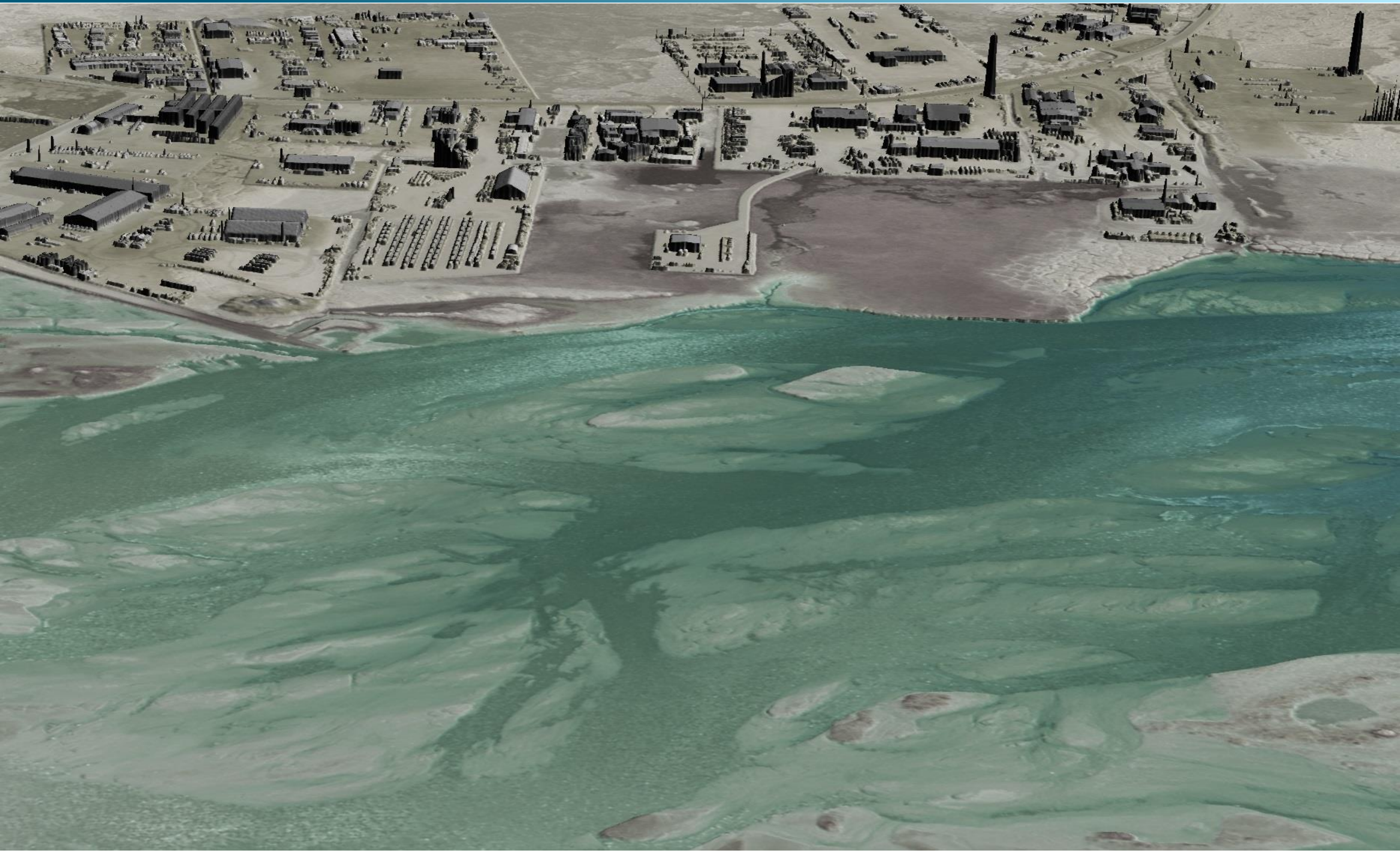
May 3, 2019



North Slope Borough Communities, Alaska 3DEP LiDAR Technical Data Report

Contract No. G16PC00016, Task Order No. 140G0218F0333

Prepared For:

