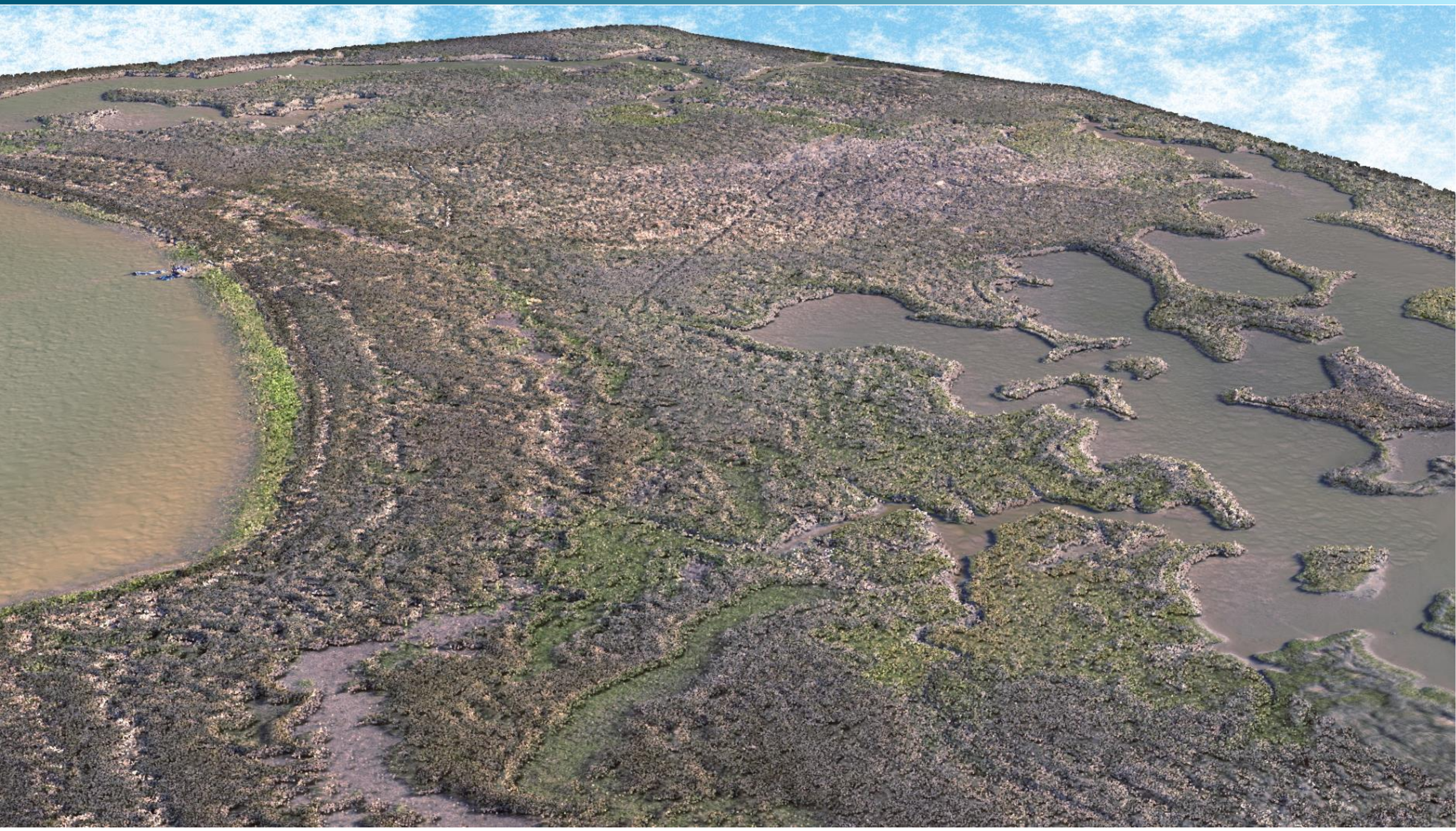
July 17, 2017



NOAA NERR Sites UAS LiDAR & Digital Imagery – Grand Bay, Mississippi

Technical Data Report

OFFICE FOR COASTAL MANAGEMENT
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

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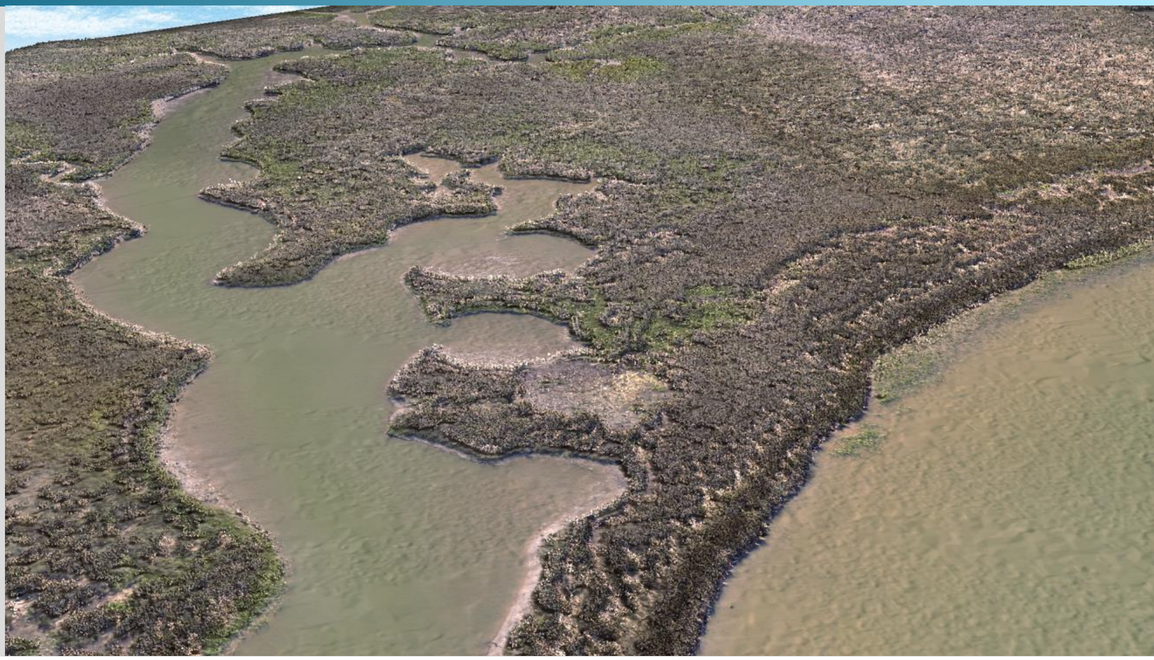
TABLE OF CONTENTS

Cover Photo: A view looking over the MB AOI in the Grand Bay, Mississippi project area. The image was created from the LiDAR bare earth model overlaid with the 3D LiDAR point cloud, and colored by the delivered Orthoimagery.

INTRODUCTION

This image shows a view of the Grand Bay National Wildlife Refuge landscape, created from the LiDAR bare earth model overlaid with the above ground point cloud and colored with Orthoimagery.



In June 2016, Quantum Spatial (QSI) was contracted by the National Oceanic and Atmospheric Administration (NOAA) to collect Light Detection and Ranging (LiDAR) data and digital imagery in the spring of 2017 using Unmanned Aerial Systems (UAS), for three National Estuarine Research Reserve (NERR) areas of interest comprising the NOAA NERR Sites LiDAR project. QSI worked with Precision Hawk to acquire and process UAS LiDAR data over the Brigantine AOI in March 2017, with Grand Bay acquisition and processing following in May and June 2017. The Grand Bay, Mississippi project area is comprised of four areas of interest in the Grand Bay National Wildlife Refuge along the Gulf of Mexico. The UAS NERR Sites project will serve as a basis to evaluate the capability and effectiveness of UAS LiDAR collection and mapping for natural resources management and monitoring.

This report accompanies the delivered Grand Bay LiDAR data and imagery, and documents contract specifications, data acquisition parameters, processing methods, and analysis of the final dataset including LiDAR accuracy and density. Acquisition dates and acreage are shown in Table 1, a complete list of contracted deliverables provided to NOAA is shown in Table 2, and the project extent is shown in Figure 1.

Table 1: Acquisition dates, acreage, and data types collected on the NOAA NERR Sites site

Project Site	Total Acres	Acquisition Dates	Data Type
Grand Bay, Mississippi Sites	206	05/09/17, 05/10/17, 05/11/17	LiDAR
			4 band Digital Imagery

Deliverable Products

Table 2: Products delivered to NOAA for the Grand Bay, Mississippi sites

<table>
<tr><th colspan="2">Grand Bay, Mississippi LiDAR and Imagery Products
Projection: UTM Zone 16
Horizontal Datum: NAD83 (2011)
Vertical Datum: NAVD88 (GEOID12B)
Units: Meters</th></tr>
<tr><td>Points</td><td>LAS v 1.2 & Compressed to LAZ
• All Classified Returns</td></tr>
<tr><td>Rasters</td><td>1.0 Meter ESRI Grids
• Bare Earth Model
• Highest Hit Model</td></tr>
<tr><td>Vectors</td><td>Shapefiles (*.shp)
• Site Boundary
• Water’s Edge Breakline
• LiDAR & DEM Indices</td></tr>
<tr><td>Digital Imagery</td><td>6.5 Centimeter GeoTiffs
• Imagery Mosaics</td></tr>
</table>

