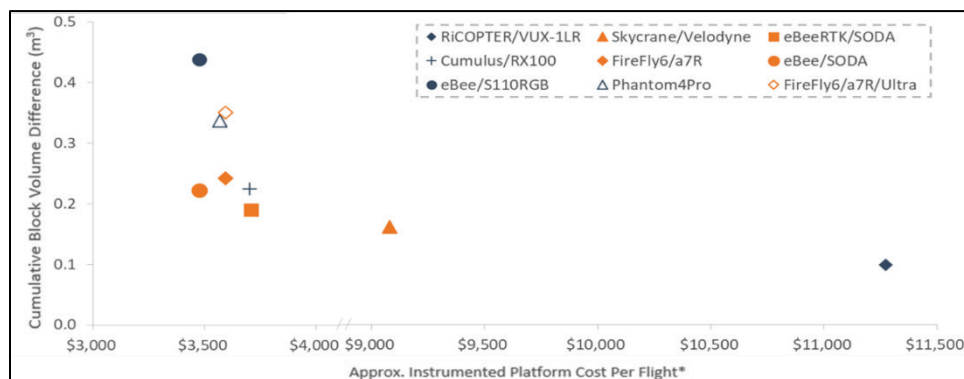
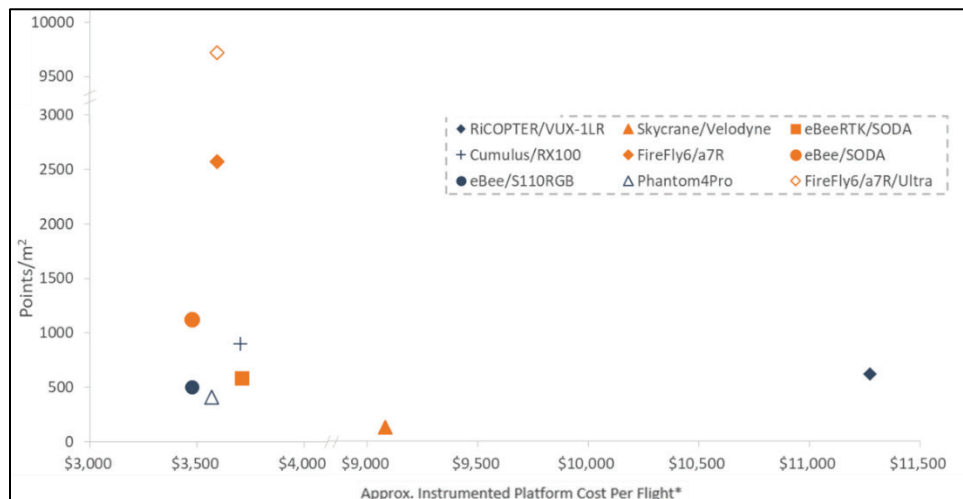


Figure 5-7. Comparison of point cloud points/m² volume against approximate cost per flight for selected UAS data for the blocks in the infrastructure area (Chapter 3).

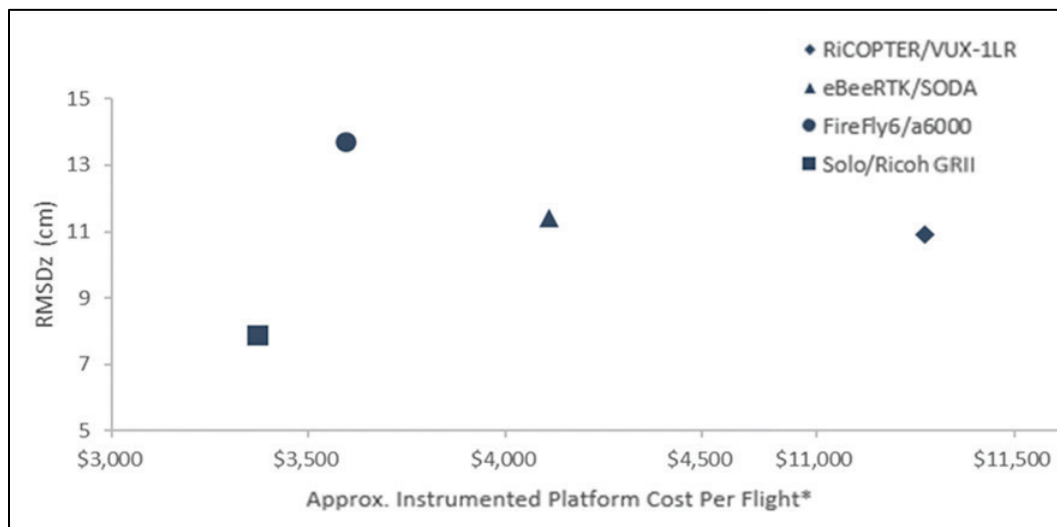


5.6.3 Dune costs and benefits

As detailed in Chapter 4, RMSDz values calculated against dune control data show that all UAS-based generated point clouds met the accuracy requirements for numerous coastal Civil Works design, operations, and maintenance activities summarized in Table 2-15. Figure 5-8 illustrates that better data accuracy correlated with higher UAS operational cost on steeper north property foredunes, with one major exception. The data collected by the Ricoh-equipped 3DR Solo actually provided the most accurate point cloud for the dunes, despite its lower deployment cost.

As explored in Chapter 4, the unique angles and vegetation along dunes could have affected performance, especially given the oblique mount of the Ricoh GR11 camera, which may have improved performance along an angled slope relative to instrumentation on other UAS. The Ricoh GR11 camera also flew at lower altitude than the other non-lidar UAS.

Figure 5-8. Comparison of RMSDz values for dunes on the FRF property as compared to monitored dune areas.