USGS science for a changing world

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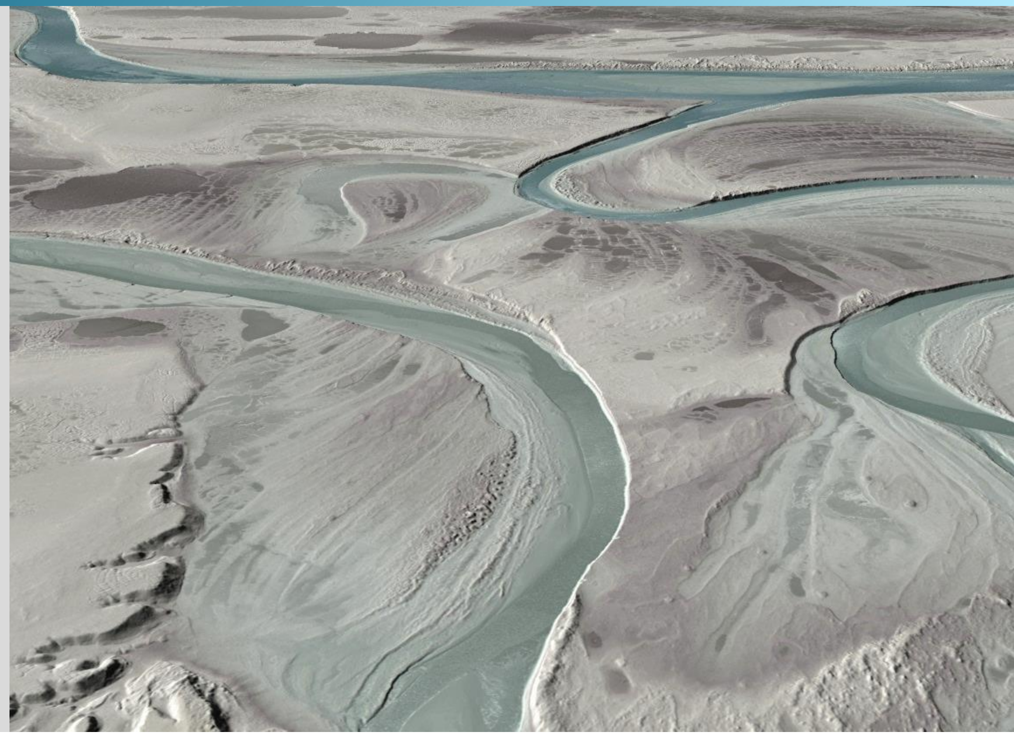
Cover Photo: A view of the Deadhorse community on Alaska's North Slope; created from the LiDAR bare earth model colored by elevation and intensity.

INTRODUCTION



This image displays the tundra landscape in the Atqasuk area of interest, created from the LiDAR-derived bare earth digital elevation model colored by elevation.

In July 2018, Quantum Spatial (QSI) was contracted by the United States Geological Survey (USGS) to collect Light Detection and Ranging (LiDAR) data in the summer of 2018 for several areas of interest (AOIs), comprising the North Slope Borough Communities 3DEP LiDAR project in Alaska. Data were collected to aid USGS in assessing the topographic and geophysical properties of the study area, to support its mission to gather high quality 3D elevation data over the state of Alaska.

Due to inclement weather and the short acquisition timeframe in Alaska, QSI was able to collect LiDAR data in eight out of the eleven contracted AOIs in the 2018 acquisition season: Atqasuk, Barrow North, Barrow South, Barrow Village, Deadhorse, Kaktovic, Nuiqsut and Wainwright. Data collection for the remaining AOIs (Anaktuvuk Pass, Point Lay, and Point Hope) is anticipated for the summer of 2019, weather conditions permitting.

This report accompanies the delivered 2018 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 USGS 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 North Slope Borough Communities sites

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
North Slope Borough Communities, Alaska 2018	184,346	193,163	07/14/2018 – 09/29/2018	QL1 & QL2 LiDAR

Deliverable Products

Table 2: Products delivered to USGS for the North Slope Borough Communities sites

