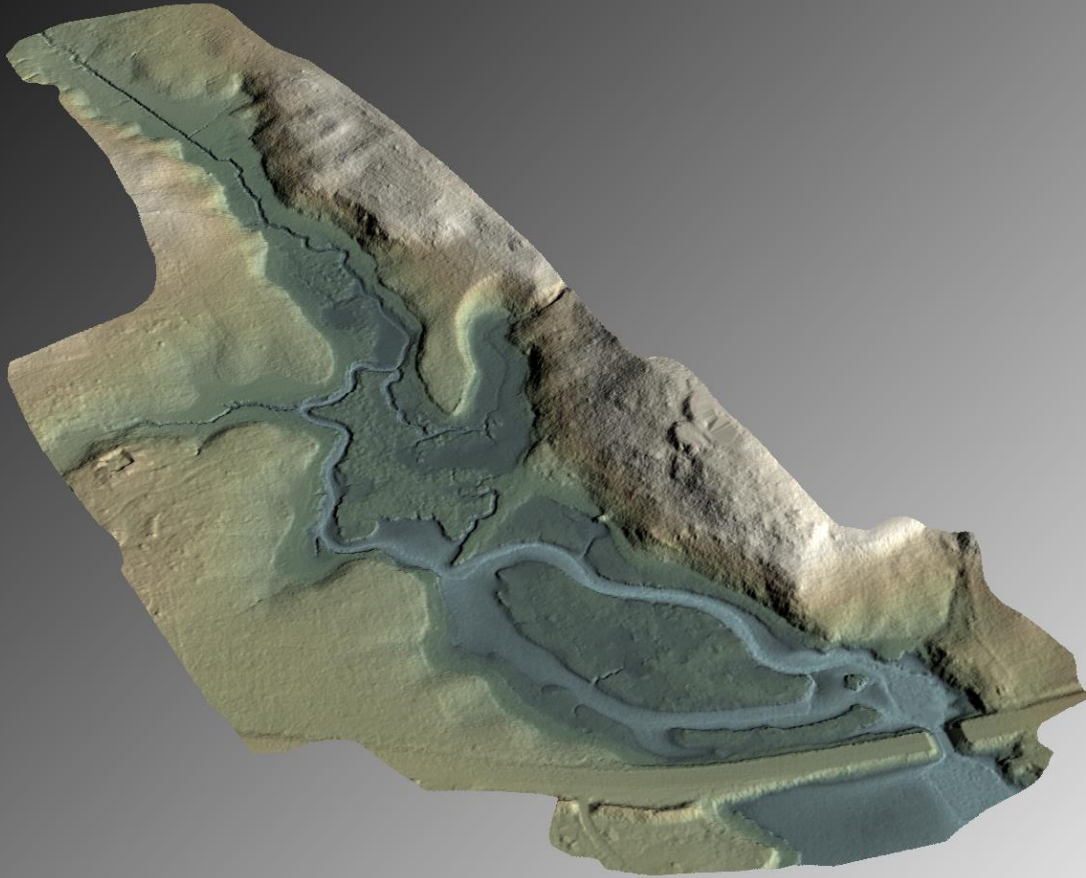**July 12, 2019**

NOAA Great Bay UAS, New Hampshire LiDAR Technical Data Report

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Cover Photo: A view looking north over Site 4 just east of the city of Durham, New Hampshire. The image was created from the LiDAR bare earth model and colored by elevation.

This photo taken by Air Shark acquisition staff shows a view of tidal marsh grass landscape within one of the NOAA Great Bay UAS sites in New Hampshire.

In April 2019, Quantum Spatial (QSI) was contracted by The National Oceanic and Atmospheric Administration (NOAA) Office for Coastal Management (OCM) in partnership with the Great Bay National Estuarine Research Reserve (GBNERR) to collect high resolution Light Detection and Ranging (LiDAR) data in the spring of 2019 for four research sites within the GBNERR in New Hampshire. These four sites are "Sentinel Sites" within the GBNERR where vegetation and elevation parameters have previously been continuously monitored and surveyed using traditional methods that require extensive person hours and manual labor. Data were collected to aid NOAA & GBNERR in assessing the viability of using non-invasive remote sensing survey techniques to monitor these sentinel sites and reduce the impacts of traditional survey techniques on the marsh environment.

This report accompanies the delivered LiDAR data and documents contract specifications, data acquisition procedures, 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 Great Bay UAS sites

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
NOAA Great Bay UAS, NH	64	142	05/01/2019, 05/07/2019 – 05/09/2019	NIR High Resolution LiDAR

Deliverable Products

Table 2: Products delivered to NOAA for the NOAA Great Bay UAS sites

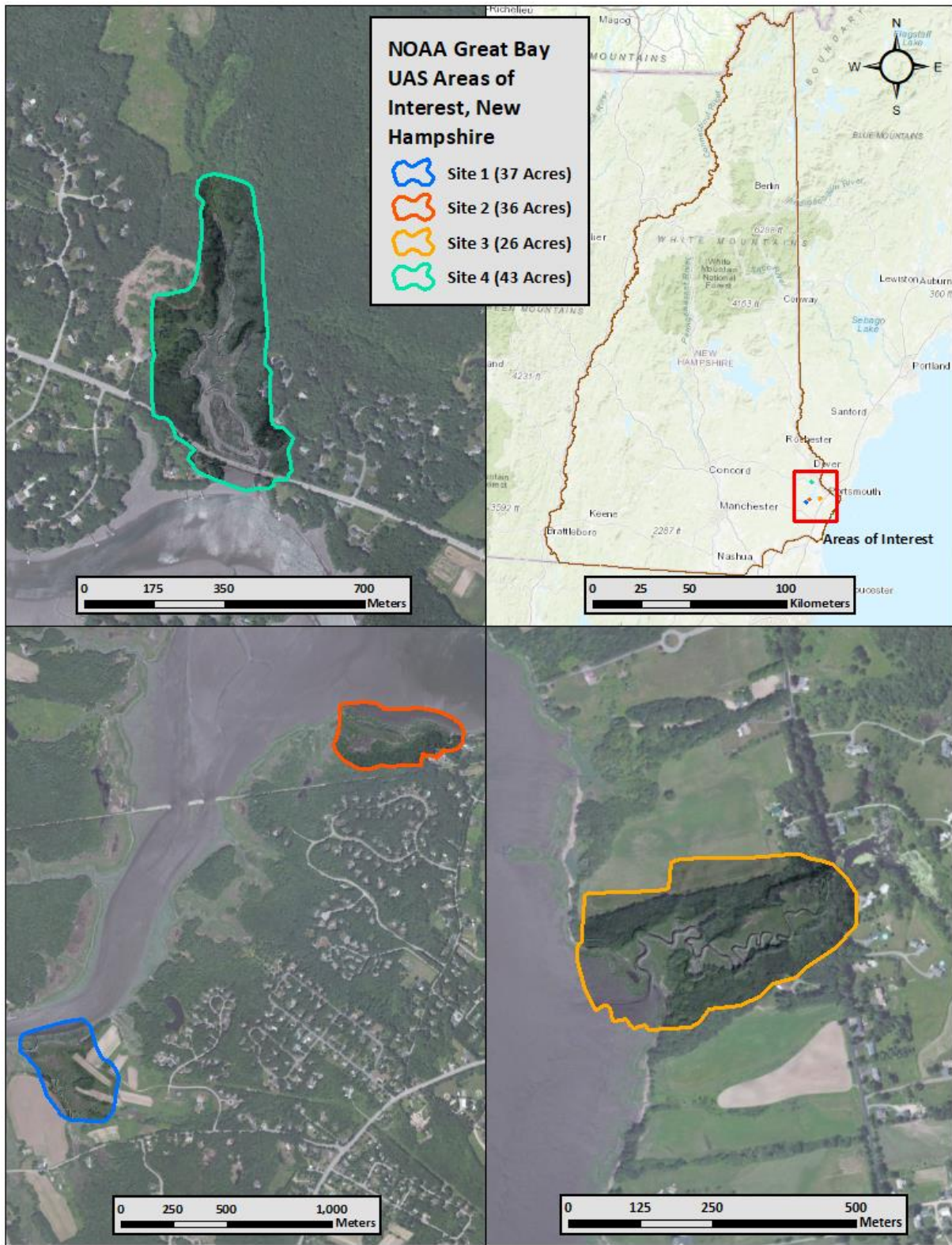| NOAA Great Bay UAS LiDAR Products Projection: UTM Zone 19 North Horizontal Datum: NAD83 (2011) Vertical Datum: NAVD88 (GEOID12B) Units: Meters	
Points	LAS v 1.4 • All Classified Returns
Rasters	0.5 Meter ERDAS Imagine Files (*.img) • Bare Earth Digital Elevation Model (DEM)
Vectors	Shapefiles (*.shp) • Area of Interest • Flightline Shapes