5.7 Additional cost-benefit considerations

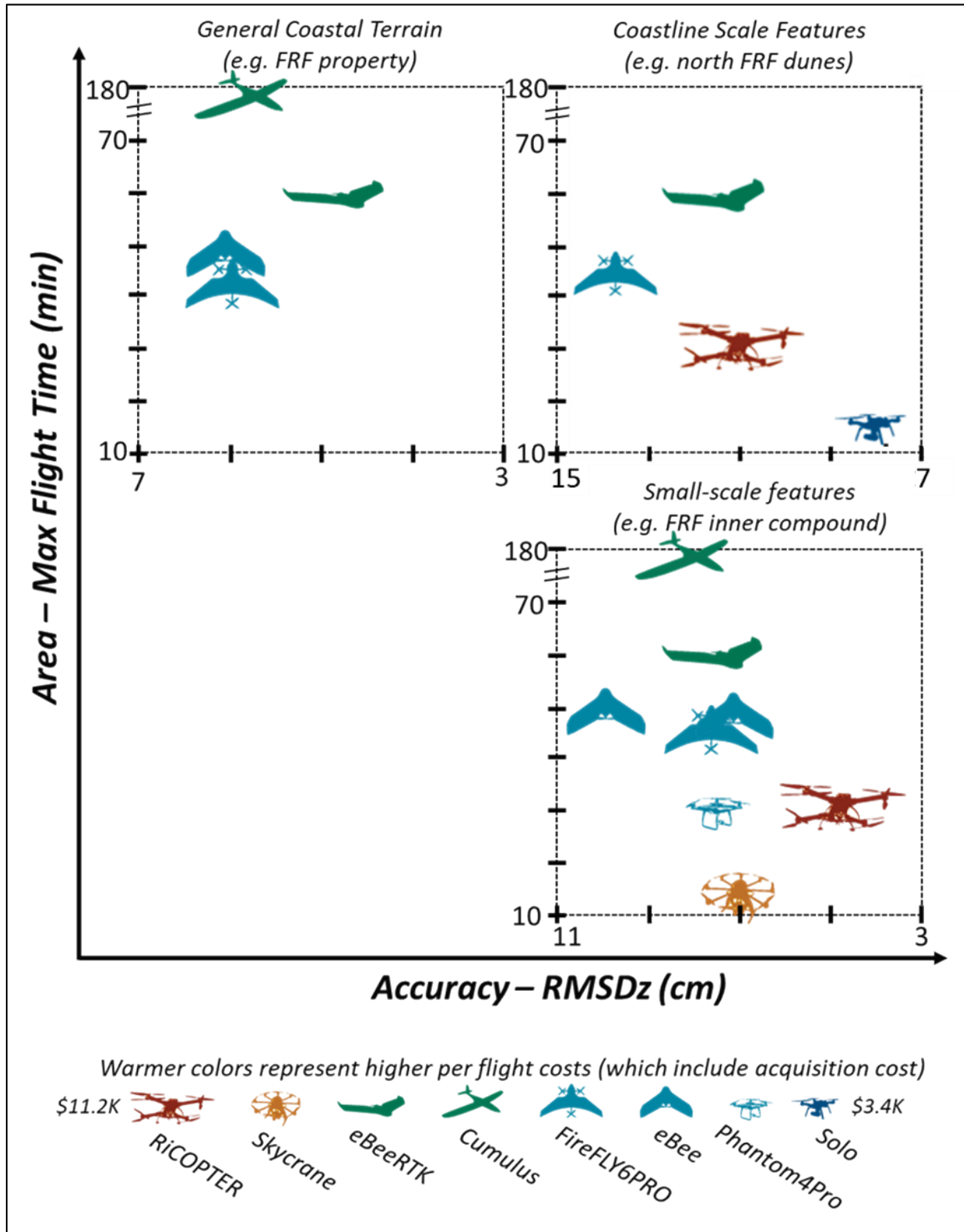
This chapter has shown UAS across a wide range of price points can support a variety of Civil Works activities. Chapters 3 and 4 show that these data can match the accuracy of terrestrial lidar. While there is a general trend towards increased accuracy with increased UAS cost, this trend is by no means absolute within these selected datasets. Given acceptable performance by many UAS, potential USACE UAS operators should consider a number of other factors beyond accuracy and operating

price. The following sub-sections briefly identify other significant factors that may influence selections of UAS beyond cost and accuracy.

Flight Time – UAS have significantly different flight times, as summarized in Bruder et al. (2018). Flight time is a factor that affects survey efficiency, as UAS that stay longer in the air require fewer flights to survey any given area. By requiring less time in takeoffs and landings, the UAS may therefore be able to cover more ground in any given day. For example, the RiCOPTER and G4 Skycrane both provide UAS lidar, but the RiCOPTER provides twice the flight time. The same might be argued for imagery data collected from FW UAS relative to more traditional COTS quadcopters. Greater flight times may also facilitate coverage of greater areas of coastline (such as Federal Beach Projects). These benefits are still constrained at some level however, as line-of-sight (LOS) requirements will demand numerous take offs and landings than otherwise necessary. Figure 5-9 attempts to integrate flight time with the accuracy and cost considerations examined in previous sections, with the assumption that extended flight times allow for more area to be covered.

Extended flight time may reduce the number of complications associated with each additional takeoff and landing, such as the failure of video links or a human error associated with each pre-flight check list. When combined with RTK/PPK capabilities, extended flight time may also support survey patterns that provide more diversity of look angles to improve accuracy in more complex coastal terrain or structures where GCPs cannot be deployed. If no known CORS network station is available near the AOI, UAS relying on RTK/PPK may require occupying a GPS base station point for at least 2 hr to achieve acceptable positioning data. This demand may limit the team's ability to cover larger coastal areas beyond the range of the UAS and the receiver.

Figure 5-9. Summary comparing maximum flight times of UAS (see Bruder et al. 2018) against selected UAS datasets collected during the 2017 Duck UAS Pilot experiment reported on in this report, as organized by the coastal data collection application used to organize this chapter, general terrain, dunes, and small-scale features/structures. Note: RMSD used as equivalent to Chapter 2 RMSE. Dune eBeeRTK data uses no GCPs.