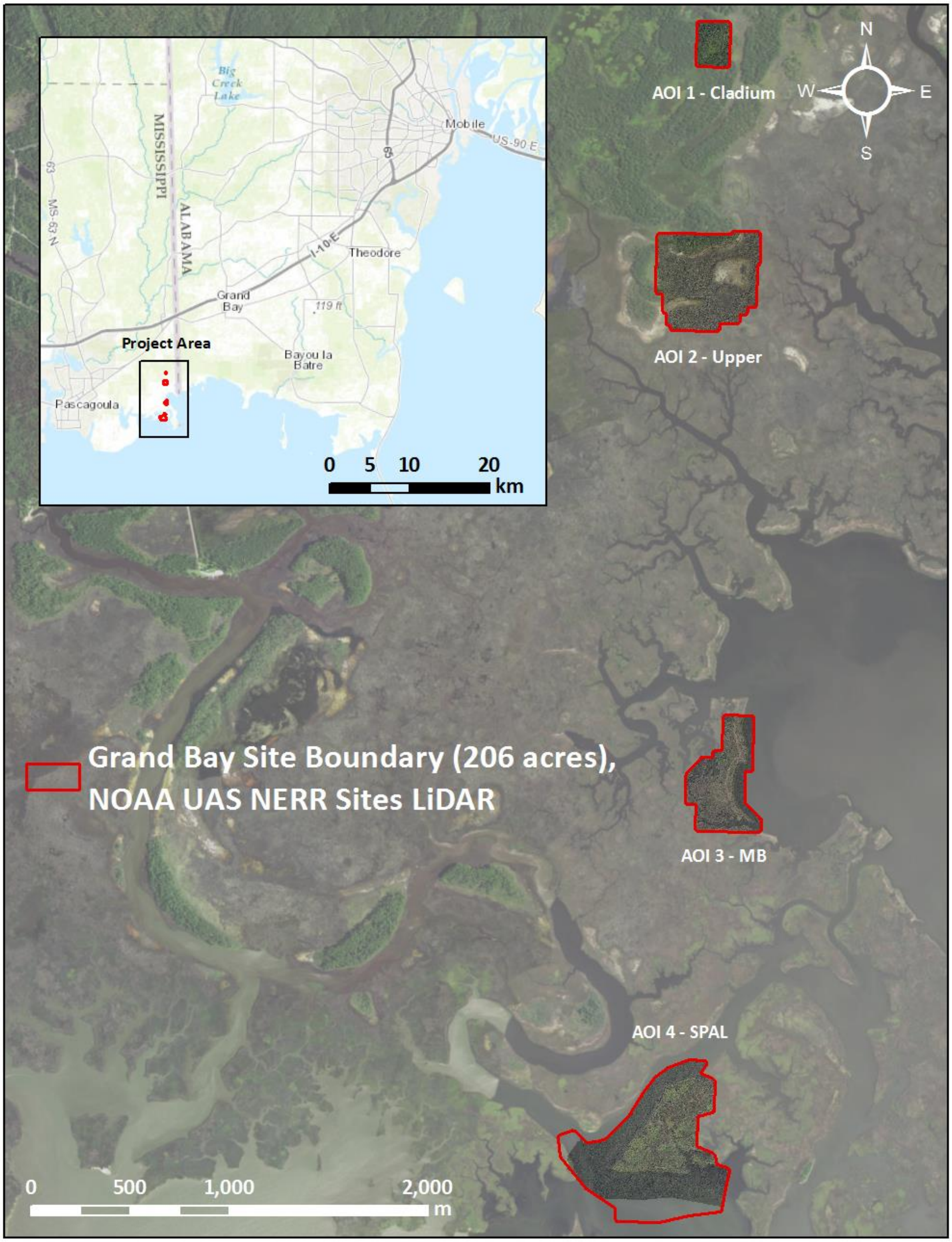
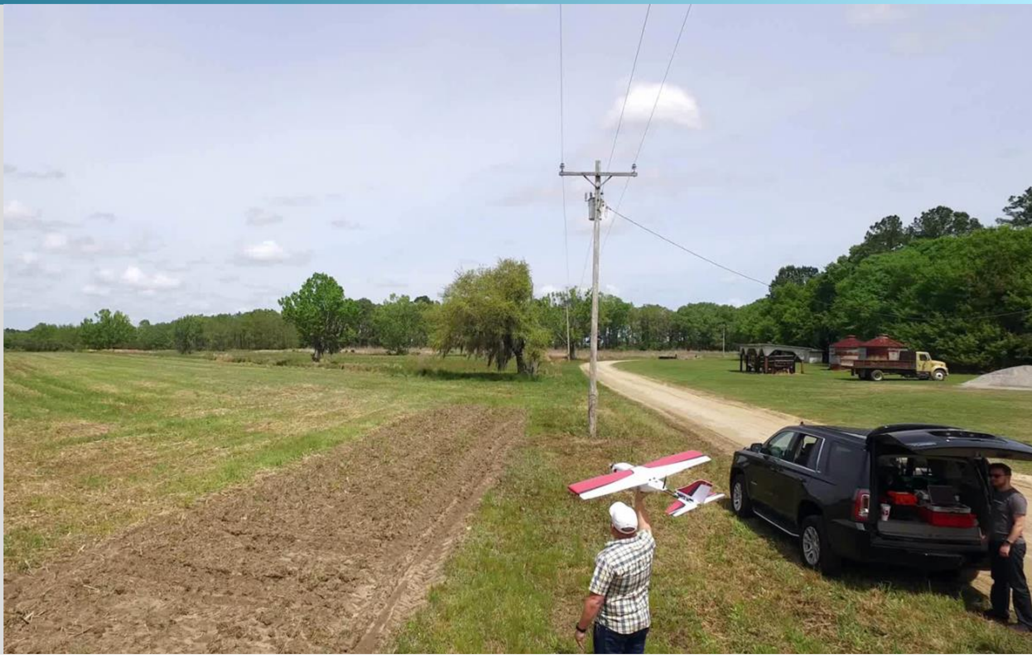


Figure 1: Location map of the Grand Bay sites in Mississippi

This photo shows Precision Hawk's Lancaster Rev 5 and crew preparing to hand launch the UAS.



Planning

All flight planning and data collection for the Grand Bay project area was completed by Precision Hawk. LiDAR data was collected using Precision Hawk's Lancaster Rev 5 Dual-Frequency GPS system, while digital imagery was collected with a DJI's Matrice 100 UAV system. Precision Hawk developed a flight plan designed to ensure complete coverage of the Grand Bay study area, with the LiDAR sensor configured to acquire a point density of ≥30.0 points/m^2 per swath.

Airborne LiDAR Survey

The LiDAR survey was accomplished using a Velodyne Puck VLP-16 laser system mounted in Precision Hawk's Lancaster Rev 5 Dual-Frequency GPS UAS. Table 3 summarizes the settings used to yield an average pulse density of ≥30 pulses/m^2 over the NOAA NERR Sites project areas.

Table 3: LiDAR specifications and survey settings

Grand Bay LiDAR Survey Settings & Specifications	
Acquisition Dates	05/09/17, 05/10/17, 05/11/17
Aircraft Used	Precision Hawk Lancaster Rev 5 Dual-Frequency GPS
Sensor	Velodyne Puck VLP-16
Maximum Returns	2 (Strongest/Last Return)
Nominal Pulse Density	30 pulses/m^2
Nominal Pulse Spacing	18 cm
Survey Altitude (AGL)	50 m
Target Speed	27.2 kts
Field of View	110^o
Scan Frequency	5 – 20 Hz
Pulse Rate	300 kHz
Pulse Duration	6 ns
Pulse Width	15 cm
Wavelength	903 nm
Pulse Mode	Single Pulse in Air (SPiA)
Beam Divergence	3 mrads
Swath Width	143 m
Overlap	50%

Left: Lancaster Rev5 UAS, Right: Velodyne Puck LiDAR Sensor

Digital Imagery

Precision Hawk acquired aerial imagery over the Grand Bay site on May 9th 10th, and 11th, 2017. Imagery was acquired using the Zenmuse X5 digital camera manufactured by DJI, Inc., mounted on a Matrice 100 UAV platform. For the Grand Bay sites, images were collected in four spectral bands (red, green, blue, near-infrared). The acquisition flight parameters were designed to yield a native pixel resolution of 3 centimeters. Orthophoto specifications are listed in Table 4.

Table 4: Manufacturer and project-specific orthophoto specifications

Digital Orthophotography Specifications	
Equipment	DJI Zenmuse X5
Spectral Bands	Red, Green, Blue, Near-Infrared
Ground Sample Distance	3cm per pixel at 50m
Megapixels	16.0 MP
Frame Rate	Max 7 frame/sec
Final Project Resolution	3cm pixel size
Image	8-bit GeoTiff

DJI's Matrice 100 UAV system, the Zenmuse X5 is shown on the right.

Ground Control Data

Ground control surveys, including collection of ground control points and air targets, were conducted by Precision Hawk and provided to QSI to support the airborne acquisition. Ground control point locations were used to geospatially correct the UAV positional coordinate data, and to perform accuracy checks on the final LiDAR and Imagery datasets. Precision Hawk verified base station coordinates by triangulating static GPS data with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS[1]) for precise positioning. Please see Appendix B for the OPUS solution report provided by Precision Hawk.

Upon receipt of the ground control point locations, QSI ran output control reports between the ground control points and the triangulated surface generated by the LiDAR points. Each AOI was found to have a vertical offset from control between 0.25 to 0.35 meters, so QSI processing staff applied vertical shifts to each AOI individually; calculated shifts applied are shown in the table below, and accuracy assessment before and after shifting is provided in LiDAR Absolute Vertical Accuracy, page 16.

