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SECTION 2: PUBLIC SUMMARY

Unmanned Aerial Systems (UAS) are a new and relatively untapped resource within the USGS and the scientific community for coastal surveying.
UAS offer a number of advantages over ground-based surveys and manned aerial systems, including the ability to rapidly deploy and efficiently collect remote sensing data, and to derive high-resolution elevations over variable terrain. The purpose of this project was to evaluate mapping, data processing, and analysis capabilities for pilot surveys of coastal beaches and marshes using UAS. The project was designed to provide a low-risk, low-cost means to explore the utility of UAS for coastal mapping on beaches and marshes, and develop methodology and capacity to acquire, process, and analyze data. The collaborative project brought together USGS scientists and technical staff, with Marine Biological Laboratory (MBL) researchers and students, and supported both research and education through coursework including observational biodiversity and informatics, system design, and both field and laboratory collaboration. Products from this effort include: 1) a peer-reviewed journal manuscript documenting the mapping routines developed and modified for UAS surveys in coastal environments; 2) a U.S. Geological Survey Data Release publishing aerial imagery and associated data sets generated from a representative UAS survey; and 3) information used to develop a 2015 bioinformatics course.

SECTION 3: PROJECT SUMMARY

The accessibility of Unmanned Aerial Systems into remote and variable terrain and structure-from-motion (SfM) processing for scientific research has expanded the potential for rapid and cost-effective spatial data acquisition. The U.S. Geological Survey worked in collaboration with members of the Marine Biological Laboratory at five sites on Cape Cod, Massachusetts to explore scientific research opportunities for UAS technology in topographic and habitat mapping applications. Here we assess the application of in-house UAS platforms coupled with SfM as an alternative to lidar and aerial/satellite imagery to support coastal studies requiring high-resolution elevation or imagery data. In Phase 1, we examine data acquisition and processing time and requirements across the study sites to hone a standardized workflow. In Phase 2, data from a representative site are used to assess UAS-SfM data for mapping and measuring coastal beach and marsh systems by evaluating: 1) the accuracy of derived digital elevation models (DEMs); 2) the extraction of morphologic metrics, including beach topography and profiles using methods previously established for application to lidar data; and 3) coastal habitat mapping applications. We find that the high resolution and correspondingly high density of UAS data requires some simple modifications to existing analysis techniques and processing workflows, and that the data quality and landscape information provided is equivalent to, and in some cases surpasses that of data collected using established methods.

SECTION 4: REPORT BODY

Purpose and Objectives

The purpose of this project was to evaluate mapping, data processing, and analysis capabilities for pilot surveys of coastal beaches and marshes using UAS and SfM. Our goals were two-fold: 1) to build and test the UAS platform sufficiently to collect coastal data and develop content for a UAS bioinformatics course; and 2) to evaluate how data collected with UAS-SfM compares with data that might be derived from other remote sensing technologies (e.g. lidar, satellite imagery) commonly used to evaluate change in the coastal environment. Initially, we assessed the capabilities and limitations of the UAS platform to conduct field surveys by performing experimental UAS data collection at a variety of sites. From those data we developed SfM data processing routines to create digital elevation models and orthoimagery. We then used data from the most comprehensive UAS survey to modify workflows currently applied to data from manned flights lidar-derived data and to develop new routines for geomorphology and habitat inference in coastal systems (Phase 2). Co-PI Remsen at MBL developed a bioinformatics course and the UAS platform, as well as acquired the remote sensing data at several locations in coastal Massachusetts; repeat surveys were collected as part of a MBL summer 2015 biodiversity and informatics course. Results of Phase 2 are published in a peer-reviewed manuscript and accompanying U.S. Geological Survey Data Release (Sturdivant et al., *in press*).