Figure 1: Location map of the NOAA Great Bay UAS sites in New Hampshire

A DJI Matrice 600 equipped with a
Riegl MiniVUX-1UAV LiDAR Sensor

Planning

QSI subcontracted Air Shark, a subsidiary of ARE, to perform the aerial survey of the four sites. A specially designed flight plan relative to the NOAA Great Bay LiDAR study areas was collaboratively developed by Air Shark and QSI to ensure complete coverage at the target point density of ≥8.0 points/m^2 (0.74 points/ft^2) and availability of ground control. Acquisition parameters including orientation relative to terrain, flight altitude, pulse rate, scan angle, and ground speed were adapted to optimize flight paths and flight times while meeting all contract specifications.

Factors such as satellite constellation availability and weather windows must be considered during the planning stage. Any weather hazards or conditions affecting the flight were continuously monitored due to their potential impact on the daily success of airborne and ground operations. In addition, logistical considerations including private property access and potential air space restrictions were reviewed. Line of site flight was also taken into consideration to meet FAA small UAS regulations as well as maintaining the safety of participants and safe operation of the UAS.

Airborne LiDAR Survey

The LiDAR survey was accomplished using a Riegl MiniVUX-1UAV system mounted on a DJI Matrice 600 drone. Table 3 summarizes the settings used to yield an average pulse density of ≥8 pulses/m^2 over the NOAA Great Bay UAS project area. The Riegl MiniVUX-1UAV laser system has multiple target capability and can record up to five range measurements (returns) per pulse. It is not uncommon for some types of surfaces (e.g., dense vegetation or water) to return fewer pulses to the LiDAR sensor than the laser originally emitted. The discrepancy between first return and overall delivered density will vary depending on terrain, land cover, and the prevalence of water bodies. All discernible laser returns were processed for the output dataset.

Table 3: LiDAR specifications and survey settings

LiDAR Survey Settings & Specifications	
Acquisition Dates	May 01, 2019 – May 09, 2019
Aircraft Used	DJI Matrice 600
Sensor	Riegl
Laser	MiniVUX–1UAV
Maximum Returns	5
Resolution/Density	Average 8 pulses/m^2
Nominal Pulse Spacing	0.35 m
Survey Altitude (AGL)	60 m
Survey speed	7.775 knots
Field of View	90⁰
Mirror Scan Rate	40.38 Hz
Target Pulse Rate	100 kHz
Laser Pulse Footprint Diameter	9.6 cm x 3.0 cm
Central Wavelength	905 nm
Pulse Mode	Linear Mode LiDAR
Beam Divergence	1.6 mrads x 0.5 mrads
Swath Width	120 m
Swath Overlap	50%
Intensity	16-bit
Accuracy	RMSE$_Z$ (Non-Vegetated) ≤ 5 cm
	NVA (95% Confidence Level) ≤ 9.8 cm
	VVA (95th Percentile) ≤ 15 cm

Riegl MiniVUX-1UAV LiDAR sensor mounted on a DJI Matrice 600.

All areas were surveyed with an opposing flight line side-lap of ≥50% (≥100% overlap) in order to reduce laser shadowing and increase surface laser painting. To accurately solve for laser point position (geographic coordinates x, y and z), the positional coordinates of the airborne sensor and the attitude of the aircraft were recorded continuously throughout the LiDAR data collection mission. Position of the aircraft was measured twice per second (2 Hz) by an onboard differential GPS unit, and aircraft attitude was measured 200 times per second (200 Hz) as pitch, roll and yaw (heading) from an onboard inertial measurement unit (IMU). To allow for post-processing correction and calibration, aircraft and sensor position and attitude data are indexed by GPS time.

A photo taken by Air Shark acquisition staff showing the tidal marsh grass landscape within Site 2.

Ground Control

Ground control surveys, including monumentation and ground survey points (GSPs) were conducted by NOAA to support the airborne acquisition. Ground control data were used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on final LiDAR data products. NOAA completed ground survey point collection on behalf of QSI, at locations determined suitable by QSI surveying professionals while minimizing impact on the habitat.

Table 4: Monuments established for the NOAA Great Bay UAS acquisition. Coordinates are on the NAD83 (CORS96) datum, epoch 2002.00

Monument ID	Latitude	Longitude	Ellipsoid (meters)
Site_1	43° 02' 23.25599"	-70° 55' 39.24113"	-25.656
Site_2	43° 03' 20.97360"	-70° 54' 02.09225"	-25.407
Site_3	43° 03' 46.15189"	-70° 50' 00.23312"	-21.303
Site_4	43° 08' 18.48890"	-70° 53' 18.90424"	-12.993

To correct the continuously recorded onboard measurements of the aircraft position, NOAA concurrently conducted multiple static Global Navigation Satellite System (GNSS) ground surveys (1 Hz recording frequency) over each monument. During post-processing, the static GPS data were triangulated with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS[1]) for precise positioning. Multiple independent sessions over the same monument were processed to confirm antenna height measurements and to refine position accuracy.