QSI Applied Vertical Shifts to LiDAR dataset	
AOI 1 - Cladium	+0.27 meters
AOI 2 - Upper	+0.31 meters
AOI 3 - MB	+0.35 meters
AOI 4 - SPAL	+0.25 meters

Aerial Targets

Precision Hawk placed temporary air targets in each AOI prior to imagery acquisition to correct final Orthoimagery products. Although air targets were placed for each site, an imagery reflight was required for AOI 1 – Cladium after air target locations were removed. Precision Hawk mitigated the need for control by identifying features in the original RGB imagery acquired, and applied elevations from the original acquisition to the color-corrected reflight.

QSI assessed imagery accuracy for each AOI, and found that AOI 2 – Upper required an X,Y shift of (X +0.465 meters, Y -0.671 meters), which QSI performed. All other sites were found to have close alignment with collected air target control. Final imagery accuracy assessment is provided in Digital Imagery Accuracy Assessment, page 19, and all air target and ground control locations are shown in Figure 2.

[1] OPUS is a free service provided by the National Geodetic Survey to process corrected monument positions. http://www.ngs.noaa.gov/OPUS.

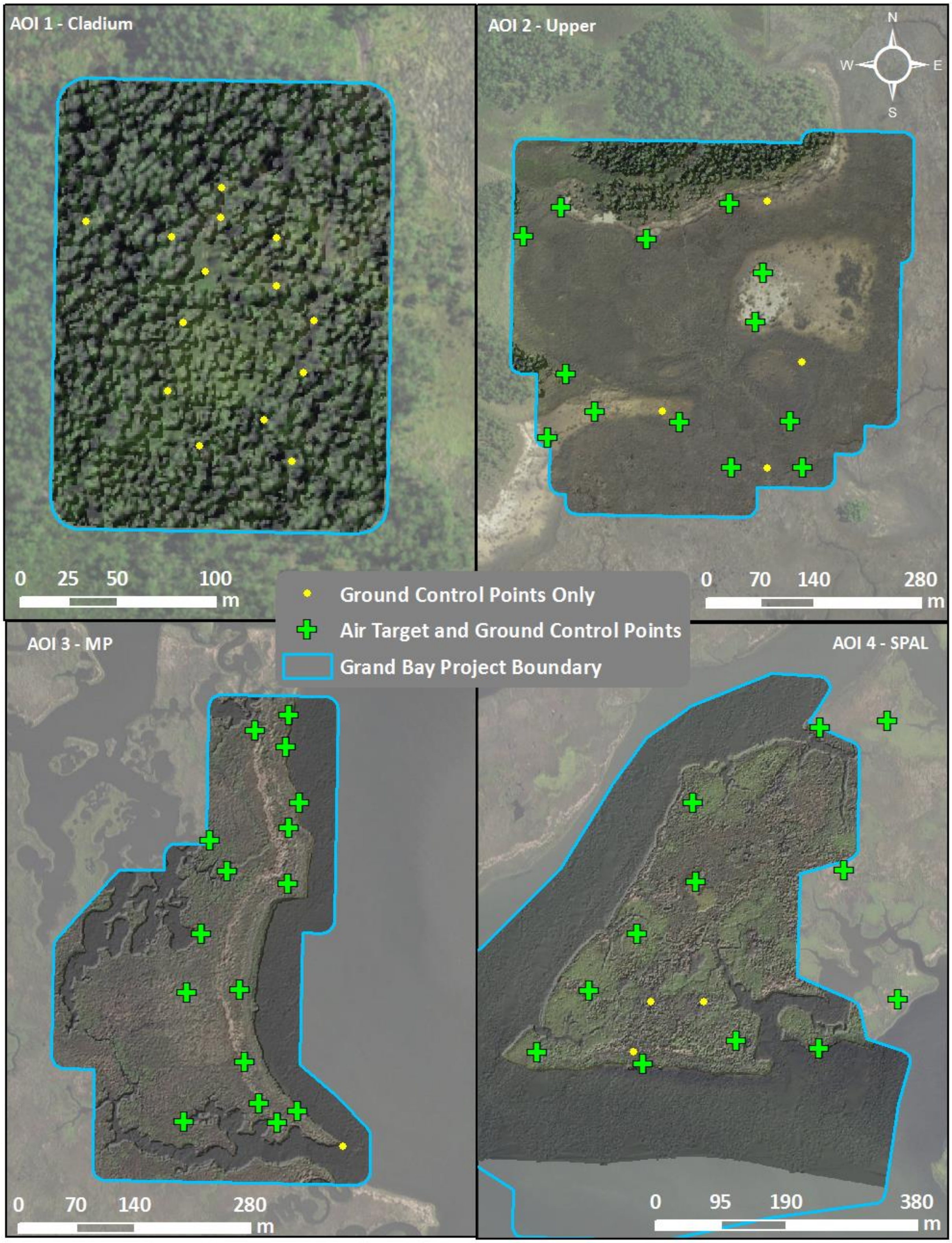
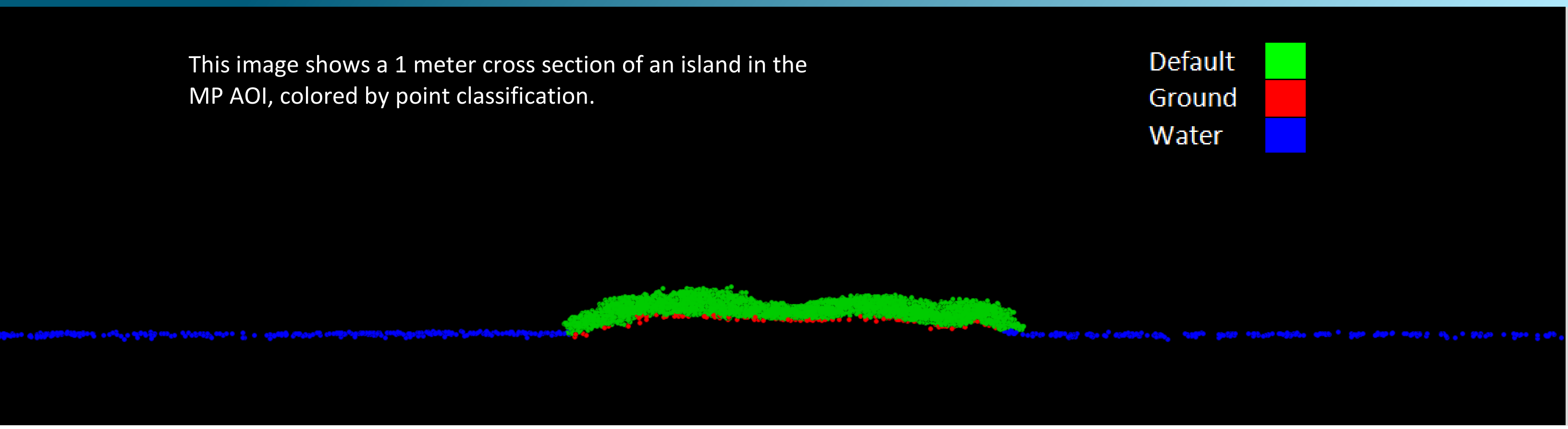


Figure 2: Ground control location map



LiDAR Data

Upon completion of data acquisition, Precision Hawk processed SBETs and raw point data into geolocated swaths. Processing tasks included GPS control computations, smoothed best estimate trajectory (SBET) calculations, kinematic corrections, and calculation of laser point position. Ground control data was collected by Precision Hawk to be used in the post-processing and calibration of the LIDAR flights. Following calibration, QSI initiated a suite of automated and manual techniques to classify the LiDAR points and create the requested deliverables. Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 6.

Table 5: ASPRS LAS classification standards applied to the NOAA NERR Sites dataset

Classification Number	Classification Name	Classification Description
1	Default/Unclassified	Laser returns that are not included in the ground class or other vegetation classes, retained in order to avoid false vegetation classing within roads or other bare ground surfaces.
2	Ground	Laser returns that are determined to be ground using automated and manual cleaning algorithms.
7	Low Noise	Laser returns that are determined to be artificial points below the ground surface.
9	Water	Laser returns that are determined to be water using manual cleaning techniques.
14	Near Ground Noise	Laser returns that are determined to be artificial points between 0 and 20 meters above the ground surface.
18	High Noise	Laser returns that are determined to be artificial points, equal to or greater than 20 meters above the ground surface.

Table 6: LiDAR processing workflow

LiDAR Processing Step	Software Used	Processor
Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data. Develop a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with sensor head position and attitude recorded throughout the survey.	Inertial Explorer	PH
Calculate laser point position by associating SBET position to each laser point return time, scan angle, intensity, etc. Create raw laser point cloud data for the entire survey in *.las (ASPRS v. 1.2) format. Convert data to orthometric elevations by applying a geoid correction.	Proprietary Software	PH
Import raw laser points into manageable blocks (less than 500 MB) to perform manual relative accuracy calibration and filter erroneous points. Classify ground points for individual flight lines.	TerraScan v.16	QSI
Using ground classified points per each flight line, test the relative accuracy. Perform automated line-to-line calibrations for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calculate calibrations on ground classified points from paired flight lines and apply results to all points in a flight line. Use every flight line for relative accuracy calibration.	TerraMatch v.16	QSI
Classify resulting data to ground and other client designated ASPRS classifications (Table 5).	TerraScan v.16 TerraModeler v.16	QSI
Generate bare earth models as triangulated surfaces. Generate highest hit models as a surface expression of all classified points. Export all surface models as ESRI GRIDs at a 1.0 meter pixel resolution.	TerraScan v.16 TerraModeler v.16 ArcMap v. 10.2	QSI

Digital Imagery

As with the NIR LiDAR, the collected digital photographs went through multiple processing steps to create final orthophoto products. Initially, camera position and orientation were calculated by linking the time of image capture to the smoothed best estimate of trajectory (SBET) file created ABGPS post-processing; this step was performed by Precision Hawk. Within Pix4D, an automated aerial triangulation was performed to tie images together and adjust the photo block to align with ground control, air targets, and photo identifiable features. Adjusted images were mosaicked by blending together seams and color balancing between images. The standard PH processing workflow for orthophotos is summarized in Table 7.