<table>
<tr><th colspan="2">North Slope Borough, Alaska LiDAR Products
Projection: Alaska State Plane, Zone per Geographic Location (2-7)
Horizontal Datum: NAD83 (2011)
Vertical Datum: NAVD88 (GEOID12B)
Units: US Survey Feet</th></tr>
<tr><td>Points</td><td>LAS v 1.4 PDRF 6
• All Classified Returns</td></tr>
<tr><td>Rasters</td><td>Tiled 3.0 Foot (QL2) and 1.5 Foot (QL1) ESRI Grids & ERDAS Imagine Files (*.img)
• Hydroflattened Bare Earth Digital Elevation Model (DEM)
• Hydroflattened Bare Earth Shaded Relief Raster (Hillshade)
• Highest Hit Digital Surface Model (DSM)
• Highest Hit Shaded Relief Raster (Hillshade)
3.0 Foot (QL2) and 1.5 Foot (QL1) GeoTiffs
• Intensity Images
Mosaicked 3.0 Foot (QL2) and 1.5 Foot (QL1) ESRI Grids
• Hydroflattened Bare Earth DEM Mosaic
• Hydroflattened Bare Earth Shaded Relief Raster Mosaic
• Highest Hit DSM Mosaic
• Highest Hit Shaded Relief Raster Mosaic</td></tr>
<tr><td>Vectors</td><td>Shapefiles (*.shp)
• Buffered Project Boundary
• LiDAR Tile Index
• 2.0 Foot Contours
• 3D Hydro Breaklines (untiled)
• Building Footprints
• Snow Polygons (Kaktovic AOI only)
• Acquisition Shapes:
(i) Swath coverage extents: (*.gdb)
(ii) Flightline Index: (*.gdb)
(iii) Calibration points: (*.xls) and (*.shp)
(iv) NVA and VVA points: (*.xls) and (*.shp)</td></tr>
</table>