Organization and Approach

Phase 1: Developing and Testing the UAS Platform and SfM Workflow

In Phase 1, we examined the appropriateness and constraints of the UAS platform to conduct field surveys of various extents at a variety of Cape Cod sites, which supported bioinformatics objectives, as well as allowing us to develop SfM data processing routines to generate high-resolution digital elevation models and orthophotography. Five Cape Cod sites (Figure 1; Table 1) were used to develop and test the UAS platform and design a SfM processing workflow. Surveys at these sites allowed us to develop and refine a continuous workflow for the application of UAS technology by engaging the major demands for scientific research, namely, hardware and software requirements, data acquisition and processing time.

Site selection was based on their proximity to development, the relevance of land cover to the research objectives, and the representativeness of the geomorphology. Furthermore, we considered proper permissions, proximity to structures, trees, and people before taking flight.

Generally, the study sites were sparsely populated, on public lands, and had wide views in all directions. The sites are as follows:

- **Peterson Farm** is a several acre farm with open fields, vegetation, limited structures, and protective tree line. It includes an isolated area to practice flight control, image acquisition and initial workflow.
- **Little Sippewissett Marsh** is a small salt-water marsh. It was a practice area for vegetation detection, flight planning and image overlap calculation.
- **Black Beach and Great Sippewissett Marsh** is an area with beach and substantial marsh. The site necessitated public interaction. It has a combination of water, beach and vegetation and is nesting habitat for piping plover. Black Beach was surveyed twice, once in 2015 and once in 2016. The 2016 survey was the primary data source used to test both beach profiling and dune detection and land cover classification (Phase 2). We placed targets for use as ground control points (GCPs).
- **Ram Island Cut and Devils Foot Island** is a submerged site that was an area to test eel grass detection. It has a rocky coastline and strong current. It is challenging for placing and surveying GCPs and for SfM processing.
- **Sage Lot Pond** had substantial water coverage with eel grass areas. The submerged area was visible, but visibility was restricted by high glare. GCP placement was difficult.

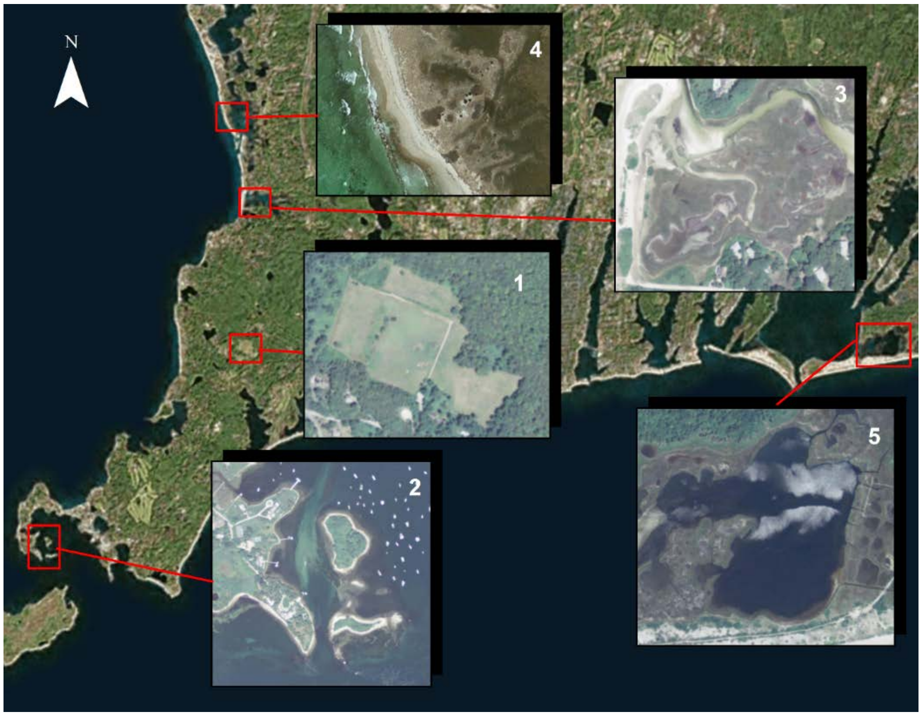

Figure 1. Five locations used to develop and test UAS platform: 1) Peterson Farm; 2) Little Sippewissett Marsh; 3) Black Beach and Great Sippewissett Marsh; 4) Ram Island Cut and Devil’s Foot Island; 5) Sage Lot Pond.