Versatility – USACE districts attempting to establish UAS capabilities without setting up a full fleet of UAS may consider the versatility of any given UAS they acquire. Fixed-wing UAS may allow for longer flight times and more efficient surveying of larger areas but may face challenges in coastal areas with trees, tall buildings, or other high-elevation features, as turns and take-offs/landings require ensuring avoidance to minimize risk to the UAS, property, or people. Fixed-wing UAS might also prove less efficient in surveying small scale structures, where a multicopter might operate at lower altitudes and angles around the feature. A hybrid FW/VTOL UAS (e.g., FireFLY6 PRO), might provide certain aspects of both.

Instrumentation payload and interchangeability and flexibility should also be considered. The large payloads of the Skycrane and RiCOPTER allow for those UAS to carry imagers alongside lidar scanners. Multiple UAS facilitate exchange of different cameras, allowing for “plug and play” (e.g., eBee, FireFLY6PRO) without rebuilding all the required hardware to properly trigger the different systems. UAS with these capabilities may also facilitate collection of different datasets during the same survey mission (e.g., collects by an RGB camera and infrared camera on a single UAS). Certain UAS (only the Phantom 4 Pro in the case of the UAS compared in this cost-benefit chapter), allow only for operation with the stock camera provided, which limits use to certain USACE missions.

GCP Deployment – As discussed at several points throughout this chapter (e.g., Sections 5.3.2 or 5.6.1), GCPs have traditionally been critical to enhanced accuracy of UAS data, but that dependence may decrease as advances in technology and approaches such as RTK-GPS and PPK lead to increased accuracies. One attraction of UAS-collected data is the ability to survey coastal terrain and structures that are less accessible or sensitive to survey on foot. These survey locations also decrease the potential to deploy GCPs. Thus, in to best take advantage of UAS, platforms that have RTK or PPK onboard should be preferred. UAS without these may prove less accurate for SfM in difficult coastal environments (e.g., extended seaward jetties).

Risk – As demanded by the mission approval process, the operation of any UAS mandates the assumption of some level of operational risk. These risks vary with the UAS. For example, a mishap with a RiCOPTER (just under 25 kg) is likely to cause more damage to USACE resources or surroundings than a mishap with a foam-winged eBee (~1 kg). Therefore,

such UAS might not be tolerated in certain developed environments relative to others. USACE personnel may want to consider this risk when initially establishing a program for any UAS.

As alluded to in the sub-section on versatility, multi-rotor systems may allow enhanced maneuverability in environments that have tall features, more development, or more people in the surrounding area. While no one should be present in a UAS survey area, in the coastal zone the more controlled landing offered by a multi-rotor system might allow for more tolerance of the people in the greater surrounding area. Meanwhile, in the case of an eBee or other FW, the slightly less-controlled landing might lead to a much smaller tolerance of any people nearby, or demand closing the beach or terrain. Experience and training with any of these UAS of course may also contribute to considering the exact level of risk for their operation in certain environments.

Turnaround Time – The PPK data from UAS such as the RiCOPTER, SkyCrane, and eBeeRTK in this report illustrate the potential, saving considerable efforts and resources demanded by ground control. In addition to time spent establishing a known point, PPK processing computed via OPUS may demand additional time to receive the OPUS solution before processing the data. This delay will likely not generally be a concern for most survey efforts. However, users trying to quickly evaluate a project with a smaller area who would like to process on the same day as a collect (perhaps immediately before a storm), may depend on quickly deploying GCPs instead.

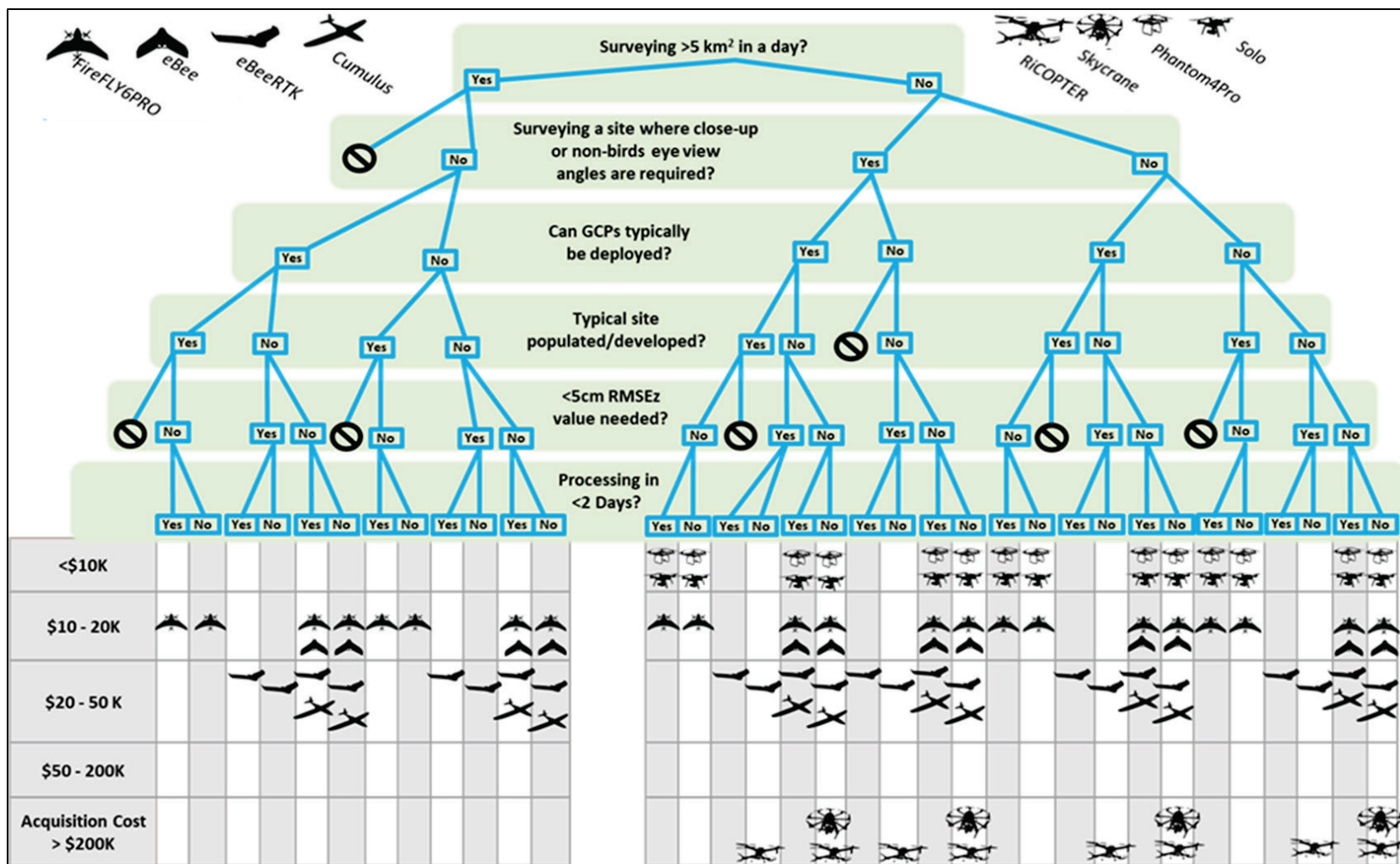
Turnaround time should be evaluated when considering the use of a lidar-equipped UAS. As detailed in prior sections, lidar data may require significant processing time for larger collects. If the additional precision offered by such a UAS is not required, an image-derived SfM-generated point cloud may provide data more quickly.