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[1] OPUS is a free service provided by the National Geodetic Survey to process corrected monument positions. http://www.ngs.noaa.gov/OPUS.
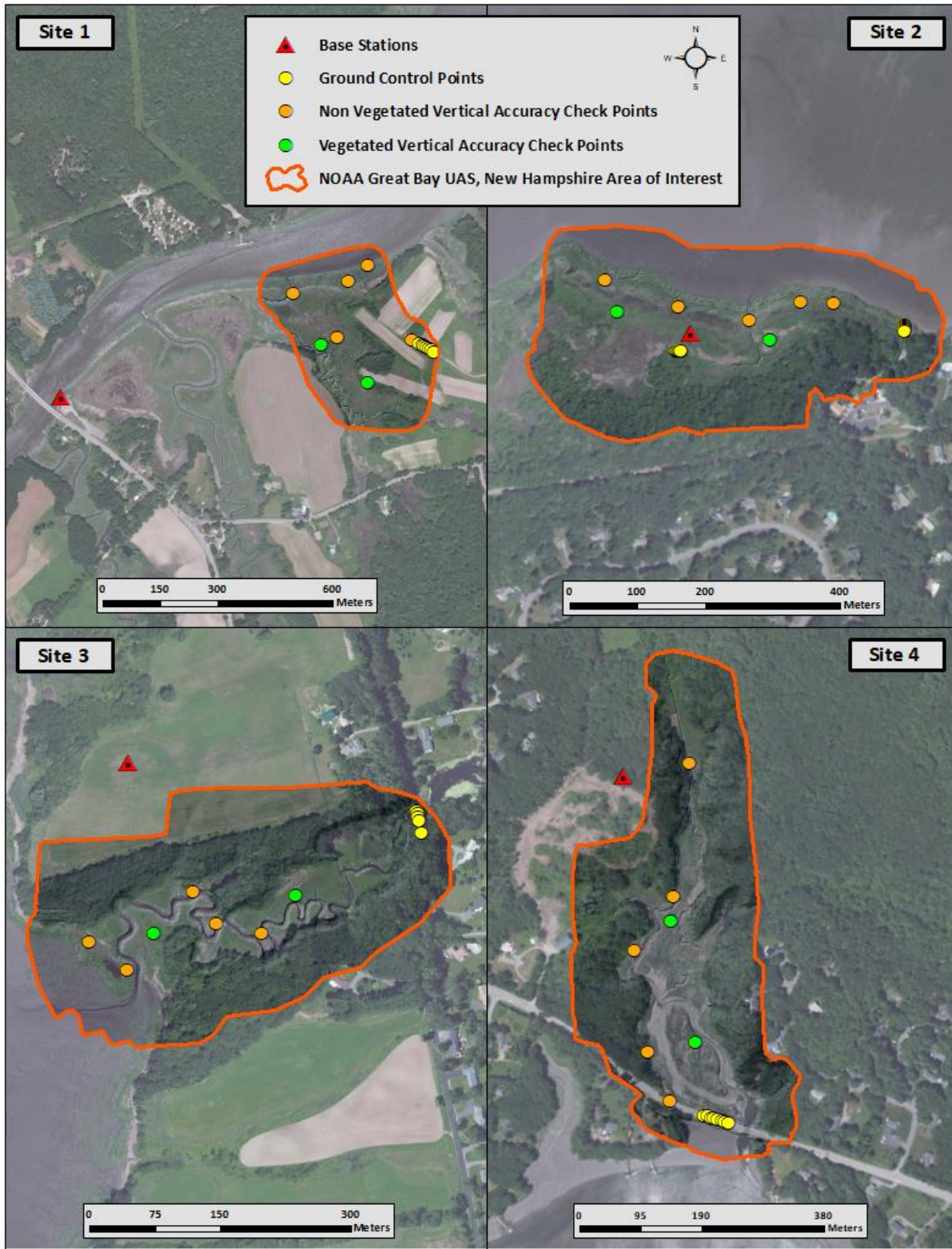
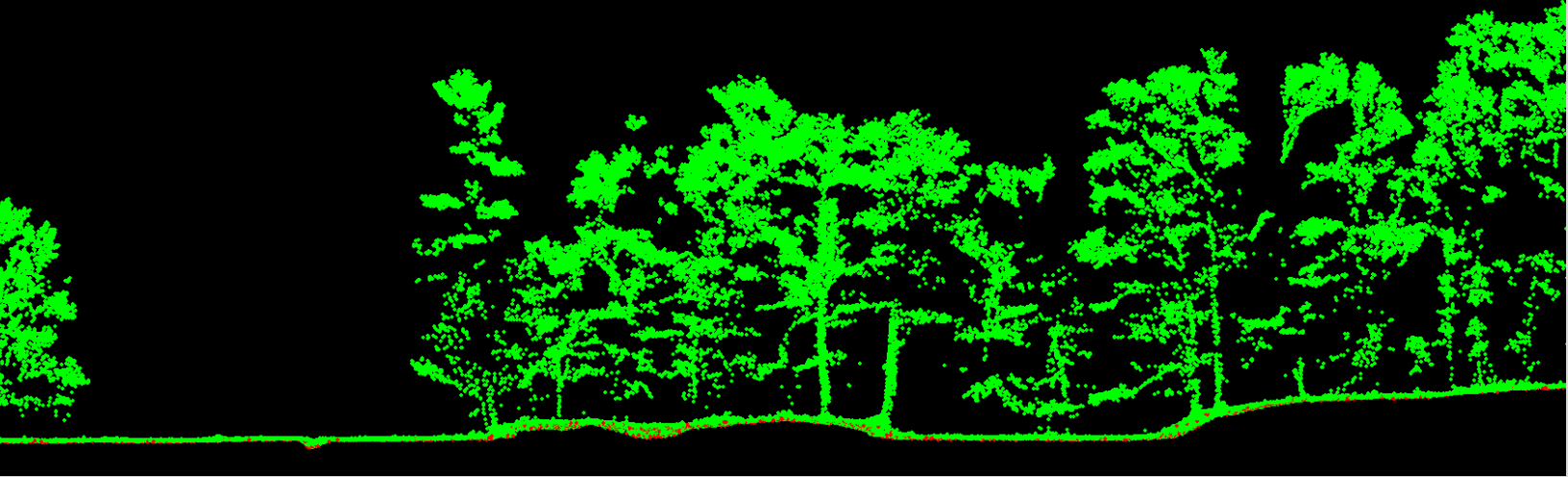**Figure 2: Ground Survey Location Map**

This 1 meter LiDAR cross section shows a view of the NOAA Great Bay UAS landscape, colored by point classification.