The Marine Biological Laboratory (MBL) provided the UAS platform, a DJI Phantom 3 Professional[1] quadcopter, and necessary flight certifications and permissions. MBL also provided the additional tablet (Apple iPad) for the DJI flight application and later Maps Made Easy flight planning software. Earlier surveys used a combination of Apple iPhones and Android devices to collect GPS point data; later surveys incorporated ground control points collected via RTK GPS. Desktop and laptop computers were used for processing; however, because of the demanding nature of the software the majority of the processing was done using a multi-core workstation with dedicated GPU and large RAM capacity.

The software used and tested included both proprietary and open source software. The proprietary software included Adobe Photoshop CS6 to convert from RAW to TIFF format, Agisoft PhotoScan Professional, Open source software included QGIS, VisualSFM (http://ccwu.me/vsfm/), Clustering Views for Multi-View Stereo (CMVS), GRASS GIS, Path-based Mult-View Stereo (PMVS) software libraries, and Meshlab.

We developed the workflow outlined in Table 2 using Agisoft Photoscan Professional for SfM to process the survey data. Data collected during field surveys required minimal reformatting prior to SfM processing, and included photos collected by the UAS with accompanying Exchangeable Image File (EXIF) data, as well as the ground control point geographic locations collected by GPS (Sturdivant et al., 2017). The EXIF data, logged by the UAS, recorded camera parameters specific to each photo, including xyz and pitch, roll, and yaw values. Photos with ground obstructions, poor image quality, or anomalous altitude, pitch, or roll values were removed from subsequent analysis.

Table 2. General workflow for structure-from-motion processing, with specific values added from the 2016 Black Beach survey. 'Camera' is used to indicate the camera parameters associated with a single photo (i.e., 'camera coordinates' means the geographic coordinates of the camera when a given photo was taken).

General workflow	Specific processing steps	Parameters used for processing in PhotoScan
Photo alignment	Photo quality control Alignment Alignment optimization Camera calibration optimization	Imported all 250 photos. Spot-checked photos for quality and computed quality score. All photos scored greater than 0.6 (where 1 is perfect quality as estimated by PhotoScan based on sharpness, exposure, etc.) so none were removed. Converted camera coordinates from WGS84 to UTM Zone 19N. Used camera coordinates to generate photo pairs. Aligned with photos downscaled by a factor of four.
Geo-registration	Target detection in photos GCP coordinate import Register sparse point cloud to GCPs	Detected all 18 markers. Imported file of accurate GCP coordinates in NAD83 UTM Zone 19N.

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[1] Any use of trade, firm, or product names in this document is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Optimization	Iteratively eliminate poor quality tie points.	Iteratively optimized camera calibration/alignment. Eliminated points that fell below the following thresholds of tie point quality: Reconstruction uncertainty threshold: 10 Projection accuracy threshold: 3 Reprojection error threshold: 0.3
	Iteratively calibrate camera.	Camera calibration coefficients: focal length *(f)*, principal point offset (*cx*, *cy*), radial distortion(*k1*, *k2*, *k3*), skew (*b2*), tangential distortion (*p1* and *p2*)
Dense point cloud	Low and high quality reconstruction	Built dense point cloud with low accuracy Built dense point cloud with high accuracy
Export outputs	Export point cloud	Exported low accuracy point cloud as text file with 6-figure precision
	Production of DEM	Built DEM from high accuracy dense point cloud at original resolution of photos (2.5 cm) Exported DEM in TIFF format
	Production of orthomosaic	Built orthomosaic projected over DEM Exported orthomosaic in TIFF format

Phase 2: Evaluating Coastal Mapping Abilities using Black Beach Survey

In Phase 2, we used results from our most successful UAS survey at Black Beach to modify existing mapping routines currently applied to lidar-derived data and develop new feature extraction and habitat classification methods in the coastal environment. We used the workflow outlined in Table 2 to process the 2016 Black Beach survey (Figure 2); specific parameters for this survey are described in Sturdivant et al., *in press*. This process used 250 photographs collected by the UAS and the locations of 18 temporary targets used as GCPs as inputs to the SfM processing.