It should be noted that the NIR band for each acquisition was captured in a separate flight than the RGB bands. The NIR band was co-registered with the RGB and delivered as a 4 Band image. Ground surface features are well aligned, but above ground features such as trees and their associated shadows are not perfectly co-registered between bands. This should be considered for application of the Grand Bay imagery for analysis. Misalignment of shadows and above ground features as well as slightly different lighting and atmospheric conditions, will manifest as artifacts in band indices such as NDVI.

Table 7: Standard orthophoto processing workflow

Orthophoto Processing Step	Software Used	Processor
Create an exterior orientation file (EO) for each photo image with omega, phi, and kappa.	Pix4D	PH
Apply EO to photos, measure ground control points and perform aerial triangulation.	Pix4D	PH
Orthorectify and mosaic images blending seams and color balancing.	Pix4D	PH
Perform shift to align with collected Air Target locations.	ArcMap v. 10.2	QSI

This image shows a view of the Grand Bay LiDAR-derived bare earth digital elevation model colored by Orthoimagery.

LiDAR Density

The acquisition parameters were designed to acquire an average first-return density of 30 points/m^2. First return density describes the density of pulses emitted from the laser that return at least one echo to the system. Multiple returns from a single pulse were not considered in first return density analysis. Some types of surfaces (e.g., breaks in terrain, water and steep slopes) may have returned fewer pulses than originally emitted by the laser. First returns typically reflect off the highest feature on the landscape within the footprint of the pulse. In forested or urban areas the highest feature could be a tree, building or power line, while in areas of unobstructed ground, the first return will be the only echo and represents the bare earth surface.

The density of ground-classified LiDAR returns was also analyzed for this project. Terrain character, land cover, and ground surface reflectivity all influenced the density of ground surface returns. In vegetated areas, fewer pulses may penetrate the canopy, resulting in lower ground density.

The average first-return density of LiDAR data for the Grand Bay, Mississippi sites was 105.74 points/m^2 while the average ground classified density was 3.23 points/m^2 (Table 8). The statistical and spatial distributions of first return densities and classified ground return densities per 100 m x 100 m cell are portrayed in Figure 3 through Figure 6.

Table 8: Average LiDAR point densities

Classification	Point Density
First-Return	105.74 points/m^2
Ground Classified	3.23 points/m^2

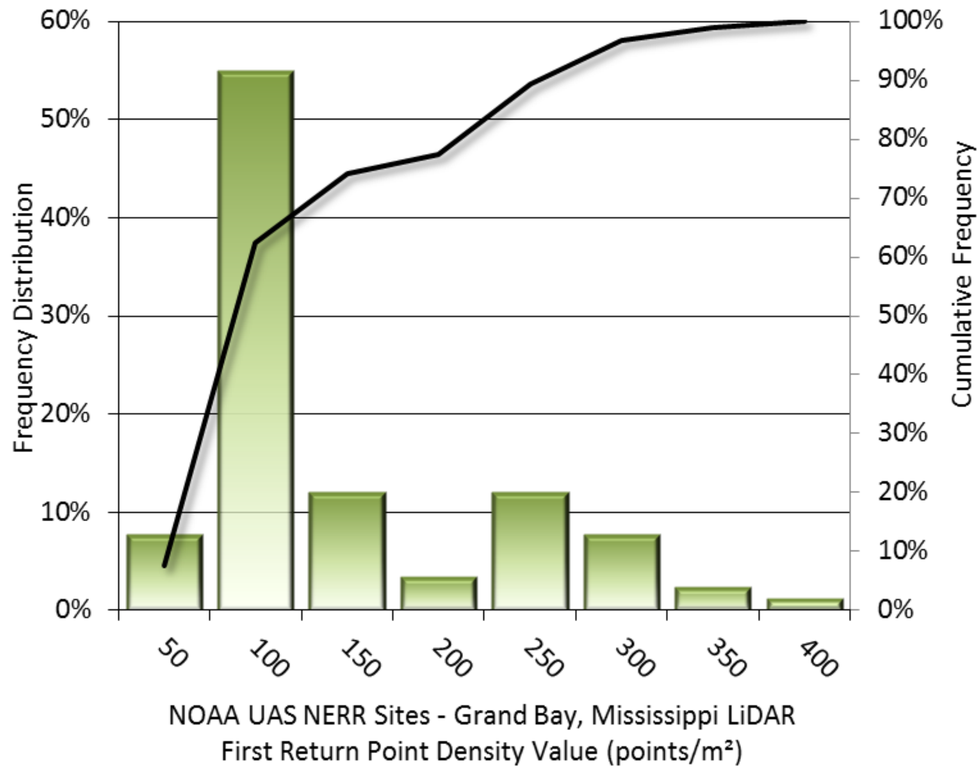


Figure 3: Frequency distribution of first return point density values per 100 m x 100 m cell

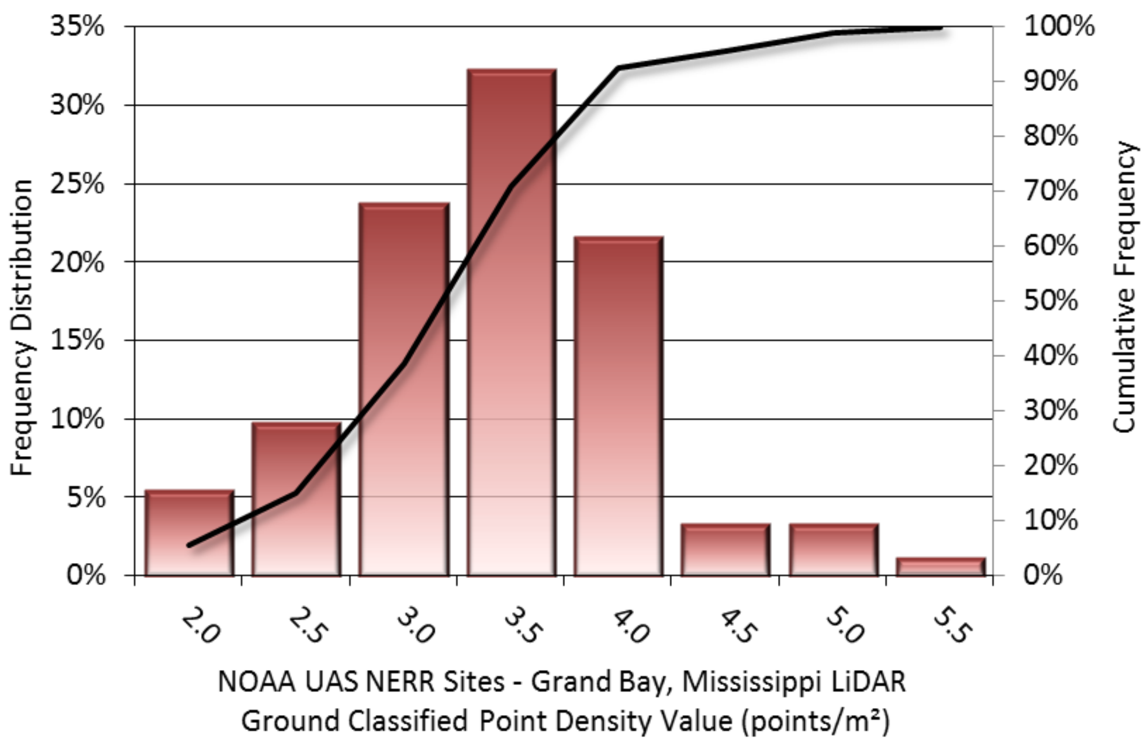


Figure 4: Frequency distribution of ground-classified return point density values per 100m x 100m cell