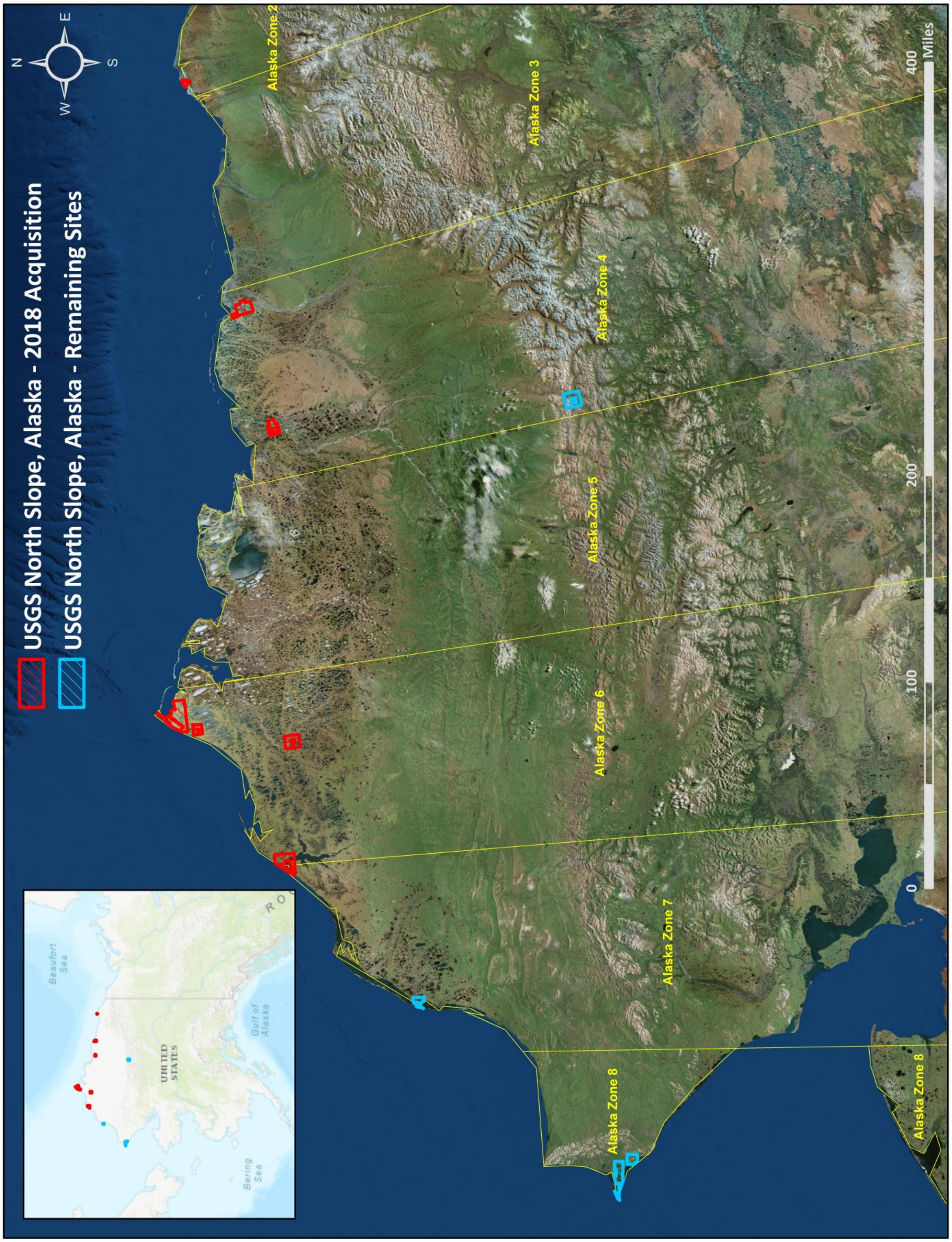


Figure 1: Location map of the North Slope Borough Communities site in Alaska

QSI's Cessna Caravan

Planning

In preparation for data collection, QSI reviewed the project area and developed a specialized flight plan to ensure complete coverage of the North Slope Borough Communities LiDAR study area at the target point density of ≥8.0 points/m^2 for the QL1 portion of the AOI and ≥ 2 points/m^2 for the QL2 portion of the AOI. 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 flights were continuously monitored due to their potential impact on the daily success of airborne operations, including the presence of snow in the region. Likewise, logistical considerations such as private property access, airplane fuel, and hangar availability required careful coordination because of the remote nature of the project sites.

Additionally, QSI takes pride in our commitment to abstain from disturbing the local native cultural practices; while in transit over the Colville River Delta we required our flight crew to maintain a cruising altitude above 4,000 feet, as to not disturb the local hunters in the area.

Airborne LiDAR Survey

The LiDAR survey was accomplished using a Leica ALS80 system mounted in a Cessna Caravan. Table 3 summarizes the settings used to yield an average pulse density of ≥8 pulses/m^2 over the North Slope Borough Communities QL1 project areas, and ≥2 pulses/m^2 over the North Slope Borough Communities QL2 project areas. The Leica ALS80 laser system can record unlimited range measurements (returns) per pulse; however, 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		
Areas of Interest	Nuiqsut, Kaktovik, Wainwright, Atqasuk, Barrow	Nuiqsut, Kaktovik, Wainwright, Atqasuk, Barrow Village, Barrow South, Deadhorse
Quality Level	QL1	QL2
Acquisition Dates	7/20/18, 7/22/18, 9/7/18, 9/8/18, 9/29/18	7/14/18, 7/20/18, 7/22/18, 9/11/18, 9/13/18, 9/29/18
Aircraft Used	Cessna Caravan	Cessna Caravan
Sensor	Leica	Leica
Laser	ALS80	ALS80
Maximum Returns	Unlimited	Unlimited
Resolution/Density	Average 8 pulses/m^2	Average 2 pulses/m^2
Nominal Pulse Spacing	0.35 m	0.71 m
Survey Altitude (AGL)	1,750 m	1,350 – 1,750 m*
Survey Speed	115 knots	140 knots
Field of View	30º	38º
Mirror Scan Rate	58.4 Hz	53.3 Hz
Target Pulse Rate	321.4 kHz	202 kHz
Pulse Length	2.5 ns	2.5 ns
Laser Pulse Footprint Diameter	38.5 cm	29.7 – 38.5 cm
Central Wavelength	1064 nm	1064 nm
Pulse Mode	Multi Pulse in Air (2PiA)	Single Pulse in Air (SPiA)
Beam Divergence	0.22 mrad	0.22 mrad
Swath Width	938 m	932 – 1205 m
Swath Overlap	60 %	30 %
Intensity	8-bit, scaled to 16-bit	8-bit, scaled to 16-bit
Accuracy	$RMSE_Z$ (Non-Vegetated) ≤ 10 cm	$RMSE_Z$ (Non-Vegetated) ≤ 10 cm
	NVA (95% Confidence Level) ≤ 19.6 cm	NVA (95% Confidence Level) ≤ 19.6 cm
	VVA (95^{th} Percentile) ≤ 30 cm	VVA (95^{th} Percentile) ≤ 30 cm

**Some QL2 flights were conducted at a lower elevation due to cloud cover at the planned elevation.*

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.