Our Black Beach survey covered a 350 x 500 meter area. The UAS flew 15 transects of approximately 350 m across the width of the survey site (east-west oriented) with photos automatically taken every 20 meters (~17 photos per transect). This design ensured an overlap of 80 percent between photos. In 2016, UAS survey planning and deployment at Black Beach required 2 hours for a 17.5 hectare area.

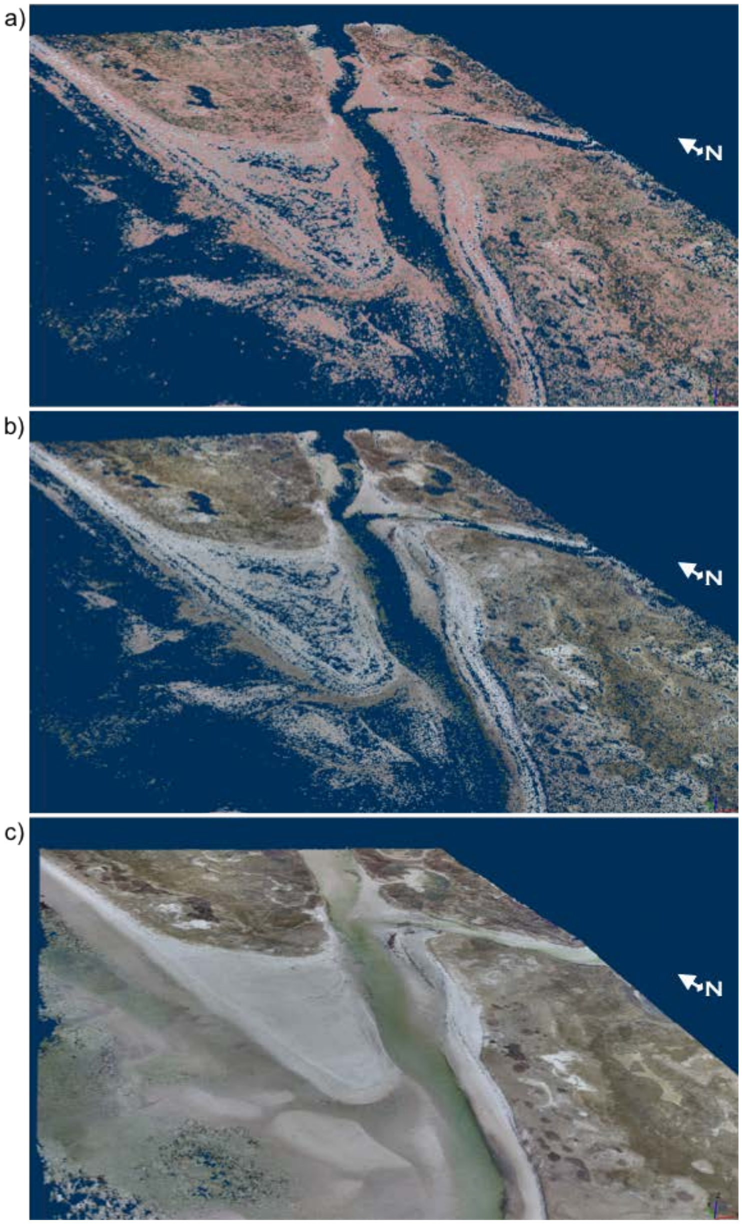

Figure 2. XYZ-RGB point clouds produced through SfM in PhotoScan at three stages of processing: (**a**) cloud of tiepoints with imprecise points (reprojection error greater than 0.37) highlighted in pink; (**b**) cloud of tiepoints after optimization, which is used as the basis for building the dense cloud and (**c**) dense point cloud created with a "high" accuracy setting.