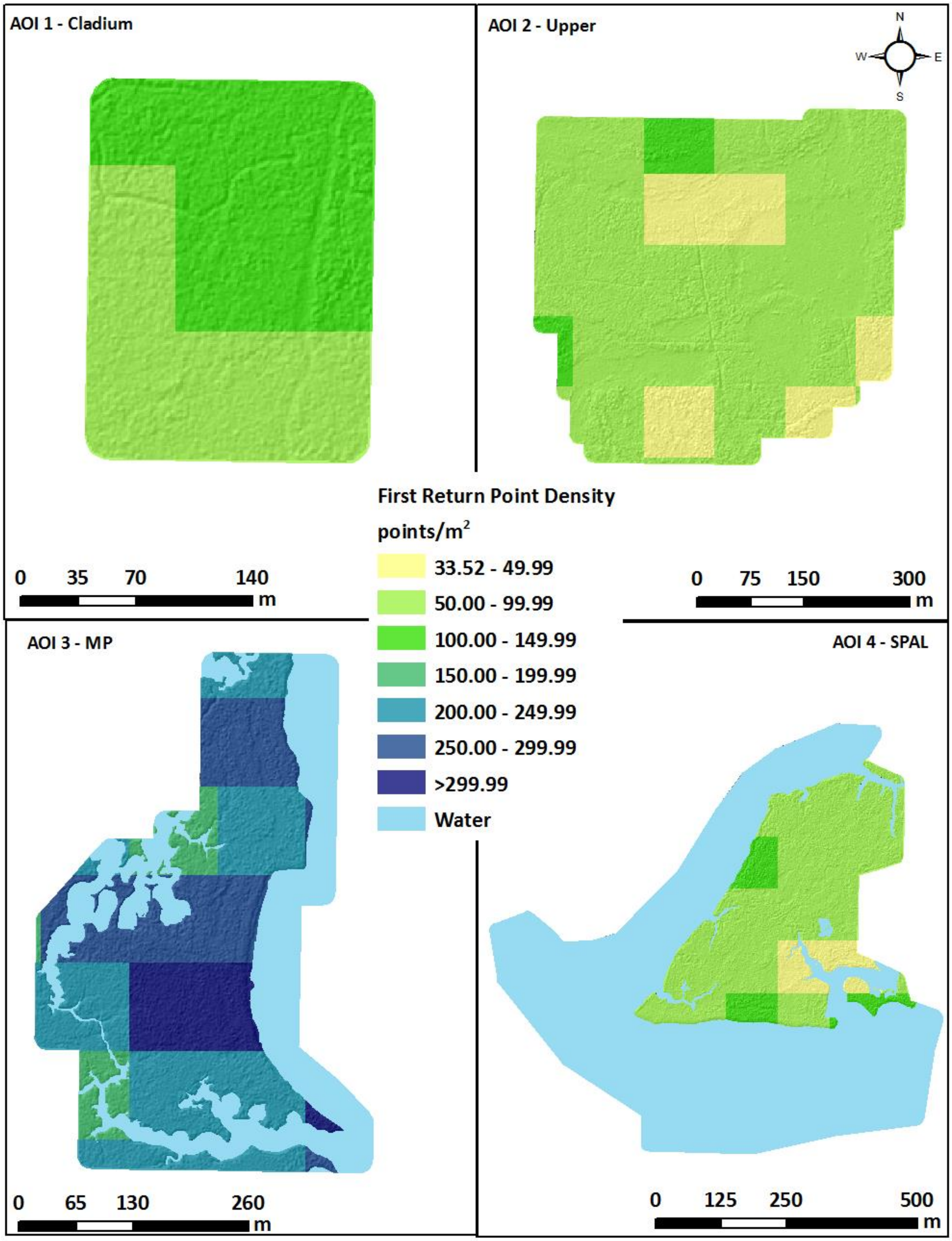


Figure 5: First return point density map of the Grand Bay Sites (100 m x 100 m cells)

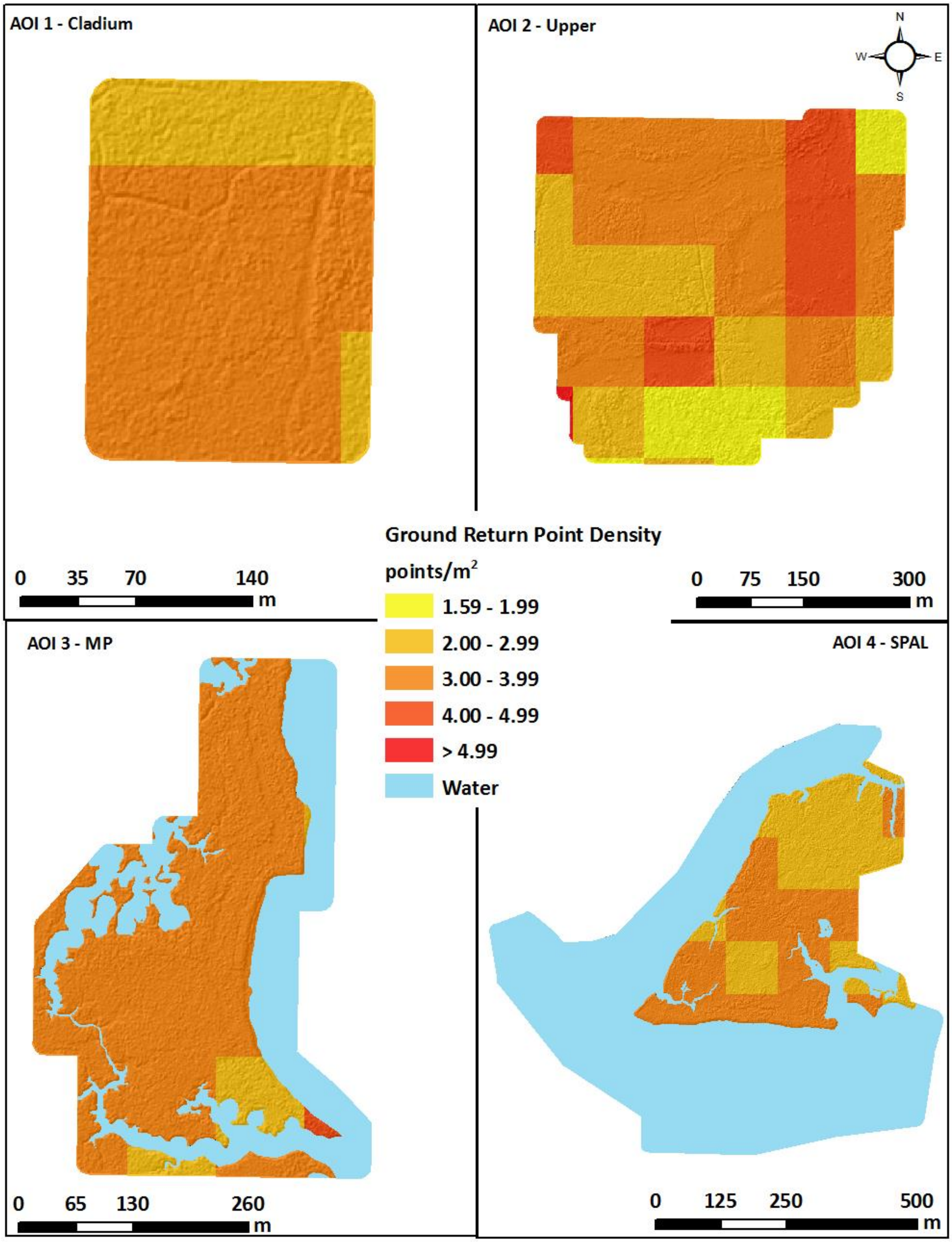


Figure 6: Ground classified point density map of the Grand Bay Sites (100 m x 100 m cells)

LiDAR Absolute Vertical Accuracy

Absolute accuracy was assessed using known ground control point data collected by Precision Hawk on open, bare earth surfaces with level slope (<20°). Control point elevations were compared to the triangulated surface generated by the LiDAR points. Although the points utilized in this analysis were used for vertical corrections to the LiDAR dataset, QSI has provided accuracy statistics before and after shifts were performed, as shown in the table below. Absolute Accuracy is a measure of the accuracy of LiDAR point data in open areas where the LiDAR system has a high probability of measuring the ground surface and is evaluated at the 95% confidence interval (1.96 * RMSE), as shown in Table 9.

The mean and standard deviation (sigma σ) of divergence of the ground surface model from quality assurance point coordinates are also considered during accuracy assessment. These statistics assume the error for x, y and z is normally distributed, and therefore the skew and kurtosis of distributions are also considered when evaluating error statistics. For the NOAA NERR Sites survey, 67 ground control points were analyzed, with a final resulting vertical accuracy of 0.134 meters, with 95% confidence (Table 9). The spatial distribution of the collected ground control points are shown in Figure 7 and Figure 8.

Table 9: Vertical Accuracy Results

Grand Bay, Mississippi LiDAR Absolute Vertical Accuracy		
	Before Shift Applied	**After Shift Applied**
Sample	67 points	67 points
95% Confidence (1.96*RMSE)	0.595 m	0.134 m
Average	-0.294 m	0.002 m
Median	-0.292 m	-0.013 m
RMSE	0.304 m	0.068 m
Standard Deviation (1σ)	0.077 m	0.069 m

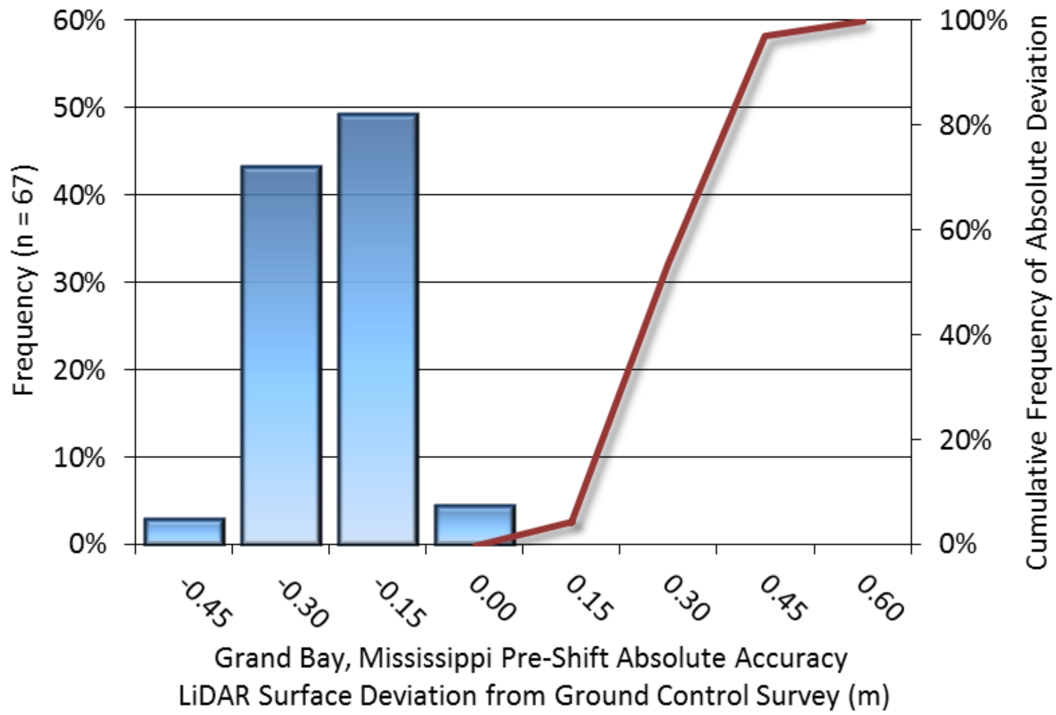


Figure 7: Frequency histogram for LiDAR surface deviation from ground control point values prior to shifting the dataset