Decision Tree – Figure 5-10 attempts to model UAS selection based on these additional factors for the UAS examined within this chapter. While UAS technology continues to evolve since the 2017 experiment was conducted, this decision tree illustrates some of the similarities and differences among the UAS involved. While certain UAS appear ideal only under certain combinations, several UAS do appear rather versatile.

To examine these UAS, the tree makes certain assumptions of non-cost, non-accuracy factors. First, in surveying larger areas it assumes that the operator would rather conduct fewer flights by using the efficiency provided by a FW. Second, it assumes that multi-rotor systems might provide additional look angles and may be safer to operate near structures/features in certain environments than FW UAS. Third, it assumes that under given technology, certain GPS antenna/receiver capabilities are required to collect the most accurate surface elevations/positions. Fourth, it assumes that the control provided by VTOL UAS make them safer to land near developed populated areas and that certain heavier UAS (e.g., RiCOPTER or Skycrane) have significantly higher operational risk. Fifth, the previous chapters have illustrated that many of these UAS perform adequately to meet USACE standards for numerous coastal survey applications. Therefore, the fifth question isolates only those UAS with the highest accuracy levels (<5 cm found during the survey). Note that there will always be some differences in absolute accuracy, depending on the UAS, operators, software, and workflows used to collect and process the data. Sixth, the decision tree assumes a longer turnaround time for any larger lidar datasets, relative to datasets derived from SfM-derived point clouds.

While most costs in this chapter have considered the sunk acquisition costs alongside per-flight operation costs, this decision tree considers only acquisition price at the bottom when presenting acceptable options for each decision tree branch. Last, since the 2017 Duck Pilot Experiment, the Army (and Department of Defense [DoD] as a whole) has increased security requirements for UAS use. While not applicable at the time of the experiment, many USACE UAS must now have secure data links and avoid UAS that have components from certain foreign sources. These types of security concerns may affect USACE choice in UAS as well as cost.

Figure 5-10. This example decision tree organizes UAS platforms examined within this chapter against key aspects of different platforms that one might consider when choosing a UAS to utilize/acquire for coastal data collection. The decisions assume some level of assuming risk and typical experiences of the authors' UAS operations. Note: the bottom of the tree examines acquisition price rather than per-flight cost, as funds available at the time of purchase may well affect the choice made when choosing a platform.



6 Conclusion

The preceding five chapters analyzed data from the 2017 Duck Pilot UAS experiment to examine the potential of different UAS to characterize coastal terrain and infrastructure at levels required by USACE for coastal management and flood risk management. By leveraging the interests of UAS teams with different UAS platforms and objectives, ERDC was able to cost-effectively collect and compare these data without any one research group having to acquire, train, and collect all the data themselves. This examination informed the research of work units designed to assess UAS Support to Flood Risk Management and UAS Support to Coastal Management by evaluating existing UAS standard operating procedures, sensors, and data processing approaches to identify tools for monitoring coastal terrain and infrastructure.

The majority of UAS evaluated under the CONOPS utilized in the Duck experiment generated data that meet accuracy standards for numerous USACE Civil Works activities, detects small-scale features and their displacement, and that is sufficient to characterize coastal dunes. With the exception of UAS equipped with lidar scanners, the cost to deploy many of these UAS fall within similar price ranges when considered on a per-flight basis. USACE district UAS selection therefore may depend on the impact of additional factors summarized in the previous section.

While UAS technology and platforms are evolving quickly, lessons learned from this study illustrate that UAS may be acquired at a variety of cost points to satisfy varying levels of accuracy. Security concerns affecting UAS use by the DoD have also increasingly played a role in UAS choice and applications. While USACE might not procure the exact UAS examined in this report in the future, the consideration of a range of UAS types here allows assessment of likely differences among available UAS. Even as the UAS and CONOPS evolve, certain elements of UAS operation will remain the same as long as the majority of associated policy constraints do. This report identifies many of the costs of regulations managing UAS operations (e.g., LOS limits or flight altitude ceilings).

Anticipated UAS advancements will improve UAS data quality and decrease the cost of obtaining data relevant to coastal management.

Development of camera and lidar technology may enhance data resolution and reduce errors associated with the movement of UAS during data acquisition. While this report calls attention to some of the costs associated with GCP distribution, it also illustrates that under ideal conditions, UAS equipped for RTK and PPK georeferencing can eliminate this requirement by providing data that is comparable to DEMs generated using GCPs. This capability will be especially beneficial for coastal terrain and infrastructure that is dangerous, sensitive, or physically inaccessible. Development in UAS autonomy may also improve efficiency by reducing survey time via UAS swarming capabilities or flying multiple self- and team-aware UAS at the same time.