LiDAR Data

Upon completion of data acquisition, QSI processing staff initiated a suite of automated and manual techniques to process the data into the requested deliverables. Processing tasks included GPS control computations, smoothed best estimate trajectory (SBET) calculations, kinematic corrections, calculation of laser point position, sensor and data calibration for optimal relative and absolute accuracy, and LiDAR point classification (Table 5). 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 Great Bay UAS dataset

| Classification Number	Classification Name	Classification Description
1	Default/Unclassified	Laser returns that are not included in the ground class, composed of vegetation and anthropogenic features
1 - O	Overlap/Edge Clip	Flightline edge clip, identified using the overlap flag
2	Ground	Laser returns that are determined to be ground using automated and manual cleaning algorithms
7	Noise	Laser returns that are often associated with birds, scattering from reflective surfaces, or artificial points below the ground surface

Table 6: LiDAR processing workflow

LiDAR Processing Step	Software Used
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.	POSPac MMS v.8.3
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. 1.4) format. Convert data to orthometric elevations by applying a geoid correction. Calibration was completed using Riegl's RiPrecision to tie together scan lines to control.	RiProcess v.1.8.5
Import raw laser points into manageable blocks to perform manual relative accuracy calibration and filter erroneous points. Classify ground points for individual flight lines.	TerraScan v.19.005
Check Riegl's calibration by generating final measure matches and Z shifting to control. Use every flight line for relative accuracy assessment.	TerraMatch v.19.002
Classify resulting data to ground and other client designated ASPRS classifications (Table 5). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.19.005 TerraModeler v.19.005 Las Monkey 2.3.4(QSI proprietary)
Generate bare earth models as triangulated surfaces. Export all surface models in EDRAS Imagine (.img) format at a 0.5 meter pixel resolution.	LAS Product Creator 3.3.7 (QSI proprietary)
Correct intensity values for variability.	Las Monkey 2.3.4(QSI proprietary)

Only Echo — (green)
First of Many — (red)
Intermediate — (yellow)
Last of Many — (cyan)

This 2 meter LiDAR cross section shows a view of vegetation and bare ground in the NOAA Great Bay project area, colored by point laser echo.
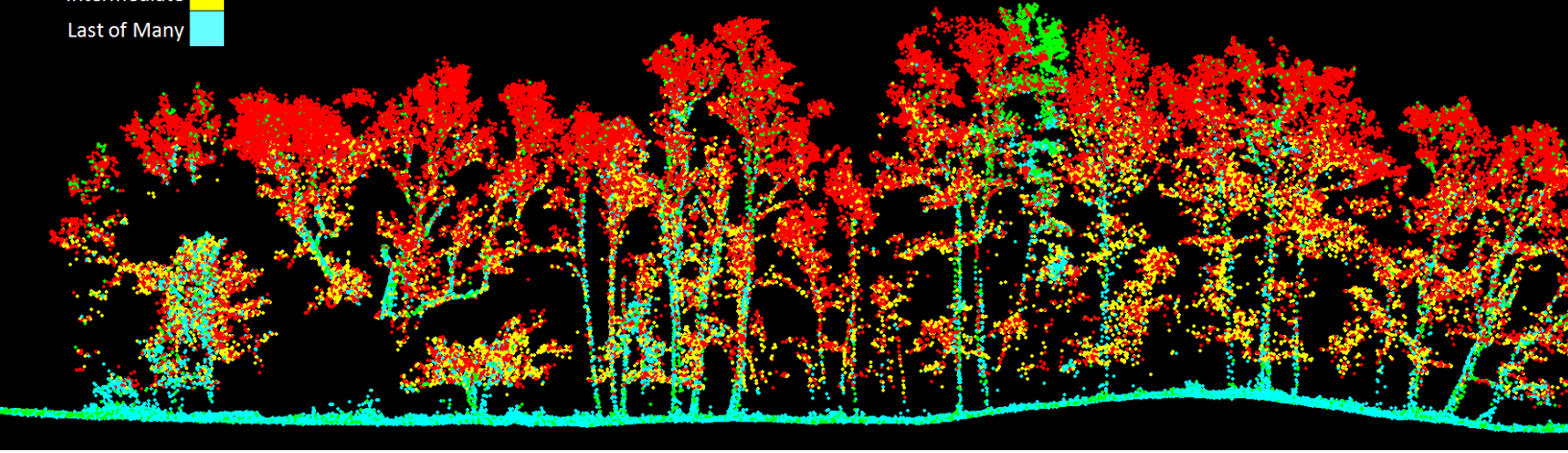
LiDAR Density

The acquisition parameters were designed to acquire an average first-return density of 8 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 NOAA Great Bay UAS project was 425.69 points/m^2 while the average ground classified density was 22.85 points/m^2 (Table 7). 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 7: Average LiDAR point densities

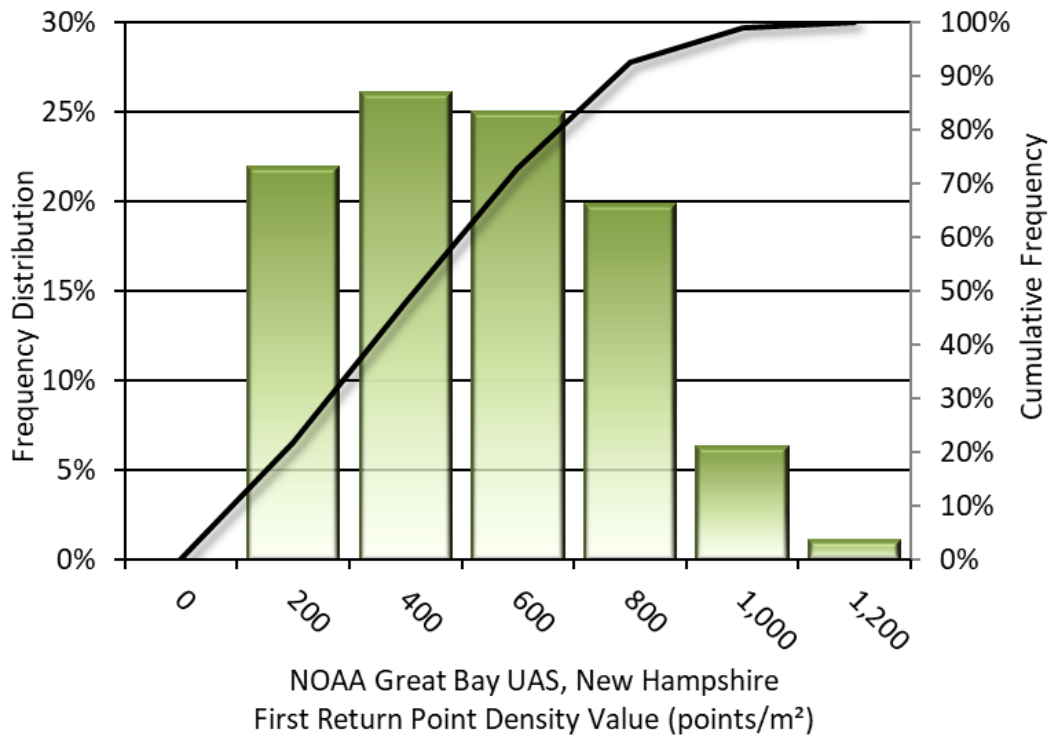| Classification	Point Density
First-Return	425.69 points/m^2
Ground Classified	22.85 points/m^2