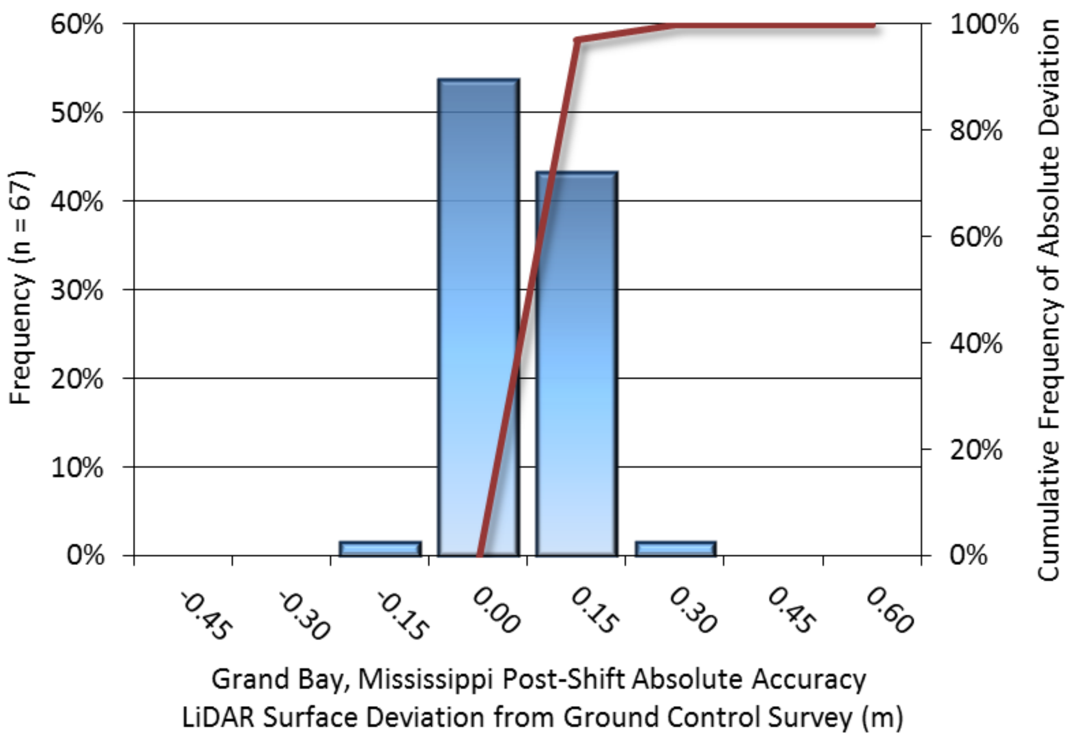


Figure 8: Frequency histogram for LiDAR surface deviation from ground control point values after shifting dataset

LiDAR Relative Vertical Accuracy

Relative vertical accuracy refers to the internal consistency of the data set as a whole: the ability to place an object in the same location given multiple flight lines, GPS conditions, and aircraft attitudes. When the LiDAR system is well calibrated, the swath-to-swath vertical divergence is low (<0.10 meters). The relative vertical accuracy was computed by comparing the ground surface model of each individual flight line with its neighbors in overlapping regions. The average (mean) line to line relative vertical accuracy for the Grand Bay LiDAR sites was 0.097 meters (Table 10, Figure 9).

Table 10: Relative accuracy results

Relative Accuracy	
Sample	189 surfaces
Average	0.097 m
Median	0.095 m
RMSE	0.095 m
Standard Deviation (1σ)	0.013 m
1.96σ	0.025 m

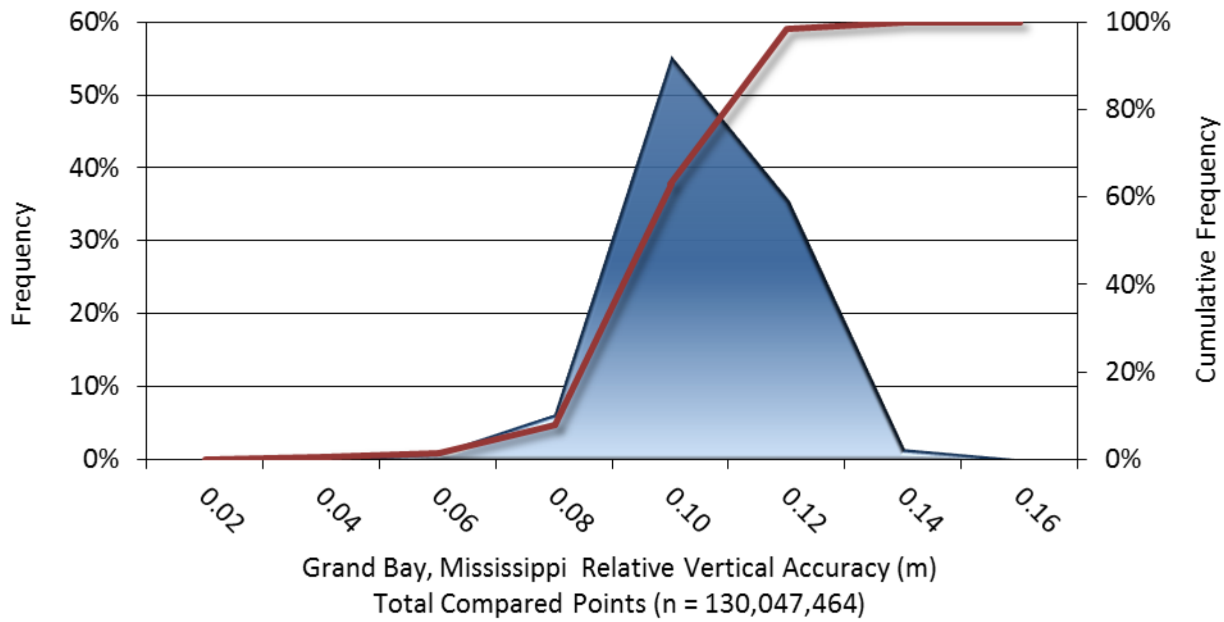


Figure 9: Frequency plot for relative vertical accuracy between flight lines

Digital Imagery Accuracy Assessment

Image accuracy was measured by air target locations collected by Precision Hawk. Air target GPS points were measured against the coordinate locations of the air target in the imagery. Once the ground survey air targets were identified in the collected digital imagery, the known coordinates were compared to the coordinates held in the digital imagery and the displacement was recorded for statistical analysis.

The circular standard error (CSE) for the Grand Bay, Mississippi sites was 0.092 meters measured by air targets. Table 11 presents the complete photo accuracy statistics, and Figure 10 contains a scatterplot showing congruence between orthophotos and aerial target locations. Circular standard error was approximated based on the FGDC National Standard for Spatial Data Accuracy for horizontal accuracy[2]. The CSE (at 39.35% confidence level) was computed as follows:

where $0.6 \leq RMSE_{min}/RMSE_{max} < 1.0$: $CSE = 0.5 * RMSE_{x} + RMSE_{y}$

Table 11: Orthophotography accuracy statistics for NOAA NERR Sites

Grand Bay, Mississippi Othophoto Accuracy Statistics			
	Air Targets$_x$	Air Targets$_y$	Air Targets$_{xy}$
(meters)	N = 41 points		
Mean	-0.002 m	0.014 m	0.014 m
Average Magnitude	0.091 m	0.057 m	0.107 m
RMSE	0.113 m	0.071 m	0.133 m
Standard Deviation (1σ)	0.114 m	0.070 m	0.134 m
1.96σ	0.223 m	0.138 m	0.262 m

[2] Federal Geographic Data Committee, Geospatial Positioning Accuracy Standards (FGDC-STD-007.3-1998). Part 3: National Standard for Spatial Data Accuracy, Appendix 3-A, page 3-10. http://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part3/chapter3

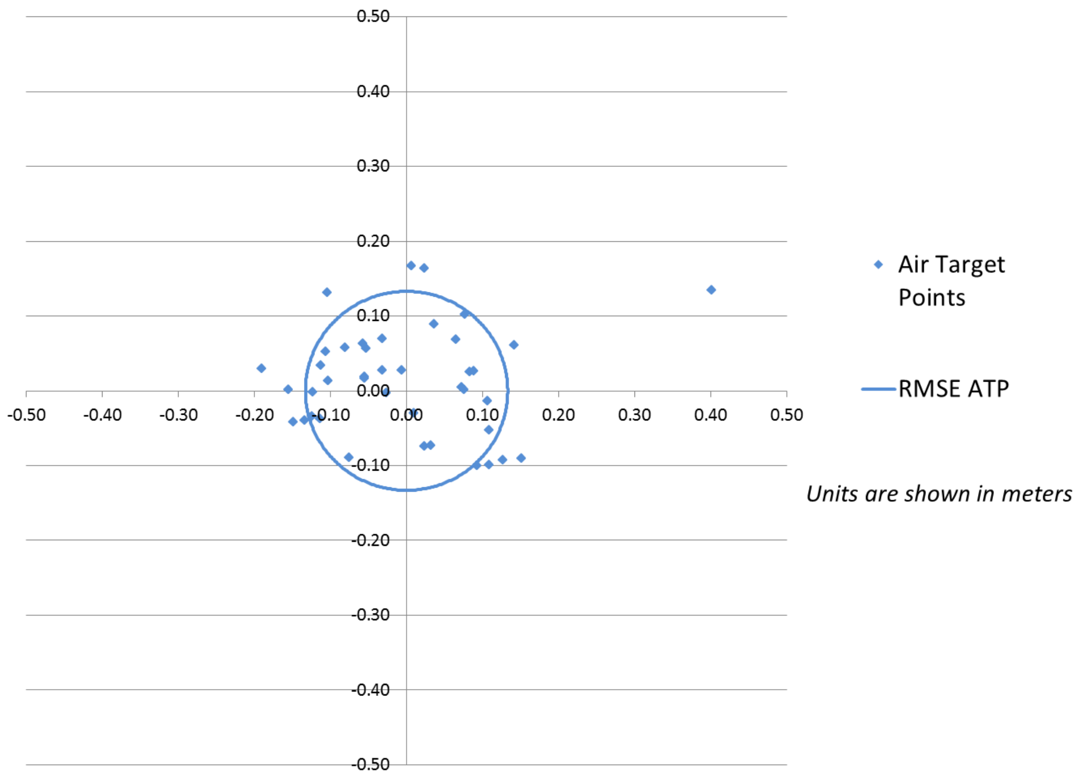


Figure 10: Scatterplot displaying the XY deviation of aerial target coordinates with imagery extracted coordinate locations.