ERDC is also currently expanding the capability of UAS to collect data to inversely calculate bathymetry in the nearshore zone, thereby enabling the continuity of topographical and bathymetric data where current technologies face limitations. Finally, by exploring technology to archive and develop algorithms to assimilate all this information, UAS should be able to better support USACE ability to forecast change and risk in the coastal zone. In the meantime, this report will inform USACE adoption of UAS capabilities until the next generation of technology fully arrives.

References

- Agisoft. 2018. *Photoscan Professional* (Version 1.2.6).
<http://www.agisoft.com/downloads/installer/>.
- Agüera-Vega, F., F. Carvajal-Ramírez, and P. Martínez-Carricondo. 2017. "Assessment of Photogrammetric Mapping Accuracy Based on Variation Ground Control Points Number Using Unmanned Aerial Vehicle." *Measurement* 98 (February 2017): 221–227.
- Birkemeier, W., R. Dolan, and N. Fisher. 1984. "The Evolution of a Barrier Island: 1930–1980." *Shore and Beach* 52(2): 3–12.
- Birkemeier, W., H. Miller, S. Wilhelm, A. DeWall, and C. Gorbics. 1985. *A User's Guide to the Coastal Engineering Research Center's (CERC's) Field Research Facility*. Instruction Report CERC-85-1. Vicksburg, MS: US Army Engineer Waterways Experiment Station.
- Bridges, T. S., K. A. Burks-Copes, M. E. Bates, Z. A. Collier, J. C. Fischenich, C. D. Piercy, E. J. Russo, D. J. Shafer, B. C. Suedel, J. Z. Gailani, and J. D. Rosati. 2015. *Use of Natural and Nature-Based Features (NNBF) for Coastal Resilience*. ERDC SR-15-1. Vicksburg, MS: US Army Engineer Research and Development Center.
- Brock, J. C., C. W. Wright, A. H. Sallenger, W. B. Krabill, and R. N. Swift. 2002. "Basis and Methods of NASA Airborne Topographic Mapper Lidar Surveys for Coastal Studies." *Journal of Coastal Research* 18(1): 1–13.
- Brodie, K. L., N. J. Spore, B. L. Bruder, A. D. Renaud, T. Hesser, V. Wilhelm, and K. Hodgins. 2019a. *Post-Irma Unmanned Aircraft System (UAS) Coastal Storm Impact Surveys*. ERDC/CHL CHETN-IV-116. Vicksburg, MS: US Army Engineer Research and Development Center.
- Brodie, K. L., B. L. Bruder, R. K. Slocum, and N. J. Spore. 2019b. "Simultaneous Mapping of Coastal Topography and Bathymetry from a Lightweight Multicamera UAS." *IEEE Transactions on Geoscience and Remote Sensing* 57(9): 6844–6864.
- Brodie, K., I. Conery, N. Cohn, N. Spore, and M. Palmsten. 2019c. "Spatial Variability of Coastal Foredune Evolution, Part A: Timescales of Months to Years." *Journal of Marine Science and Engineering* 7(5): 124.
- Brodie, K. L., and N. J. Spore. 2015. "Foredune Classification and Storm Response: Automated Analysis of Terrestrial Lidar DEMs." Proceedings, *Coastal Sediments 2015*.
- Bruder, B. L., A. D. Renaud, N. J. Spore, and K. L. Brodie. 2018. *Evaluation of Unmanned Aircraft Systems for Flood Risk Management: Field Experiment Conspectus*. ERDC/CHL SR-18-2. Vicksburg, MS: US Army Engineer Research and Development Center.
- Bryant, D. B., M. A. Bryant, and A. S. Grzegorzewski. 2017. *Erosion of Coastal Foredunes: A Review on the Effect of Dune Vegetation*. ERDC/CHL CHETN-I-94. Vicksburg, MS: US Army Engineer Research and Development Center.

- Campbell, L., and D. Katz. 2019. *How to Use Ground Control in Drone Surveying*. <https://www.pobonline.com/articles/101529-how-to-use-ground-control-in-drone-surveying>.
- Charbonneau, B. R., J. P. Wnek, J. A. Langley, G. Lee, and R. A. Balsamo. 2016. "Above vs. Belowground Plant Biomass along a Barrier Island: Implications for Dune Stabilization." *Journal of Environmental Management* 182: 126–133.
- Conery, I., K. Brodie, N. Spore, and J. Walsh. 2019. "Terrestrial Lidar Monitoring of Coastal Foredune Evolution in Managed and Unmanaged Systems." *Earth Surface Processes and Landforms* 45(40): 877–892.
- Conery, I. W., N. Cohn, N. Spore, and K. L. Brodie. 2020. *Evaluating Collection Parameters for Mobile Lidar Surveys in Vegetated Beach-Dune Settings*. ERDC-CHL CHETN-II-58. Vicksburg, MS: US Army Engineer Research and Development Center.
- Conlin, M., N. Cohn, and P. Ruggiero. 2018. "A Quantitative Comparison of Low-Cost Structure from Motion (SfM) Data Collection Platforms on Beaches and Dunes." *Journal of Coastal Research* 34(6): 1341–1357.
- Dietz, E. M. 2019. *Evaluating the Use of UAS-Derived Imagery for Monitoring Flood Protection Infrastructure*. Master's thesis. Oxford, MS: University of Mississippi.
- Elko, Nicole, Kate Brodie, Hilary Stockdon, Karl Nordstrom, Chris Houser, Kim McKenna, Laura Moore, Julie Rosati, Peter Ruggiero, Roberta Thuman, and Ian Walker. 2016. *Dune Management Challenges on Developed Coasts* 84(1): 15–28.
- FAADroneZone. 2020. *Welcome to the FAADroneZone*. <https://faadronezone.faa.gov/#/>.
- Feygels, V. I., J. Y. Park, J. Wozencraft, J. Aitken, C. Macon, A. Mathur, A. Payment, and V. Ramnath. 2013. "CZMIL (Coastal Zone Mapping and Imaging Lidar): From First Flights to First Mission through System Validation." *Ocean Sensing and Monitoring V* 8724: 87240A. International Society for Optics and Photonics.
- Fischer, R., J. Ruby, A. Armstrong, J. D. Edwards, N. J. Spore, and K. L. Brodie. 2019. *Geospatial Accuracy of Small Unmanned Airborne System Data in the Coastal Environment*. ERDC SR-19-1. Vicksburg, MS: US Army Engineer Research and Development Center.
- Ghorbanidehno, H., J. Lee, M. Farthing, T. Hesser, P. K. Kitanidis, and E. F. Darve. 2019. "Novel Data Assimilation Algorithm for Nearshore Bathymetry." *Journal of Atmospheric and Oceanic Technology* 36(4): 699–715.
- Gillins, M. N., D. T. Gillins, and C. Parrish. 2016. "Cost-Effective Bridge Safety Inspections Using Unmanned Aircraft Systems (UAS)." *Geotechnical and Structural Engineering Congress 2016*: 1931–1940. The American Society of Civil Engineers, Reston, Virginia, 2016.
- Gonçalves, G., U. Andriolo, L. Pinto, and F. Bessa. 2019. "Mapping Marine Litter Using UAS on a Beach-Dune System: A Multidisciplinary Approach." *Science of The Total Environment* 706(1 March 2020).