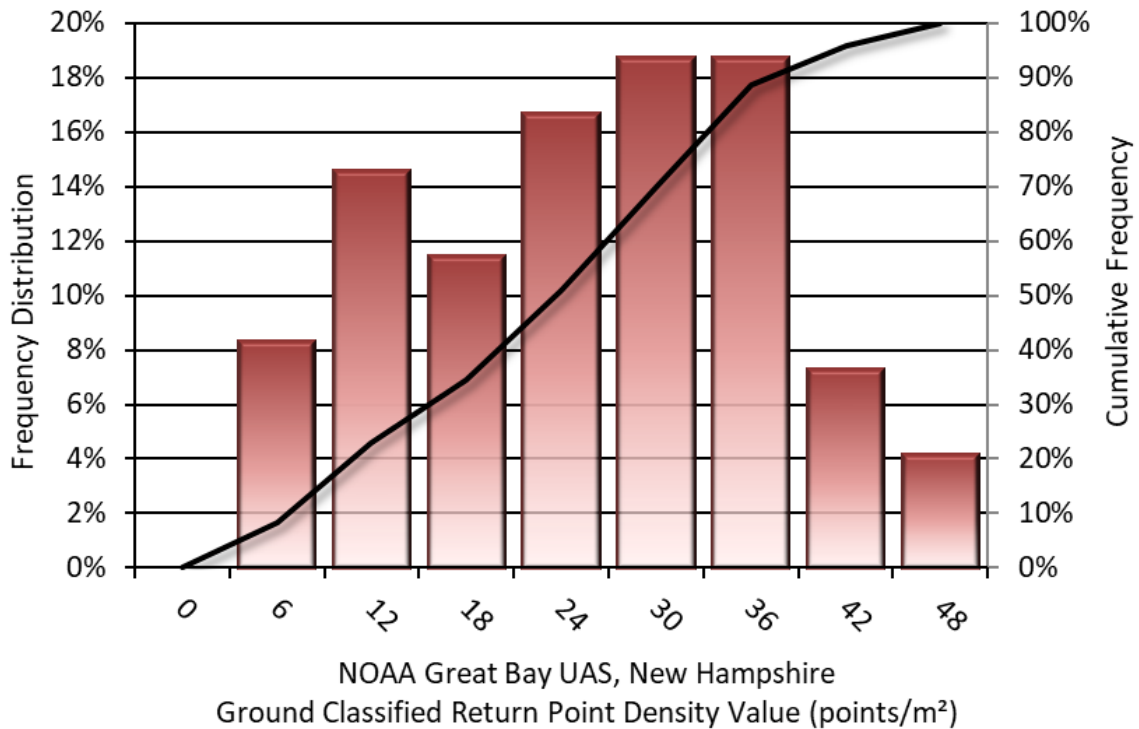**Figure 3: Frequency distribution of first return point density values per 100 x 100 m cell**

Figure 4: Frequency distribution of ground-classified return point density values per 100 x 100 m cell
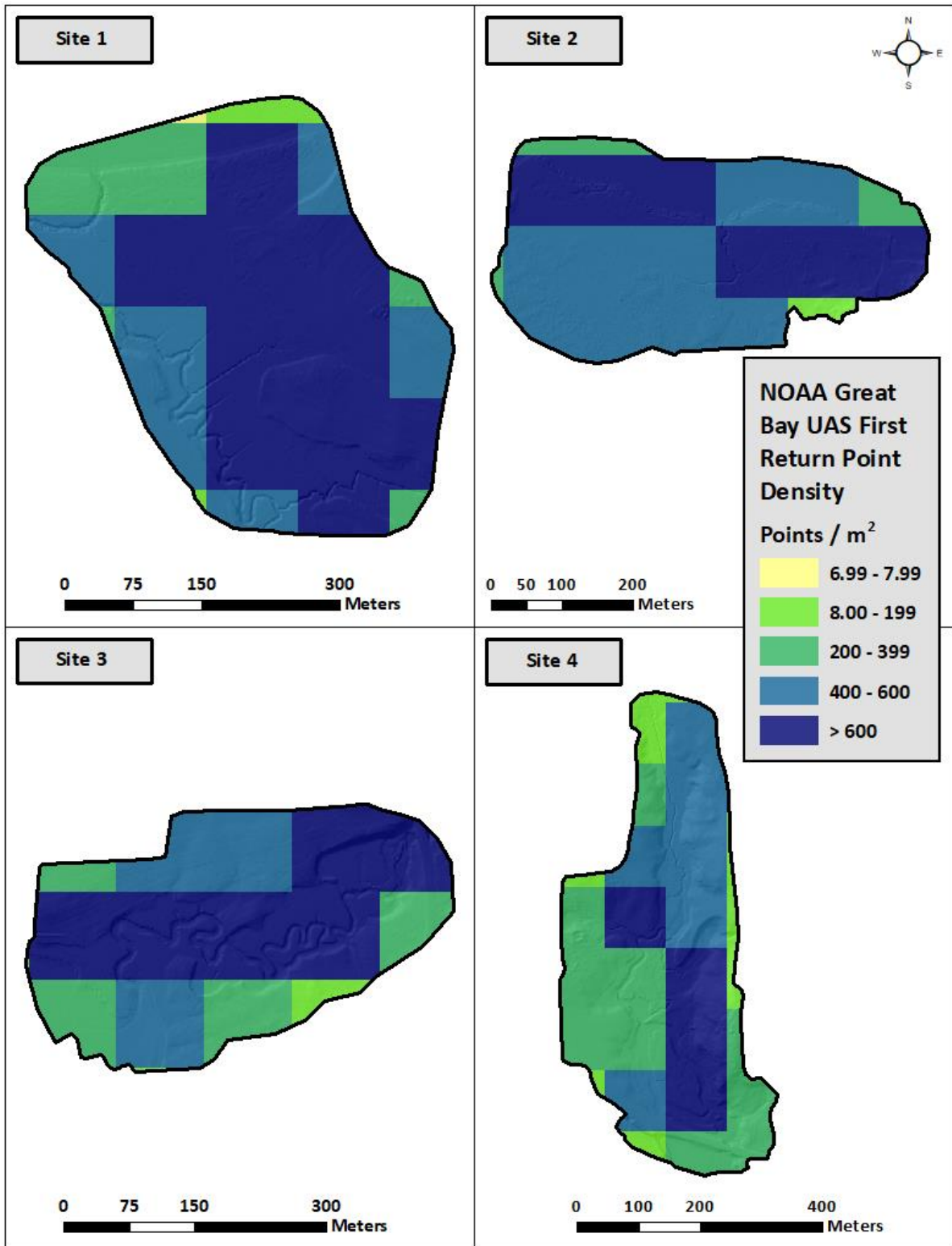
Figure 5: First return and ground-classified point density map for the NOAA Great Bay UAS sites (100 m x 100 m cells)
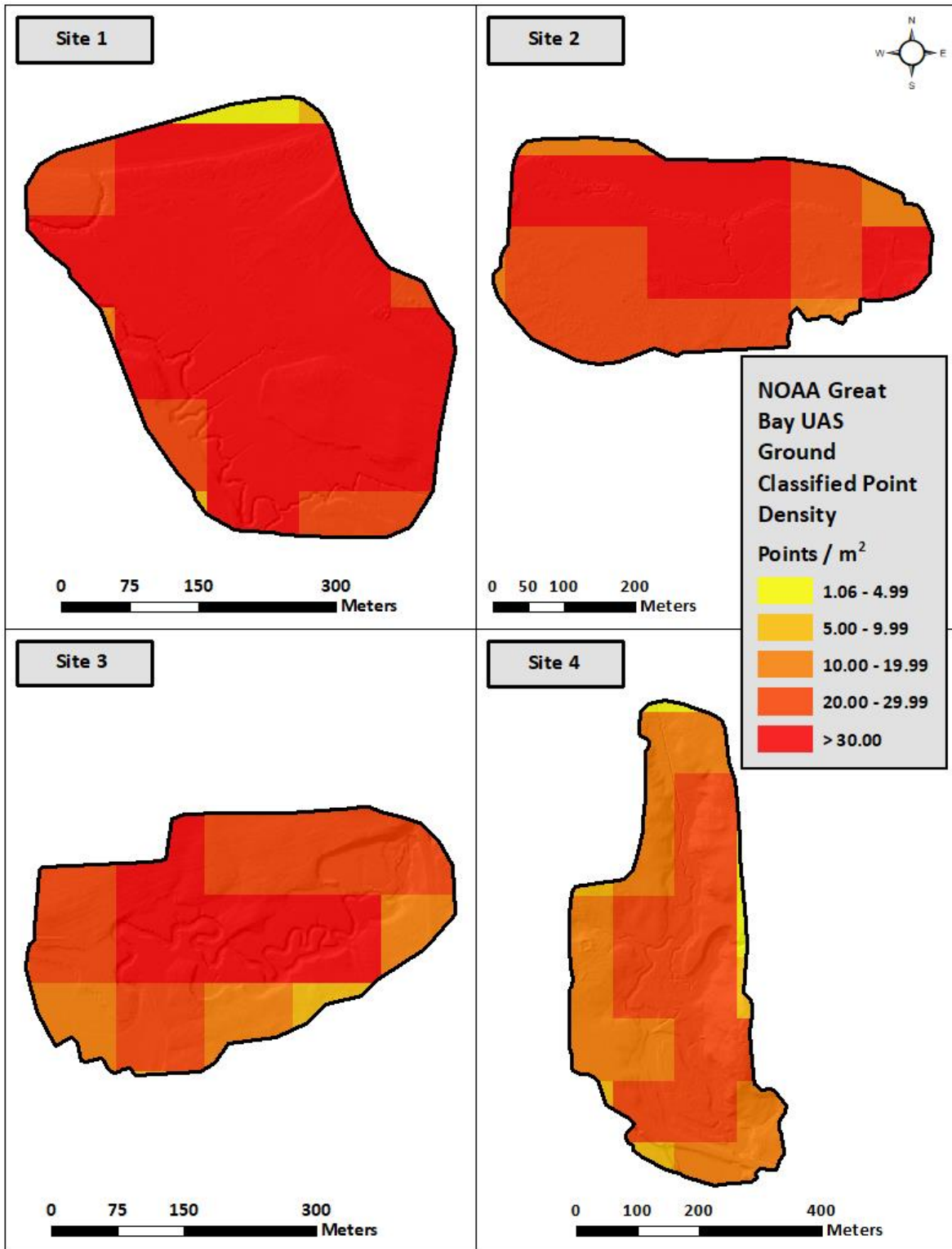
Figure 6: Ground point density map for the NOAA Great Bay UAS sites (100 m x 100 m cells)