GLOSSARY

1-sigma (σ) Absolute Deviation: Value for which the data are within one standard deviation (approximately 68th percentile) of a normally distributed data set.

1.96 * RMSE Absolute Deviation: Value for which the data are within two standard deviations (approximately 95th percentile) of a normally distributed data set, based on the FGDC standards for Non-vegetated Vertical Accuracy (NVA) reporting.

Accuracy: The statistical comparison between known (surveyed) points and laser points. Typically measured as the standard deviation (sigma σ) and root mean square error (RMSE).

> **Absolute Accuracy:** The vertical accuracy of LiDAR data is described as the mean and standard deviation (sigma σ) of divergence of LiDAR point coordinates from ground survey point coordinates. To provide a sense of the model predictive power of the dataset, the root mean square error (RMSE) for vertical accuracy is also provided. These statistics assume the error distributions for x, y and z are normally distributed, and thus we also consider the skew and kurtosis of distributions when evaluating error statistics.
>
> **Relative Accuracy:** Relative accuracy refers to the internal consistency of the data set; i.e., the ability to place a laser point in the same location over multiple flight lines, GPS conditions and aircraft attitudes. Affected by system attitude offsets, scale and GPS/IMU drift, internal consistency is measured as the divergence between points from different flight lines within an overlapping area. Divergence is most apparent when flight lines are opposing. When the LiDAR system is well calibrated, the line-to-line divergence is low (<10 cm).
>
> **Root Mean Square Error (RMSE):** A statistic used to approximate the difference between real-world points and the LiDAR points. It is calculated by squaring all the values, then taking the average of the squares and taking the square root of the average.

Data Density: A common measure of LiDAR resolution, measured as points per square meter.

Digital Elevation Model (DEM): File or database made from surveyed points, containing elevation points over a contiguous area. Digital terrain models (DTM) and digital surface models (DSM) are types of DEMs. DTMs consist solely of the bare earth surface (ground points), while DSMs include information about all surfaces, including vegetation and man-made structures.

Nadir: A single point or locus of points on the surface of the earth directly below a sensor as it progresses along its flight line.

Overlap: The area shared between flight lines, typically measured in percent. 55% overlap is essential to ensure complete coverage and reduce laser shadows.

Pulse Rate (PR): The rate at which laser pulses are emitted from the sensor; typically measured in thousands of pulses per second (kHz).

Pulse Returns: For every laser pulse emitted, the number of wave forms (i.e., echos) reflected back to the sensor. Portions of the wave form that return first are the highest element in multi-tiered surfaces such as vegetation. Portions of the wave form that return last are the lowest element in multi-tiered surfaces.

Scan Angle: The angle from nadir to the edge of the scan, measured in degrees. Laser point accuracy typically decreases as scan angles increase.

Native LiDAR Density: The number of pulses emitted by the LiDAR system, commonly expressed as pulses per square meter.

Relative Accuracy Calibration Methodology:

Manual System Calibration: Calibration procedures for each mission require solving geometric relationships that relate measured swath-to-swath deviations to misalignments of system attitude parameters. Corrected scale, pitch, roll and heading offsets were calculated and applied to resolve misalignments. The raw divergence between lines was computed after the manual calibration was completed and reported for each survey area.

Automated Attitude Calibration: All data were tested and calibrated using TerraMatch automated sampling routines. Ground points were classified for each individual flight line and used for line-to-line testing. System misalignment offsets (pitch, roll and heading) and scale were solved for each individual mission and applied to respective mission datasets. The data from each mission were then blended when imported together to form the entire area of interest.

Automated Z Calibration: Ground points per line were used to calculate the vertical divergence between lines caused by vertical GPS drift. Automated Z calibration was the final step employed for relative accuracy calibration.

LiDAR accuracy error sources and solutions:

Type of Error	Source	Post Processing Solution
GPS (Static/Kinematic)	Long Base Lines	None
	Poor Satellite Constellation	None
	Poor Antenna Visibility	Reduce Visibility Mask
Relative Accuracy	Poor System Calibration	Recalibrate IMU and sensor offsets/settings
	Inaccurate System	None
Laser Noise	Poor Laser Timing	None
	Poor Laser Reception	None
	Poor Laser Power	None
	Irregular Laser Shape	None

Operational measures taken to improve relative accuracy:

Low Flight Altitude: Terrain following was employed to maintain a constant above ground level (AGL). Laser horizontal errors are a function of flight altitude above ground (about 1/3000th AGL flight altitude).

Focus Laser Power at narrow beam footprint: A laser return must be received by the system above a power threshold to accurately record a measurement. The strength of the laser return (i.e., intensity) is a function of laser emission power, laser footprint, flight altitude and the reflectivity of the target. While surface reflectivity cannot be controlled, laser power can be increased and low flight altitudes can be maintained.

Reduced Scan Angle: Edge-of-scan data can become inaccurate. The scan angle was reduced to a maximum of $\pm 30^{o}$ from nadir, creating a narrow swath width and greatly reducing laser shadows from trees and buildings.

Quality GPS: Flights took place during optimal GPS conditions (e.g., 6 or more satellites and PDOP [Position Dilution of Precision] less than 3.0). Before each flight, the PDOP was determined for the survey day. During all flight times, a dual frequency DGPS base station recording at 1 second epochs was utilized and a maximum baseline length between the aircraft and the control points was less than 13 nm at all times.

Ground Survey: Ground survey point accuracy (<1.5 cm RMSE) occurs during optimal PDOP ranges and targets a minimal baseline distance of 4 miles between GPS rover and base. Robust statistics are, in part, a function of sample size (n) and distribution. Ground survey points are distributed to the extent possible throughout multiple flight lines and across the survey area.

50% Side-Lap (100% Overlap): Overlapping areas are optimized for relative accuracy testing. Laser shadowing is minimized to help increase target acquisition from multiple scan angles. Ideally, with a 50% side-lap, the nadir portion of one flight line coincides with the swath edge portion of overlapping flight lines. A minimum of 50% side-lap with terrain-followed acquisition prevents data gaps.

Opposing Flight Lines: All overlapping flight lines have opposing directions. Pitch, roll and heading errors are amplified by a factor of two relative to the adjacent flight line(s), making misalignments easier to detect and resolve.

APPENDIX B - OPUS SOLUTION

(OPUS Solution Report provided by Precision Hawk, this page intentionally left blank)

Base station coordinates OPUS solution

May 9, 2017

FILE: base_0905.17_ OP1494864688113

1008 NOTE: Antenna offsets supplied by the user were <=0. Coordinates
1008 returned will be for the antenna reference point (ARP).
1008

NGS OPUS SOLUTION REPORT
========================

All computed coordinate accuracies are listed as peak-to-peak values.
For additional information: https://www.ngs.noaa.gov/OPUS/about.jsp#accuracy

USER: v.miller@precisionhawk.com DATE: May 15, 2017
RINEX FILE: base129s.17o TIME: 16:12:52 UTC

SOFTWARE: page5 1209.04 master56.pl 160321 START: 2017/05/09 18:00:00
EPHEMERIS: igr19482.eph [rapid] STOP: 2017/05/09 20:03:00
NAV FILE: brdc1290.17n OBS USED: 5604 / 5753 : 97%
ANT NAME: APSAPS-NR2 NONE # FIXED AMB: 39 / 42 : 93%
ARP HEIGHT: 0.000 OVERALL RMS: 0.015(m)

REF FRAME: NAD_83(2011)(EPOCH:2010.0000) IGS08 (EPOCH:2017.3529)

X: 152877.051(m) 0.004(m) 152876.239(m) 0.004(m)
Y: -5504695.421(m) 0.018(m) -5504693.921(m) 0.018(m)
Z: 3207169.427(m) 0.007(m) 3207169.252(m) 0.007(m)

LAT: 30 23 2.96169 0.006(m) 30 23 2.98178 0.006(m)
E LON: 271 35 26.93847 0.004(m) 271 35 26.90963 0.004(m)
W LON: 88 24 33.06153 0.004(m) 88 24 33.09037 0.004(m)
EL HGT: -25.907(m) 0.019(m) -27.308(m) 0.019(m)
ORTHO HGT: 2.192(m) 0.037(m) [NAVD88 (Computed using GEOID12B)]