Ground Control

Ground control surveys were conducted by UMIAQ, LLC. Ground control and check point data collected by UMIAQ survey staff was provided to QSI to support geospatial corrections to the aircraft positional coordinate data and to perform quality assurance checks on final LiDAR data. Due to the remote nature of the project site, QSI utilized TerraPos Precise Point Positioning (PPP) to post-process the LiDAR flight trajectories.

Ground Survey Points (GSPs)

Collected ground survey points provided to QSI were used during LiDAR calibration, post-processing, and accuracy assessment. Ground control points were collected on hard surfaces as feasible, and ground check point data were collected over a variety of land surface types to be used in non-vegetated and vegetated vertical accuracy assessment. Relative errors for any GSP position must be less than 1.5 cm horizontal and 2.0 cm vertical in order to be accepted. GSPs were collected within as many flightlines as possible; however, the distribution of GSPs depended on ground access constraints and will not be equitably distributed throughout the study area due to the remote nature of the project sites (Figure 2).

Table 4: Vegetated and Non-Vegetated Check Point Types

Land cover type	Land cover code	Example	Description	Accuracy Assessment Type
Shrub	SH		Maintained or low growth herbaceous shrubland	VVA

Land cover type	Land cover code	Example	Description	Accuracy Assessment Type
Tall Grass	TG	(No photo available)	Unmaintained grasslands, tundra in advanced stages of growth	VVA
Tundra	TU		Arctic areas characterized by permanently frozen subsoil and flat terrain	VVA
Bare Earth	BE		Areas of bare earth surface	NVA
Urban	UA		Areas dominated by urban development, including parks and pavement	NVA