LiDAR Accuracy Assessments

The accuracy of the LiDAR data collection can be described in terms of absolute accuracy (the consistency of the data with external data sources) and relative accuracy (the consistency of the dataset with itself). See Appendix A for further information on sources of error and operational measures used to improve relative accuracy.

LiDAR Non-Vegetated Vertical Accuracy

Absolute accuracy was assessed using Non-Vegetated Vertical Accuracy (NVA) reporting designed to meet guidelines presented in the FGDC National Standard for Spatial Data Accuracy[2]. NVA compares known ground check point data that were withheld from the calibration and post-processing of the LiDAR point cloud to the triangulated surface generated by the unclassified LiDAR point cloud as well as the derived gridded bare earth DEM. NVA 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 8.

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 Great Bay UAS survey, 20 ground check points were withheld from the calibration and post processing of the LiDAR point cloud, with resulting non-vegetated vertical accuracy of 0.069 meters as compared to classified LAS, and 0.082 meters as compared to the bare earth DEM, with 95% confidence (Figure 7, Figure 8).

QSI also assessed absolute accuracy using 33 ground control points. Although these points were used in the calibration and post-processing of the LiDAR point cloud, they still provide a good indication of the overall accuracy of the LiDAR dataset, and therefore have been provided in Table 8 and Figure 9.

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[2] Federal Geographic Data Committee, ASPRS POSITIONAL ACCURACY STANDARDS FOR DIGITAL GEOSPATIAL DATA EDITION 1, Version 1.0, NOVEMBER 2014. http://www.asprs.org/PAD-Division/ASPRS-POSITIONAL-ACCURACY-STANDARDS-FOR-DIGITAL-GEOSPATIAL-DATA.html.

Table 8: Absolute accuracy results

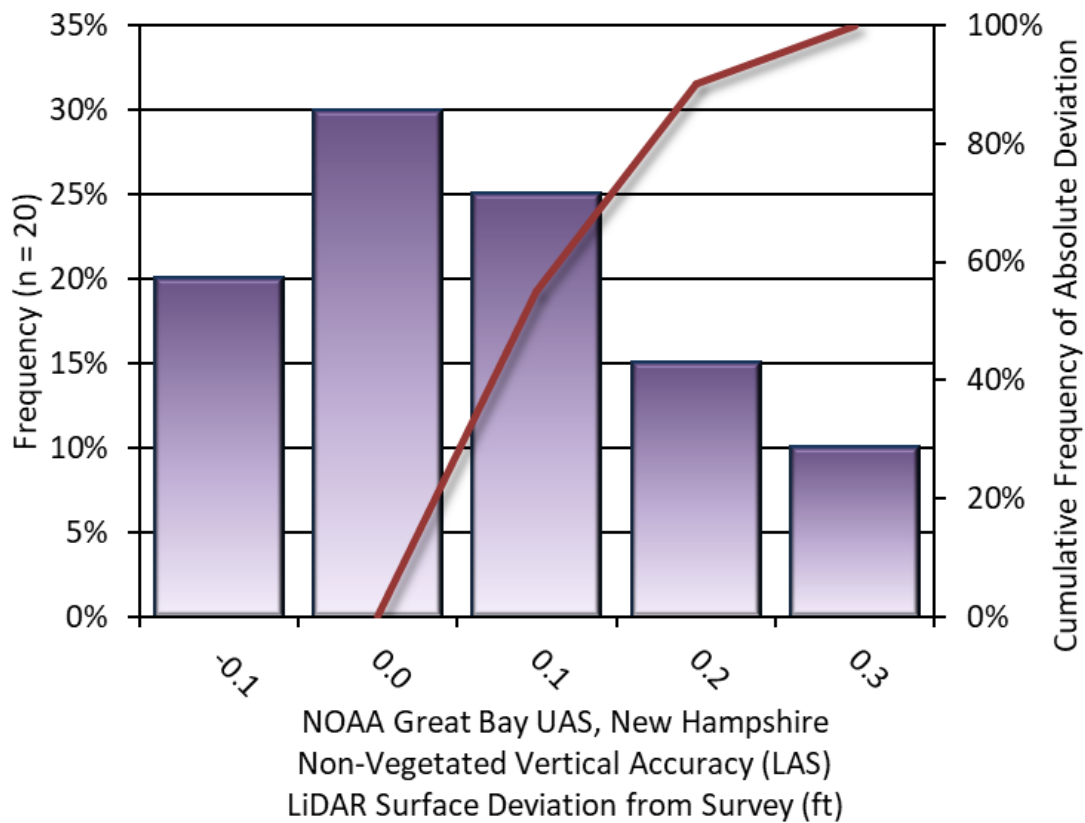|	NVA, as compared to classified LAS	NVA, as compared to bare earth DEM	Ground Control Points
Absolute Vertical Accuracy			
Sample	20 points	20 points	33 points
95% Confidence (1.96*RMSE)	0.069 m	0.082 m	0.031 m
Average	0.005 m	-0.012 m	0.001 m
Median	0.003 m	-0.004 m	0.001 m
RMSE	0.035 m	0.042 m	0.016 m
Standard Deviation (1σ)	0.036 m	0.041 m	0.016 m