We evaluated the accuracy of the products using metrics generated by Photoscan and by comparing the point cloud and DEM elevations to 254 independently surveyed reference elevations. Horizontal (XY) and vertical (Z) error for the Black Beach 2016 survey were calculated by summarizing the deviation between the DEM and the reference point elevations (mean error, mean absolute error, and RMSEz); see Sturdivant et al., *in press*, for further detail. We used these products for two applications to coastal research: geomorphic feature extraction and land cover classification.

To assess the use of UAS-SfM for feature extraction, we employed shoreline, dune toe, and dune crest detection methods developed for application to lidar datasets [e.g., Stockdon et al.

2002, Hapke et al., 2010, Stockdon et al. 2012]. UAS-SfM point clouds can be produced in the same format as lidar, but tend to have greater point density. This means that the same methods could be applied but moderate downsampling of the point cloud was necessary. Detailed methods are available in Sturdivant et al., *in press*.

We assessed the applicability of UAS SfM to habitat classification by comparing supervised image classification outcomes from UAS orthoimagery with and without elevation and resampled to different resolutions. We applied a maximum likelihood supervised classification algorithm, which uses one of the most common classification decision rules (Myint et al., 2011). Five land cover classes common to coastal habitat modeling (e.g. Gieder et al., 2014) were used in the supervised classification including: water, sand, marsh, non-marsh herbaceous vegetation, and woody vegetation. Detailed methods are available in Sturdivant et al., *in press*.

Project Findings

Input and output data sets from the 2016 Black Beach survey – aerial imagery and survey ground control points, as well as SfM products, including the elevation point cloud, digital elevation model (DEM), and orthomosaic – were published by Sturdivant et al. (2017). Results of Phase 2 are published in a peer-reviewed manuscript (Sturdivant et al., *in press*).

Refining testing and application of UAS platform

A number of improvements were made to our surveying techniques through the course of the project. Lacking mission planning software in early surveys, we used a combination of DJI software and Google Maps to determine a flight path and experiment with the amount of image overlap required to capture sufficient detail of the study area. SfM software relies on image pixel matching, therefore ensuring the correct amount of overlap in images is important to ensure correct photo alignment in SfM processing (Figure 3). Flight planning software used in the Black Beach survey, Maps Made Easy (MME), designed the flight route and ensured appropriate photo overlap by conducting camera shutter control on the flight. We also improved upon the distribution, accuracy, and precision of ground control points collected with mobile devices used in earlier surveys by including Spectra Precision SP80 GNSS (Global Navigation Satellite System) receivers to collect RTK GPS point data in the Black Beach survey. Portable targets for ground control points (automatically detected by SfM software) were printed on plastic sheets and fiberglass, an upgrade from earlier targets made with painted cardboard (Figure 4), although stationary structures of high visibility could be used in place of GCPs if available. The GNSS receivers were connected to the Massachusetts Continuously Operating Reference Station Network (MaCORS) for RTK position corrections that yield xyz data accurate to within 1-3 cm.

Our work across sites demonstrated in coastal environments particularly, that wind, visibility, and glare are important considerations when planning a flight. Wind and gusts should be less than 20 kts; visibility must be good to 100 m; and glare can be minimized by surveying water on cloudy days. Although our onboard gimbal had the ability to stabilize the camera sensor in calmer conditions, we found that strong winds could destabilize the drone itself, causing image blur and unsafe flying conditions. We timed surveys to correspond to local low tide to maximize coverage of the intertidal zone. An important component of this work was flight elevation; at the time of this study, FAA regulation stated that maximum UAS flight height was

400 m. The amount of detail decreases as flight height increases, but fewer images are required to create a mosaic at higher flight height.