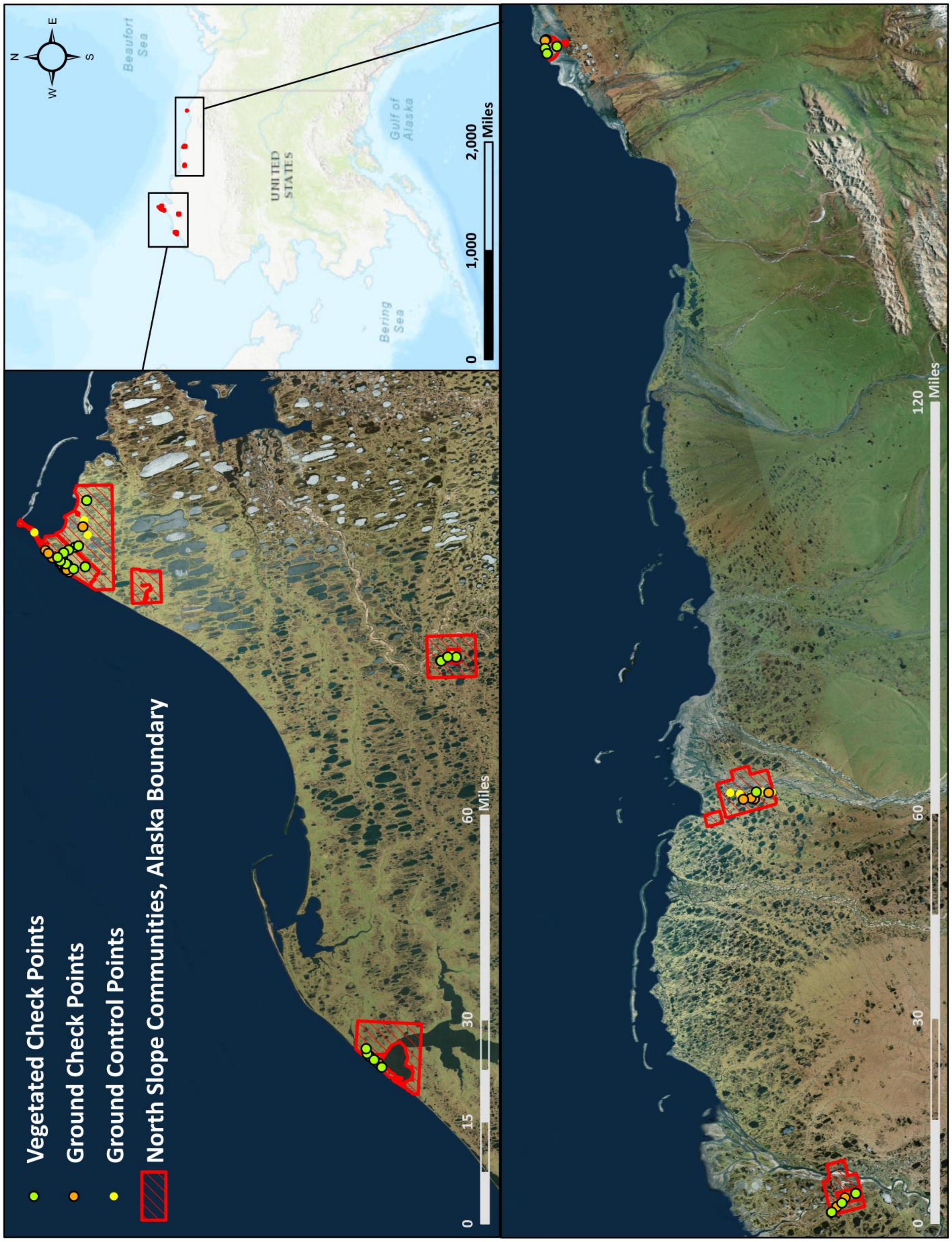
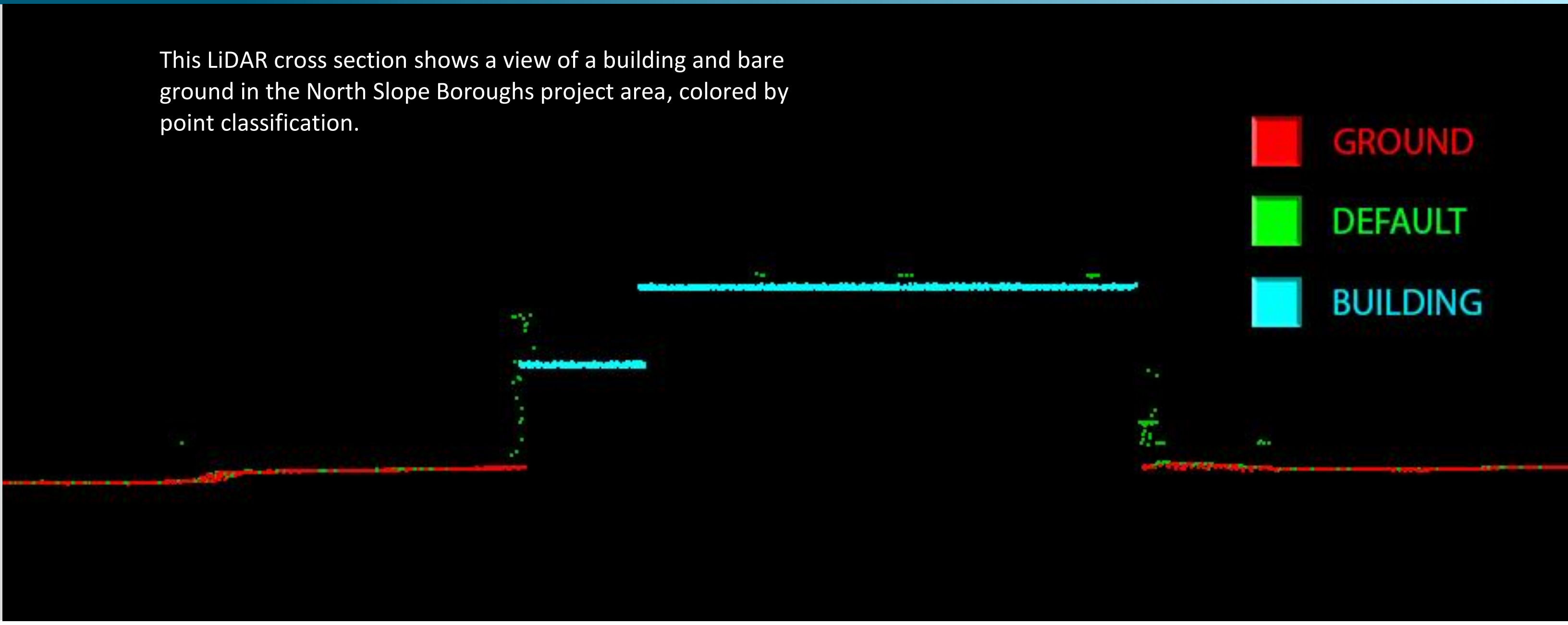