- Gottfried, M., M. Hollaus, P. Glira, M. Wieser, and M. Milenković. 2015. "First Examples from the RIEGL VUX-SYS for Forestry Applications." *Proceedings of SilviLaser 2015*, 105–107.
- GRASS Development Team. 2012. *Geographic Resources Analysis Support System (GRASS) Software, Version 6.4.2*. Open Source Geospatial Foundation. <http://grass.osgeo.org>.
- Gross, J. W., and B. W. Heumann. 2016. "A Statistical Examination of Image Stitching Software Packages for Use with Unmanned Aerial Systems." *Photogrammetric Engineering & Remote Sensing* 82(6): 419–425.
- Gutierrez, R., J. Gibeaut, R. Smyth, T. Hepner, J. Andrews, C. Weed, W. Gutelius, and M. Mastin. 2001. "Precise Airborne Lidar Surveying for Coastal Research and Geo-Hazards Applications." *International Archives of Photogrammetry Remote Sensing and Spatial Information Sciences* 34(3/W4): 185–194.
- Haala, N. 2013. "Photogrammetric Week '13." *54th Photogrammetric Week, September 9-13, 2013, University of Stuttgart*. Wichmann/VDE Verlag, Belin & Offenbach.
- Hobrough, G. L. 1959. "Automatic Stereo Plotting." *Photogrammetric Engineering* 25(5): 763–769.
- Holman, R. A., K. L. Brodie, and N. J. Spore. 2017. "Surf Zone Characterization Using a Small Quadcopter: Technical Issues and Procedures." *IEEE Transactions on Geoscience and Remote Sensing* 55(4).
- Houser, C., P. Wernette, E. Rentschlar, H. Jones, B. Hammond, and S. Trimble. 2015. "Post-Storm Beach and Dune Recovery: Implications for Barrier Island Resilience." *Geomorphology* 234: 54–63.
- Imahori, G., J. Ferguson, T. Wozumi, D. Scharff, S. Pe'eri, C. Parrish, S. A. White, I. Jeong, J. Sellars, and M. Aslaksen. 2013. *A Procedure for Developing an Acceptance Test for Airborne Bathymetric Lidar Data Application to NOAA Charts in Shallow Waters*. NOAA Technical Memorandum NOS CS 32. Silver Spring, Maryland.
- Inhofe, J. M. 2016. *S. 2848-114th Congress (2015-2016): Water Resources Development Act of 2016*. <https://www.congress.gov>
- James, M. R., and S. Robson. 2014. "Mitigating Systematic Error in Topographic Models Derived from UAV and Ground-Based Image Networks." *Earth Surface Processes and Landforms* 39(10): 1413–1420.
- Jaud, M., S. Passot, P. Allemand, N. Le Dantec, P. Grandjean, and C. Delacourt. 2019. "Suggestions to Limit Geometric Distortions in the Reconstruction of Linear Coastal Landforms by SfM Photogrammetry with PhotoScan® and MicMac® for UAV Surveys with Restricted GCPs Pattern." *Drones* 3(1): 2.
- Jozkow, G., C. Totha, and D. Grejner-Brzezinska. 2016. "UAS Topographic Mapping with Velodyne Lidar Sensor." *ISPRS Annals of Photogrammetry, Remote Sensing & Spatial Information Sciences* 3(1).