Figure 3. Map showing unsuccessful survey of Little Sippewisset Marsh. Not enough overlap was captured at a 20 m elevation resulting in poor image alignment in PhotoScan.

Figure 4. Image showing well-distributed GCPs (black and white targets) placed throughout the survey area.

Our surveys also required us to consider battery life to ensure we were able to cover the study area extent. A fully charged 4480 mAh 15.2V DJI Intelligent Flight battery had enough power for a 23 minute flight, however, as a safety concern, the Phantom 3 was grounded at 17-20% battery life, which decreased flight time to around 15 minutes. Using an additional two batteries, a total of 45 minutes of flight time was available for a survey, which we found was a sufficient amount of time to complete each survey.

Although helpful in the development of processing routines, the imagery collected at various sites in 2015 could not be used to generate products for use in comparative analyses. We found that precise GNSS measurement is critical to provide products for use in comparative analyses, as is automated flight planning software which helps to substantially reduce operator error related to image overlap and flight height. Our 2015 surveys used neither flight plan programming nor RTK GPS, resulting in processing errors that prevented the generation of products. In particular, the images did not have enough overlap nor enough quality GCP positions to create an elevation surface nor to georeference the image.

We calculated both horizontal and vertical error of less than 3 cm based on sensor and processing precision from the UAS-SfM survey at Black Beach 2016. Areas with tall or dense vegetation were found to cause the greatest errors in the SfM elevation outputs. Erroneously high elevations – in this case, areas with herbaceous vegetation on dunes and in wetlands – occurred because the imagery is recorded with a passive sensor (RGB camera) so does not penetrate vegetation like an active lidar sensor, and we are as yet unable to distinguish it from bare earth. Bare earth elevations were only possible to derive in areas of sparse or no vegetation, such as beaches, which makes SfM well suited for many coastal study sites. Further detail on vegetation effects and error is available in Sturdivant et al. *in press*.

Geomorphic Feature Extraction and Habitat Classification

It was possible to apply geomorphic feature extraction processing routines developed for lidar data to UAS SfM-derived data. Features extracted from the UAS-SfM point cloud displayed near-complete coverage of the study area. The features could be extracted from the point cloud subsampled to point spacings of 2.5, 15, 35, and 50 cm without degradation in the extraction results. In fact, with these high-density point clouds, we were able to modify the routine to extract features with greater precision and more continuous coverage. High density extraction to this degree is not possible from lidar datasets. It could be useful for smaller scale modeling of coastal change and bridging the divide between grain-scale and landscape-scale analyses. These gains result from the high resolution and well-distributed precise ground control of the UAS-SfM survey. See Sturdivant et al. (*in press*) for detailed results and discussion of the extraction of geomorphic features.

Most high-resolution imagery and elevation data available are not temporally synched, requiring a user to factor in the potential for change between the two datasets. An important advantage of SfM processing is the availability of synchronized elevation and imagery. For example, when acquiring comparison lidar and satellite datasets for habitat classification, the precise acquisition dates for the small Black Beach site were undocumented, but readily observable changes in the landscape between the two datasets suggests that the lidar elevation data we obtained labeled 2014 were collected some months before the satellite image we obtained that were also labeled 2014.

With SfM, we can use elevation data from the precise time that imagery was acquired to confirm the positions of dynamic coastal features. As we show in Sturdivant et al. (*in press*), elevation data can be used as an additional image band during habitat classification routines to dramatically increased land cover classification accuracy. The high-resolution and coincident elevation surface of the imagery facilitated the identification of contiguous features, which are then the base unit of classification in object-based classification (Figure 5; see Sturdivant et al. (*in press*) for more detail).