	UTM COORDINATES	STATE PLANE COORDINATES
	UTM (Zone 16)	SPC (2301 MS E)
Northing (Y) [meters]	3362196.447	98081.419
Easting (X) [meters]	364607.295	340764.218
Convergence [degrees]	-0.71286701	0.21453579
Point Scale	0.99982615	0.99997049
Combined Factor	0.99983022	0.99997456

US NATIONAL GRID DESIGNATOR: 16RCU6460762196(NAD 83)

BASE STATIONS USED

PID DESIGNATION LATITUDE LONGITUDE DISTANCE(m)
DL3486 ALDI DAUPHIN ISLAND CORS ARP N301456.987 W0880440.688 35195.5
DL7331 ALFO FOLEY CORS ARP N302501.021 W0874030.260 70638.5
DO2054 ALMJ MCDAVIDJONESSCH2 CORS ARP N310144.313 W0881347.068 73525.1

NEAREST NGS PUBLISHED CONTROL POINT

BH2204 MIDDLE N302303.077 W0882345.317 1274.7

May 10, 2017

FILE: base2564.17_ OP1494863518341

1008 NOTE: Antenna offsets supplied by the user were <=0. Coordinates
1008 returned will be for the antenna reference point (ARP).
1008

NGS OPUS SOLUTION REPORT
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All computed coordinate accuracies are listed as peak-to-peak values.
For additional information: https://www.ngs.noaa.gov/OPUS/about.jsp#accuracy

USER: v.miller@precisionhawk.com DATE: May 15, 2017
RINEX FILE: base130v.17o TIME: 15:53:51 UTC

SOFTWARE: page5 1209.04 master95.pl 160321 START: 2017/05/10 21:00:00
EPHEMERIS: igr19483.eph [rapid] STOP: 2017/05/10 23:59:00
NAV FILE: brdc1300.17n OBS USED: 8142 / 8374 : 97%
ANT NAME: APSAPS-NR2 NONE # FIXED AMB: 49 / 50 : 98%
ARP HEIGHT: 0.000 OVERALL RMS: 0.018(m)

REF FRAME: NAD_83(2011)(EPOCH:2010.0000) IGS08 (EPOCH:2017.3560)

X: 152876.926(m) 0.011(m) 152876.114(m) 0.011(m)
Y: -5504696.899(m) 0.017(m) -5504695.399(m) 0.017(m)
Z: 3207167.059(m) 0.010(m) 3207166.884(m) 0.010(m)

LAT: 30 23 2.87114 0.003(m) 30 23 2.89124 0.003(m)
E LON: 271 35 26.93225 0.010(m) 271 35 26.90341 0.010(m)
W LON: 88 24 33.06775 0.010(m) 88 24 33.09659 0.010(m)
EL HGT: -25.833(m) 0.020(m) -27.234(m) 0.020(m)
ORTHO HGT: 2.266(m) 0.038(m) [NAVD88 (Computed using GEOID12B)]

UTM COORDINATES   STATE PLANE COORDINATES
UTM (Zone 16)   SPC (2301 MS E)
Northing (Y) [meters]   3362193.661   98078.631
Easting (X) [meters]   364607.095   340764.063
Convergence [degrees]   -0.71286735   0.21453476
Point Scale   0.99982615   0.99997049
Combined Factor   0.99983021   0.99997455

US NATIONAL GRID DESIGNATOR: 16RCU6460762193(NAD 83)

BASE STATIONS USED

PID	DESIGNATION	LATITUDE	LONGITUDE	DISTANCE(m)
DL7331	ALFO FOLEY CORS ARP	N302501.021	W0874030.260	70638.8
DL3486	ALDI DAUPHIN ISLAND CORS ARP	N301456.987	W0880440.688	35194.5
DN8737	MSIN INFINITY CENTER CORS ARP	N301842.205	W0893615.507	115186.0

NEAREST NGS PUBLISHED CONTROL POINT

BH2204   MIDDLE   N302303.077 W0882345.317   1274.9

May 11, 2017 – FS-2562

FILE: base2562_1105.17_ OP1494863296042

1008   NOTE: Antenna offsets supplied by the user were <=0. Coordinates
1008   returned will be for the antenna reference point (ARP).
1008

NGS OPUS SOLUTION REPORT
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All computed coordinate accuracies are listed as peak-to-peak values.
For additional information: https://www.ngs.noaa.gov/OPUS/about.jsp#accuracy

USER: v.miller@precisionhawk.com   DATE: May 15, 2017
RINEX FILE: base131p.17o   TIME: 15:50:18 UTC

SOFTWARE: page5 1209.04 master58.pl 160321   START: 2017/05/11 15:00:00
EPHEMERIS: igr19484.eph [rapid]   STOP: 2017/05/11 17:59:00
NAV FILE: brdc1310.17n   OBS USED: 7794 / 8109   : 96%
ANT NAME: APSAPS-NR2   NONE   # FIXED AMB: 44 /   47   : 94%
ARP HEIGHT: 0.000   OVERALL RMS: 0.017(m)

REF FRAME: NAD_83(2011)(EPOCH:2010.0000)   IGS08 (EPOCH:2017.3580)

X:	152300.904(m)	0.006(m)	152300.092(m)	0.006(m)
Y:	-5506153.623(m)	0.013(m)	-5506152.122(m)	0.013(m)
Z:	3204709.711(m)	0.009(m)	3204709.536(m)	0.009(m)

LAT:	30 21 30.37609	0.008(m)	30 21 30.39618	0.008(m)
E LON:	271 35 3.85622	0.006(m)	271 35 3.82738	0.006(m)
W LON:	88 24 56.14378	0.006(m)	88 24 56.17262	0.006(m)
EL HGT:	-25.709(m)	0.015(m)	-27.112(m)	0.015(m)
ORTHO HGT:	2.324(m)	0.031(m) [NAVD88 (Computed using GEOID12B)]		

	UTM COORDINATES	STATE PLANE COORDINATES
	UTM (Zone 16)	SPC (2301 MS E)
Northing (Y) [meters]	3359353.753	95228.146
Easting (X) [meters]	363955.588	340158.503
Convergence [degrees]	-0.71556328	0.21113086
Point Scale	0.99982833	0.99996989
Combined Factor	0.99983237	0.99997393

US NATIONAL GRID DESIGNATOR: 16RCU6395559353(NAD 83)

BASE STATIONS USED

PID	DESIGNATION	LATITUDE	LONGITUDE	DISTANCE(m)
DN8737	MSIN INFINITY CENTER CORS ARP	N301842.205	W0893615.507	114421.9
DL7331	ALFO FOLEY CORS ARP	N302501.021	W0874030.260	71465.3
DO2054	ALMJ MCDAVIDJONESSCH2 CORS ARP	N310144.313	W0881347.068	76441.3

NEAREST NGS PUBLISHED CONTROL POINT

BH2190	JOSE	N302136.625	W0882508.981	393.2

May 11, 2017 – FS-2564

FILE: basefile_1.obs OP1494968464905

1008 NOTE: Antenna offsets supplied by the user were <=0. Coordinates
1008 returned will be for the antenna reference point (ARP).
1008

NGS OPUS SOLUTION REPORT
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All computed coordinate accuracies are listed as peak-to-peak values.
For additional information: https://www.ngs.noaa.gov/OPUS/about.jsp#accuracy

USER: v.miller@precisionhawk.com DATE: May 16, 2017
RINEX FILE: base131s.17o TIME: 21:01:56 UTC

SOFTWARE: page5 1209.04 master98.pl 160321 START: 2017/05/11 18:28:00
EPHEMERIS: igr19484.eph [rapid] STOP: 2017/05/11 20:59:00
NAV FILE: brdc1310.17n OBS USED: 6907 / 7028 : 98%
ANT NAME: APSAPS-NR2 NONE # FIXED AMB: 36 / 39 : 92%
ARP HEIGHT: 0.000 OVERALL RMS: 0.014(m)

REF FRAME:	NAD_83(2011)(EPOCH:2010.0000)		IGS08 (EPOCH:2017.3584)	
X:	152614.399(m)	0.007(m)	152613.587(m)	0.007(m)
Y:	-5505168.286(m)	0.011(m)	-5505166.785(m)	0.011(m)
Z:	3206375.554(m)	0.002(m)	3206375.379(m)	0.002(m)
LAT:	30 22 33.07816	0.007(m)	30 22 33.09827	0.007(m)
E LON:	271 35 16.61347	0.007(m)	271 35 16.58463	0.007(m)
W LON:	88 24 43.38653	0.007(m)	88 24 43.41537	0.007(m)
EL HGT:	-25.900(m)	0.009(m)	-27.302(m)	0.009(m)
ORTHO HGT:	2.178(m)	0.024(m) [NAVD88 (Computed using GEOID12B)]		

	UTM COORDINATES	STATE PLANE COORDINATES
	UTM (Zone 16)	SPC (2301 MS E)
Northing (Y) [meters]	3361279.873	97160.187
Easting (X) [meters]	364320.240	340491.994
Convergence [degrees]	-0.71414183	0.21303243
Point Scale	0.99982711	0.99997022
Combined Factor	0.99983118	0.99997429

US NATIONAL GRID DESIGNATOR: 16RCU6432061279(NAD 83)

BASE STATIONS USED

PID	DESIGNATION	LATITUDE	LONGITUDE	DISTANCE(m)
DL7331	ALFO FOLEY CORS ARP	N302501.021	W0874030.260	70969.9
DN8737	MSIN INFINITY CENTER CORS ARP	N301842.205	W0893615.507	114855.5
DL3486	ALDI DAUPHIN ISLAND CORS ARP	N301456.987	W0880440.688	35068.0

NEAREST NGS PUBLISHED CONTROL POINT

BH2204	MIDDLE	N302303.077	W0882345.317	1804.8