- Kersten, J., V. Rodehorst, N. Hallermann, P. Debus, and G. Morgenthal. 2018. "Potentials of Autonomous UAS and Automated Image Analysis for Structural Health Monitoring." *40th International Association for Bridge and Structural Engineering Symposium, Nantes*, S24–119.
- Kress, M. M., K. F. Touzinsky, E. A. Vuxton, B. Greenfeld, L. S. Lillycrop, and J. D. Rosati. 2016. "Alignment of USACE Civil Works Missions to Restore Habitat and Increase Environmental Resiliency." *Coastal Management* 44(3): 193–208.
- Levy, G. F. 1976. *Vegetative Study at the Duck Field Research Facility, Duck, North Carolina*. Miscellaneous report (Coastal Engineering Research Center (US)). No. 76-6, April 1976. Department of Biological Sciences, Old Dominion University, Norfolk, Virginia.
- LeWinter, A. L., M. Pfennigbauer, P. J. Gadowski, D. C. Finnegan, R. Schwarz, J. H. Podoski, and M. L. Truong. 2018. "Unmanned Aircraft System-Based Lidar Survey of Structures above and below the Water Surface: Hilo Deep Draft Harbor Breakwater, Hawaii." *Lidar Remote Sensing for Environmental Monitoring XVI* 10779: 107790Q. International Society for Optics and Photonics.
- Mancini, F., M. Dubbini, M. Gattelli, F. Stecchi, S. Fabbri, and G. Gabbianelli. 2013. "Using Unmanned Aerial Vehicles (UAV) for High-Resolution Reconstruction of Topography: The Structure from Motion Approach on Coastal Environments." *Remote Sensing* 5(12): 6880–6898.
- Marčíš, M. 2013. "Quality of 3D Models Generated by SFM technology." *Slovak Journal of Civil Engineering* 21(4): 13–24.
- Mitas, L., and H. Mitsova. 1999. "Spatial Interpolation." *Geographical Information Systems: Volume 1, Principles, Technical Issues*. New York NY: Wiley.
- Mosbrucker, A. R., J. J. Major, K. R. Spicer, and J. Pitlick. 2017. "Camera System Considerations for Geomorphic Applications of SfM Photogrammetry." *Earth Surface Processes and Landforms* 42(6): 969–986.
- OPUS (Online Positioning User Service). 2018. *OPUS: Online Positioning User Service*. <https://www.ngs.noaa.gov/OPUS/about.jsp>
- Pádua, L., J. Vanko, J. Hruška, T. Adão, J. J. Sousa, E. Peres, and R. Morais. 2017. "UAS, Sensors, and Data Processing in Agroforestry: A Review Towards Practical Applications." *International Journal of Remote Sensing* 38(8–10): 2349–2391.
- Sanz-Ablanedo, E., J. Chandler, J. Rodríguez-Pérez, and C. Ordóñez. 2018. "Accuracy of Unmanned Aerial Vehicle (UAV) and SfM Photogrammetry Survey as a Function of the Number and Location of Ground Control Points Used." *Remote Sensing* 10(10): 1606.
- Seymour, A. C., J. T. Ridge, A. B. Rodriguez, E. Newton, J. Dale, and D. W. Johnston. 2017. "Deploying Fixed Wing Unoccupied Aerial Systems (UAS) for Coastal Morphology Assessment and Management." *Journal of Coastal Research* 34(3): 704–717.

- Sherwood, C. R., J. A. Warrick, A. D. Hill, A. C. Ritchie, B. D. Andrews, and N. G. Plant. 2018. "Rapid, Remote Assessment of Hurricane Matthew Impacts Using Four-Dimensional Structure-from-Motion Photogrammetry." *Journal of Coastal Research* 34(6): 1303–1316.
- Sigren, J. M., J. Figlus, W. Highfield, R. A. Feagin, and A. R. Armitage. 2018. "The Effects of Coastal Dune Volume and Vegetation on Storm-Induced Property Damage: Analysis from Hurricane Ike." *Journal of Coastal Research* 34(1): 164–173.
- Sloan, J. 2017. *Agisoft PhotoScan (ver. 1.2.6) Workflow - Based on Close-Range Photogrammetry Error Reduction Techniques*. TN Photogrammetry LLC. US Geological Survey National Unmanned Aircraft Systems Project Office. Denver, Colorado. https://uas.usgs.gov/pdf/USGS_AgisoftPhotoScanWorkflow.pdf.
- Slocum, R. K., and C. E. Parrish. 2017. "Simulated Imagery Rendering Workflow for UAS-Based Photogrammetric 3D Reconstruction Accuracy Assessments." *Remote Sensing* 9(4): 396.
- Spore, N. J., and K. L. Brodie. 2017. *Collection, Processing and Accuracy of Mobile Terrestrial Lidar Survey Data in the Coastal Environment*. ERDC/CHL TR-17-5. Vicksburg, MS: US Army Engineer Research and Development Center.
- Spore, N. J., A. D. Renaud, I. W. Conery, and K. L. Brodie. 2019. *Coastal Lidar and Radar Imaging System (CLARIS) Lidar Data Report: 2011-2017*. ERDC/CHL SR-19-4. Vicksburg, MS: US Army Engineer Research and Development Center.
- Sturdivant, E., E. Lentz, E. R. Thieler, A. Farris, K. Weber, D. Remsen, S. Miner, and R. Henderson. 2017. "UAS-SfM for Coastal Research: Geomorphic Feature Extraction and Land Cover Classification from High-Resolution Elevation and Optical Imagery." *Remote Sensing* 9(10): 1020.
- Suir, G. M., M. K. Reif, S. L. Hammond, S. S. Jackson, and K. L. Brodie. 2018. *Unmanned Aircraft Systems to Support Environmental Applications within USACE Civil Works*. ERDC SR-18-3. Vicksburg, MS: US Army Engineer Research and Development Center.
- Sutton-Grier, A. E., K. Wowk, and H. Bamford. 2015. "Future of Our Coasts: The Potential for Natural and Hybrid Infrastructure to Enhance the Resilience of Our Coastal Communities, Economies and Ecosystems." *Environmental Science & Policy* 51: 137–148.
- Thoeni, Klaus, Anna Giacomini, Ron Murtagh, and Eric Kniest. 2014. "A Comparison of Multi-view 3D Reconstruction of a Rock Wall Using Several Cameras and a Laser Scanner." *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. XL-5. 573–580. <https://doi.org/10.5194/isprsarchives-XL-5-573-2014>
- Title 14 Code of Federal Regulations. 2017. Part 107 - Small Unmanned Aircraft Systems. <https://www.govinfo.gov/app/details/CFR-2017-title14-vol2/CFR-2017-title14-vol2-part107>
- Tonkin, T., and N. Midgley. 2016. "Ground-Control Networks for Image Based Surface Reconstruction: An Investigation of Optimum Survey Designs Using UAV Derived Imagery and Structure-from-Motion Photogrammetry." *Remote Sensing* 8(9): 786.