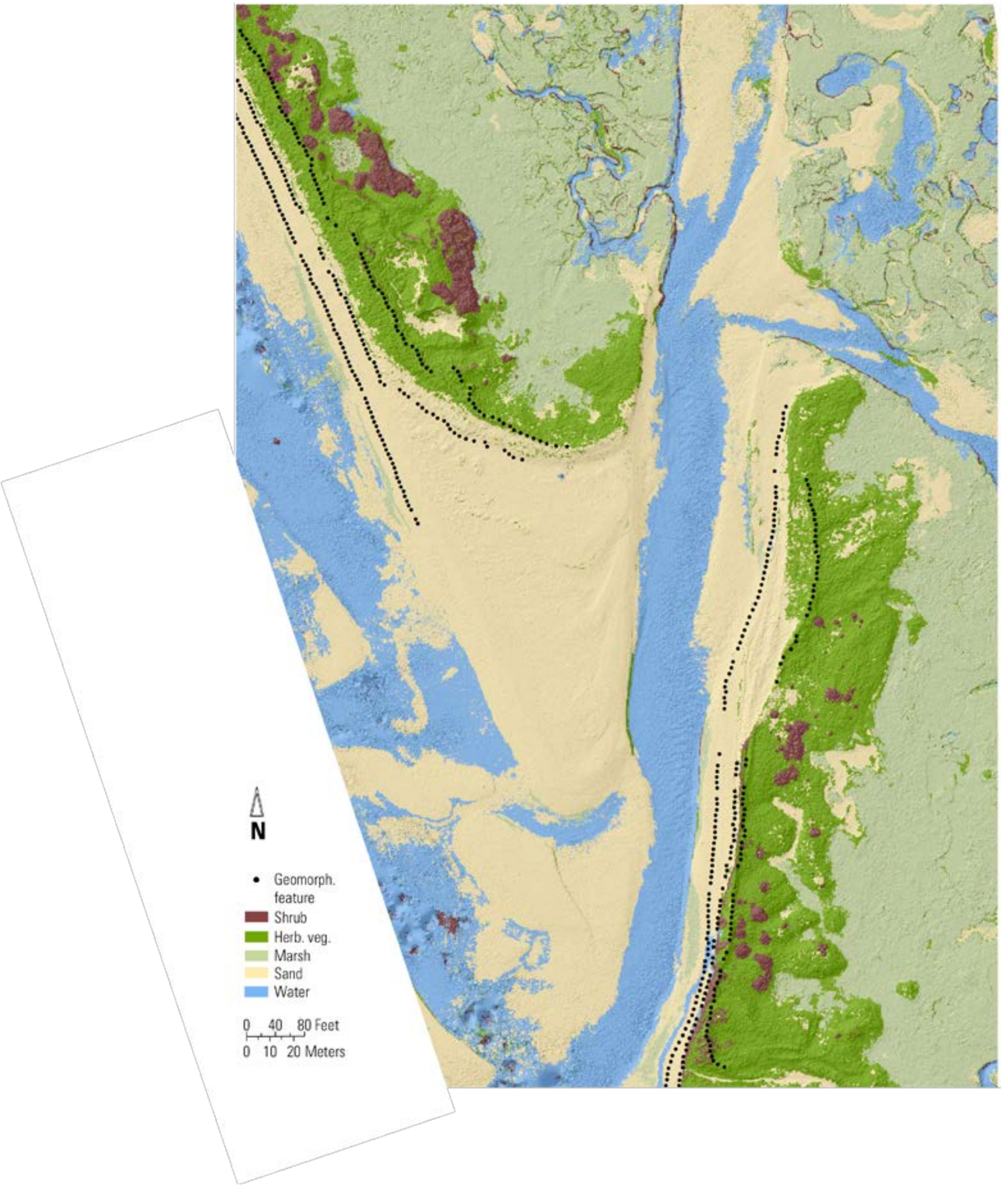

Figure 5. Land cover and beach geomorphic features at Black Beach. The analysis products were derived from UAS-SfM products and have high accuracy and precision. The map is displayed with elevation hillshading from the DEM. Black points represent locations of shoreline, dune toe, and dune crest delineated every 2 m along the shore.