Figure 7: Frequency histogram for LiDAR classified LAS deviation from ground check point values (NVA)
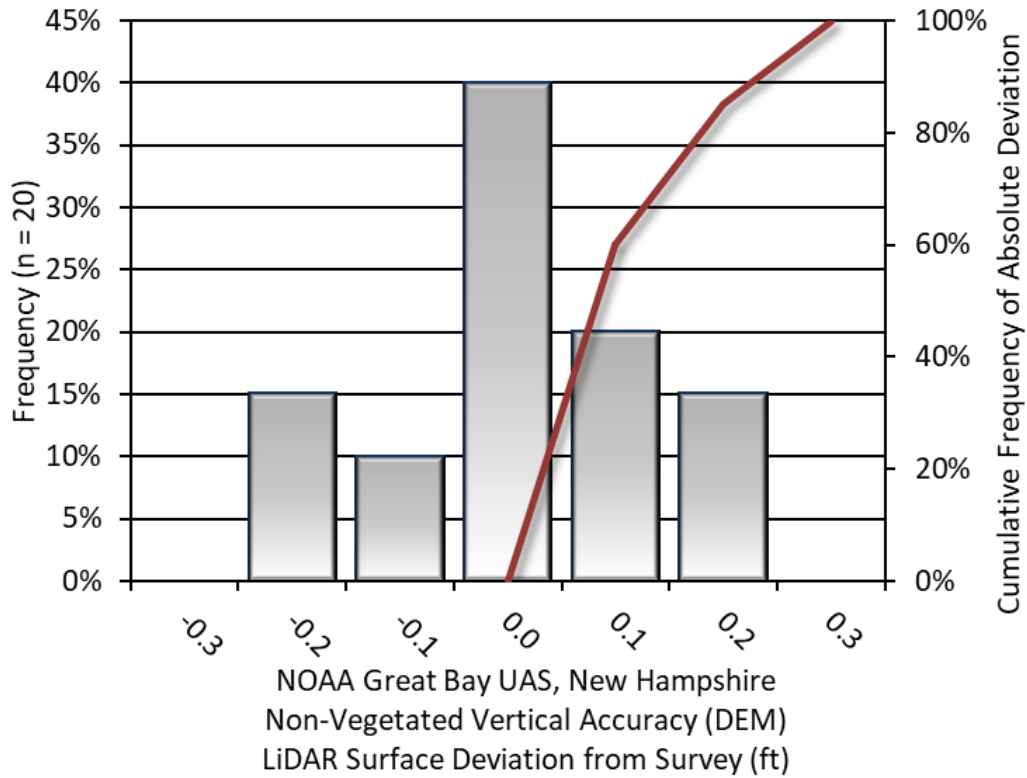
Figure 8: Frequency histogram for LiDAR bare earth DEM surface deviation from ground check point values (NVA)
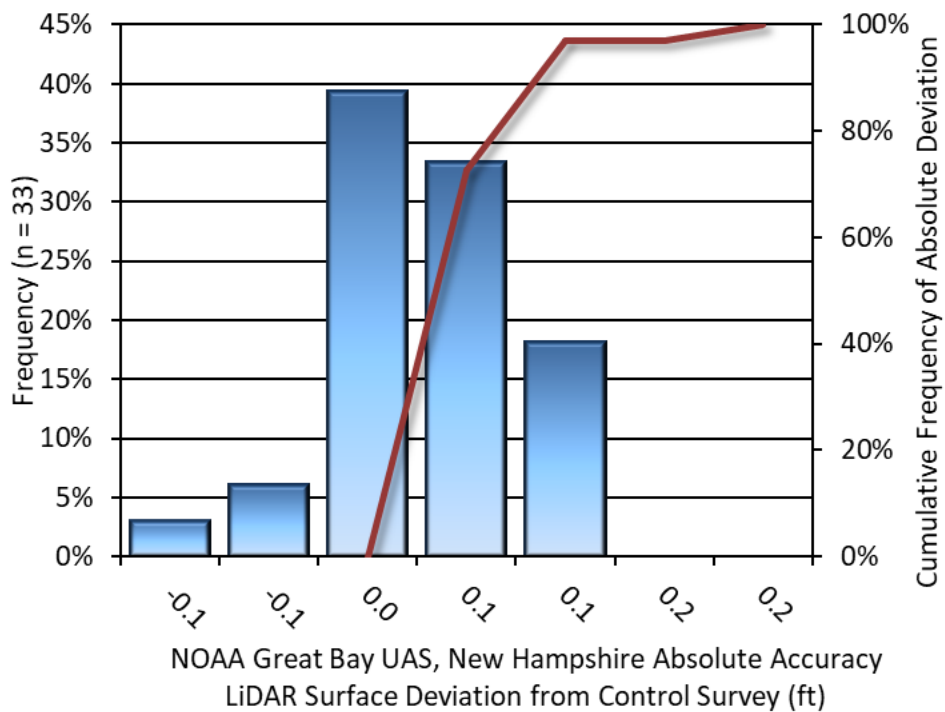

Figure 9: Frequency histogram for LiDAR surface deviation from ground control point values

LiDAR Vegetated Vertical Accuracies

QSI also assessed vertical accuracy using Vegetated Vertical Accuracy (VVA) reporting. VVA compares known ground check point data collected over vegetated surfaces using land class descriptions to the triangulated ground surface generated by the ground classified LiDAR points. For the NOAA Great Bay UAS survey, 8 vegetated check points were collected, with resulting vegetated vertical accuracy of 0.116 meters as compared to the bare earth DEM, evaluated at the 95th percentile (Table 9, Figure 10).