- Turner, I. L., M. D. Harley, and C. D. Drummond. 2016. "UAVs for Coastal Surveying." *Coastal Engineering* 114: 19–24.
- US Army. 2016. *Research, Development, and Acquisition: Airworthiness of Aircraft Systems*. Army Regulation 70-62. Washington, DC: Headquarters, Department of the Army. http://www.apd.army.mil/epubs/DR_pubs/DR_a/pdf/web/r70_62_FINAL.pdf
- US Army. 2018. *Engineering and Design: Acquisition and Operation of Unmanned Aircraft Systems (UAS) Technology*. Engineering Circular No. 1110-1-109. https://www.publications.usace.army.mil/Portals/76/Users/182/86/2486/EC_1110-1-109.pdf?ver=2018-10-31-151733-973
- USACE (US Army Corps of Engineers). 2013. *Hurricane Sandy Performance Evaluation Study*. https://www.nan.usace.army.mil/Portals/37/docs/civilworks/SandyFiles/USACE_Post-Sandy_Coastal_Projects_Performance_Evaluation_Study.pdf.
- USACE. 2015a. *North Atlantic Coast Comprehensive Study: Resilient Adaptation to Increasing Risk*. National Planning Center for Coastal Storm Risk Management US Army Corps of Engineers. Washington, DC.
- USACE. 2015b. *Photogrammetric and LiDAR Mapping*. EM 1110-1-1000. Washington, DC. https://www.publications.usace.army.mil/usace-publications/engineer-manuals/?udt_43544_param_page=23
- USACE. 2020. *Small Unmanned Aircraft Contractor and Third-Party Flights on USACE Projects and Lands (August 2020)*. Aviation Policy Letter 20-06. USACE Memorandum for Record. Washington, DC.
- Walling, K., J. K. Miller, T. Herrington, and A. Eble. 2014. "Comparison of Hurricane Sandy Impacts in Three New Jersey Coastal Communities." *Coastal Engineering Proceedings* 1(34): 38.
- Warrick, J. A., A. C. Ritchie, K. M. Schmidt, M. E. Reid, and J. Logan. 2019. "Characterizing the Catastrophic 2017 Mud Creek Landslide, California, Using Repeat Structure-From-Motion (SfM) Photogrammetry." *Landslides* 16(6): 1201–1219.
- Wehr, A., and U. Lohr. "1999. Airborne Laser Scanning—An Introduction and Overview." *ISPRS Journal of Photogrammetry and Remote Sensing* 54(2–3): 68–82.
- Westoby, M. J., J. Brasington, N. F. Glasser, M. J. Hambrey, and J. M. Reynolds. 2012. "Structure-from-Motion Photogrammetry: A Low-Cost, Effective Tool for Geoscience Applications." *Geomorphology* 179: 300–314.
- Wozencraft, J. M., and W. J. Lillycrop. 2003. "SHOALS Airborne Coastal Mapping: Past, Present, and Future." *Journal of Coastal Research Special Issue* No. 38: 207–215.
- Wozencraft, J. M., and W. J. Lillycrop. 2006. "JALBTCX Coastal Mapping for the USACE." *The International Hydrographic Review* 7(2).
- Yoon, H., J. Shin, and B. F. Spencer Jr. 2018. "Structural Displacement Measurement Using an Unmanned Aerial System." *Computer-Aided Civil and Infrastructure Engineering* 33(3): 183–192.

Unit Conversion Factors

Multiply	By	To Obtain
Acres	4,046.873	square meters
acre-feet	1,233.5	cubic meters
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
cubic yards	0.7645549	cubic meters
Fathoms	1.8288	Meters
Feet	0.3048	Meters
foot-pounds force	1.355818	Joules
Inches	0.0254	Meters
Knots	0.5144444	meters per second
Microinches	0.0254	Micrometers
Microns	1.0 E-06	Meters
miles (nautical)	1,852	Meters
miles (US statute)	1,609.347	Meters
miles per hour	0.44704	meters per second
Mils	0.0254	Millimeters
ounces (mass)	0.02834952	Kilograms
ounces (US fluid)	2.957353 E-05	cubic meters
pints (US liquid)	4.73176 E-04	cubic meters
pounds (mass)	0.45359237	Kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
pounds (mass) per cubic inch	2.757990 E+04	kilograms per cubic meter
pounds (mass) per square foot	4.882428	kilograms per square meter
pounds (mass) per square yard	0.542492	kilograms per square meter
quarts (US liquid)	9.463529 E-04	cubic meters
Slugs	14.59390	Kilograms
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters
square miles	2.589998 E+06	square meters
square yards	0.8361274	square meters
Yards	0.9144	Meters

Abbreviations

3D	Three-dimensional
AGL	Above ground level
AOI	Area of interest
APMO	Aviation Program Management Office
ATPM	Aircrew Training Program Manager
AWR	Airworthiness Release
CHL	Coastal and Hydraulics Laboratory
CLARIS	Coastal Lidar and Radar Imaging System
CMOS	Complementary metal-oxide-semiconductor
CONOPS	Concept of operations
CoP	Community of Practice
CORS	Continuously Operating Reference Station
COTS	Commercial off-the-shelf
DoD	Department of Defense
DSM	Digital surface model
ERDC	US Army Engineer Research and Development Center
FAA	Federal Aviation Administration
FEMA	Federal Emergency Management Agency
FRF	Field Research Facility

FRM	Flood risk management
FW	Fixed-wing
GCP	Ground control point
GIS	Geographic information system
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GRASS	Geographic Resources Analysis Support System
GSD	Ground sample distance
IA	Infrastructure area
IMU	Inertial Measurement Units
LOS	Line of sight
MBO	Mission Briefing Officer
MSI	Multispectral imaging
MTLS	Mobile Terrestrial Lidar
NGS	National Geodetic Survey
NGS	National Geodetic Survey
NIR	Near-Infrared
OPUS	Online Positioning User Serve
PIC	Pilot in Charge
PPK	Post Processed Kinematic
QGIS	Quantum GIS

R&D	Research and Development
RGB	Red-green-blue
RMSD	Root Mean Square Difference
RMSE	Root Mean Square Error
RST	Regularized spline with tension
RTK	Real-Time-Kinematic
SfM	Structure from Motion
TLS	Terrestrial lidar scan
UAS	Unmanned Aerial Systems
USACE	US Army Corps of Engineers
UTM	Universal Transverse Mercator
VLOS	Visual line of sight
VO	Visual observers
VTOL	Vertical Take Off Landing

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