Conclusions and Suggestions Regarding Future Research

We found UAS surveys were processed efficiently with accuracies of about 5 cm that support existing and new coastal research assessments (Sturdivant et al., *in press*). UAS imagery are higher resolution (10 cm) and derived elevation data have higher spatial point densities ($25/m^2$) than other surveying methods, consequently resulting in lower horizontal and vertical error in both derived products and extracted features, particularly in sandy beach areas. Further, their rapid deployment (on the order of hours), survey collection and data processing makes UAS an ideal survey utility to conduct repeat surveys over areas of limited spatial coverage, and can be coupled with other types of data to improve our understanding of process-based coastal change over timescales of days, weeks, and months.

The UAS platform has some limitations and for which we provide useful surveying suggestions. UAS are more susceptible to environmental conditions than larger survey platforms such as wind and atmospheric moisture (fog, rain). Although we did not test it explicitly, precipitation could have damaged instruments, both the drone and the controller, as well as contributed to poor visibility. Wind and gusts should be less than 20 kts; visibility must be good to 100 m; and glare can be minimized by surveying water on cloudy days. Precise GNSS measurement and sufficient ground control distribution is critical to provide products for use in comparative analyses. Automated flight planning software is also critical as it substantially reduces the operator error related to image overlap and flight height. Ensuring the correct amount overlap in images is important to ensure correct photo alignment in processing (Figure 3).

Our results suggest a suite of applications and further research for this new coastal data collection technique, highlighted below.

- Future surveys could explore the trade-off between survey extent and image resolution. It is possible that suitably precise results could be produced over a broader survey extent while maintaining low resource demands.
- The ongoing refinement of ground truth surveying in conjunction with the survey could streamline processing and further improve accuracy.
- Advanced capabilities of SfM processing were beyond the scope of this project, but could mitigate some of the limitations of UAS surveys. In particular, the use of point classification may help to distinguish bare earth elevation when it is available and masking may reduce alignment errors such as those caused by moving water.
- Opportunities exist for further experimentation with other image classification methods to provide useful and precise products for coastal habitat modeling. For example, an expanded object-based classification could integrate additional surfaces derived from these SfM products, such as a terrain roughness index.
- Further application to habitat classification and modeling could include the generation of analysis products that have application to other upland and wetland environments.
- An examination of the SfM processing routines to separate bare earth elevation points from top of vegetation points was beyond the scope of this study, but warrants further exploration, particularly in comparison with lidar point classifications.

Outreach and Products

Products

- Sturdivant, E.J., E.E. Lentz, E.R. Thieler, D.P. Remsen, S. Miner, K.M. Weber, A.S. Farris, R.E. Henderson, *in press*, UAS-SfM for Coastal Research: Geomorphic Feature Extraction and Land Cover Classification from High-Resolution Elevation and Optical Imagery. Accepted by *Remote Sensing*

- Sturdivant, E.J.; Lentz, E.E.; Thieler, E.R.; Remsen, D.P.; Miner, S. Topographic, imagery, and raw data associated with unmanned aerial systems (UAS) flights over Black Beach, Falmouth, Massachusetts on 18 March 2016. U.S. Geological Survey, https://doi.org/10.5066/F7KW5F04, 2017.

Presentations at scientific meetings, webinars, and workshops

- Sturdivant invited speaker at EnviroDrones Conference at Dartmouth College on June 4 and 5, 2107. Title: UAS-SfM improves geomorphic feature extraction and land cover classification for coastal vulnerability assessments

- Sturdivant, E.J., Lentz, E.E., Thieler, E.R., Remsen, D., and Miner, S., 2016. Applications of UAS-SfM for coastal vulnerability assessment: Geomorphic feature extraction and land cover classification from fine-scale elevation and imagery data. American Geophysical Union Meeting, San Francisco, CA

- Co-PI Lentz presented preliminary findings in NE CSC Webinar in April, 2016: https://necsc.umass.edu/webinars/%E2%80%9C-research-and-decision-support-framework-evaluate-coastal-landscape-change%E2%80%9D

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