Table 9: Vegetated vertical accuracy results

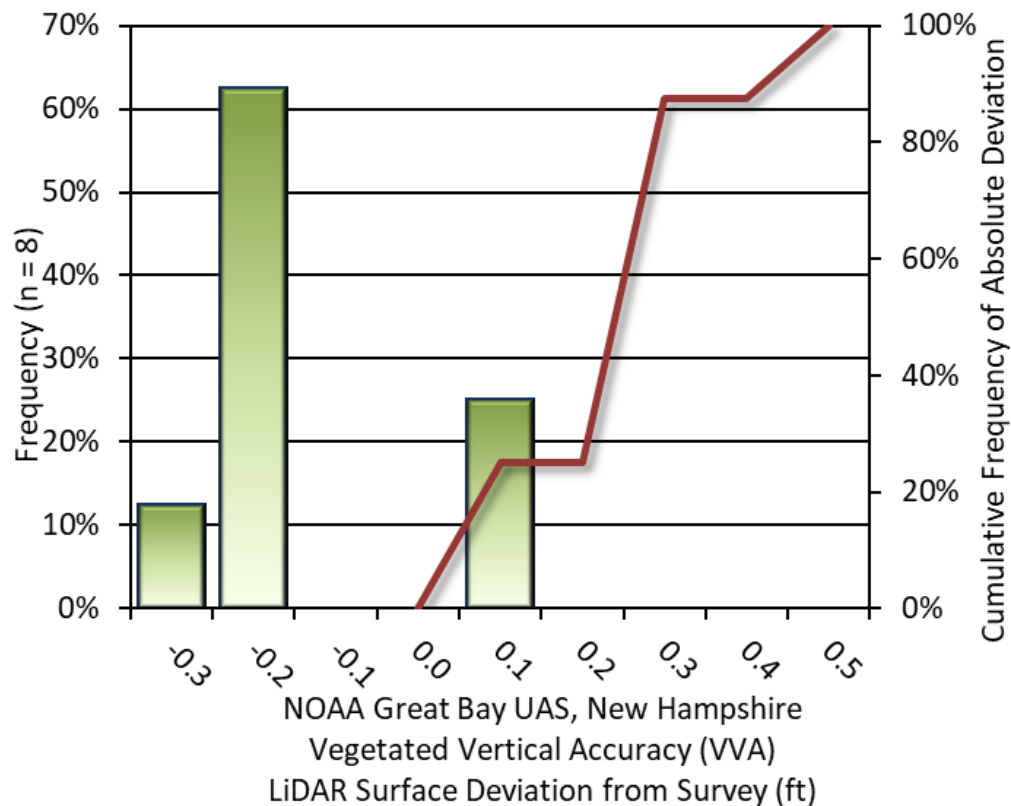| Vegetated Vertical Accuracy	
Sample	8 points
95th Percentile	0.116 m
Average	-0.056 m
Median	-0.065 m
RMSE	0.075 m
Standard Deviation (1σ)	0.052 m

Figure 10: Frequency histogram for LiDAR surface deviation from vegetated check point values (VVA)

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 NOAA Great Bay UAS LiDAR project was 0.023 meters (Table 10, Figure 11).

Table 10: Relative accuracy results

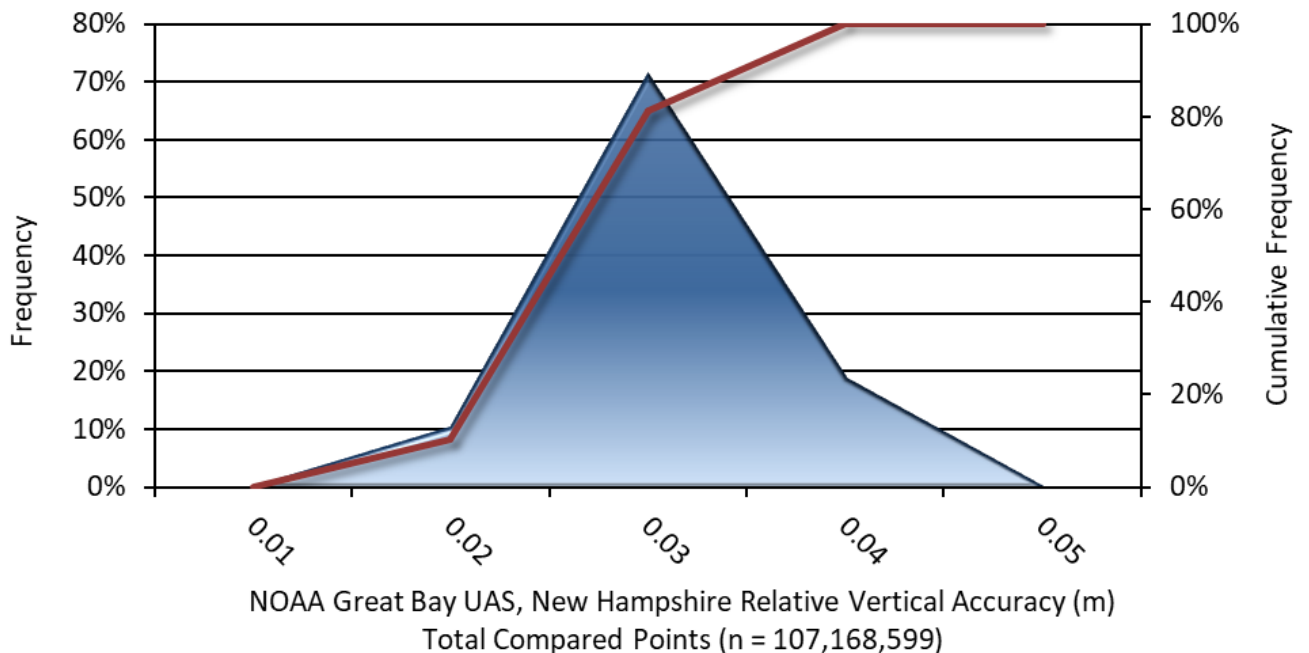| Relative Accuracy	
Sample	59 surfaces
Average	0.023 m
Median	0.025 m
RMSE	0.025 m
Standard Deviation (1σ)	0.004 m
1.96σ	0.009 m

Figure 11: Frequency plot for relative vertical accuracy between flight lines

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.

Intensity Values: The peak power ratio of the laser return to the emitted laser, calculated as a function of surface reflectivity.

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. 100% 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., echoes) 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.

Real-Time Kinematic (RTK) Survey: A type of surveying conducted with a GPS base station deployed over a known monument with a radio connection to a GPS rover. Both the base station and rover receive differential GPS data and the baseline correction is solved between the two. This type of ground survey is accurate to 1.5 cm or less.

Post-Processed Kinematic (PPK) Survey: GPS surveying is conducted with a GPS rover collecting concurrently with a GPS base station set up over a known monument. Differential corrections and precisions for the GNSS baselines are computed and applied after the fact during processing. This type of ground survey is accurate to 1.5 cm or less.

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 ±45º 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.