Figure 2: Ground survey location map



This LiDAR cross section shows a view of a building and bare ground in the North Slope Boroughs project area, 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 North Slope Borough Communities 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
3	Low Vegetation	Default points between 0.5 – 2.0 meters above ground
4	Medium Vegetation	Default points between 2.0 – 6.0 meters above ground
5	High Vegetation	Default points greater than 6.0 meters above ground
6	Buildings	Permanent structures identified using automated cleaning algorithms
7	Noise	Laser returns that are often associated with birds, scattering from reflective surfaces, or artificial points below the ground surface
9	Water	Laser returns that are determined to be water using automated and manual cleaning algorithms
17	Bridge	Bridge decks
20	Ignored Ground	Ground points proximate to water’s edge breaklines; ignored for correct model creation
21	Snow	Seasonal snow identified within the Kaktovic AOI

Table 6: LiDAR processing workflow

LiDAR Processing Step	Software Used
Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and final ephemeris information. 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.	TerraPOS 2.4.3
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.	TerraPOS 2.4.3 Leica Cloudpro v. 1.2.4
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.18
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.18
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.18 TerraModeler v.18
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 and EDRAS Imagine (.img) files at 1.5 foot (QL1), and 3.0 foot (QL2) pixel resolutions	LAS Product Creator 3.0 (QSI Proprietary) ArcMap v. 10.3.1
Export intensity images as GeoTIFFs at 1.5 foot (QL1), and 3.0 foot (QL2) pixel resolutions.	LAS Product Creator 3.0 (QSI proprietary) ArcMap v. 10.3.1

Feature Extraction

Hydroflattening and Water's Edge Breaklines

Hydroflattening was performed for all rivers, lakes, and tidal waters within the North Slope Borough Communities project area, according to USGS specifications. Bodies of water that were flattened include lakes and other closed water bodies with a surface area greater than 2 acres, all streams and rivers that are nominally wider than 30 meters, all waters bordering the project, and select smaller bodies of water as feasible. The hydroflattening process eliminates artifacts in the digital terrain model caused by both increased variability in ranges or dropouts in laser returns due to the low reflectivity of water.

Hydroflattening of closed water bodies was performed through a combination of automated and manual detection and adjustment techniques designed to identify water boundaries and water levels. Boundary polygons were developed using an algorithm which weights LiDAR-derived slopes, intensities, and return densities to detect the water's edge. The water edges were then manually reviewed and edited as necessary.

Once polygons were developed the initial ground classified points falling within water polygons were reclassified as water points to omit them from the final ground model. Elevations were then obtained from the filtered LiDAR returns to create the final breaklines. Lakes were assigned a consistent elevation for an entire polygon while rivers were assigned consistent elevations on opposing banks and smoothed to ensure downstream flow through the entire river channel.

Water boundary breaklines were then incorporated into the hydroflattened DEM by enforcing triangle edges (adjacent to the breakline) to the elevation values of the breakline. This implementation corrected interpolation along the hard edge.

Contours

Contour generation from LiDAR point data required a thinning operation in order to reduce contour sinuosity. The thinning operation reduced point density where topographic change is minimal (i.e., flat surfaces) while preserving resolution where topographic change was present. Contour key points were selected from the ground model every 20 feet with the spacing decreased in regions with high surface curvature. Generation of contour key points eliminated redundant detail in terrain representation, particularly in areas of low relief, and provided for a more manageable dataset. Contours were produced through TerraModeler by interpolating between the contour key points at even elevation increments.

Elevation contour lines were then intersected with ground point density rasters and a confidence field was added to each contour line. Contours which crossed areas of high point density have high confidence levels, while contours which crossed areas of low point density have low confidence levels. Areas with low ground point density are commonly beneath buildings and bridges, in locations with dense vegetation, over water, and in other areas where laser penetration to the ground surface was impeded.

Buildings

Building classification was performed using predominantly automated techniques. Automated algorithms were used to classify building features within the LiDAR point cloud, from which 2D polygon shapefiles were generated. QSI utilized ArcGIS tools to generalize initial results, and then reviewed the resultant polygon shapefiles for egregious errors and made edits where necessary. All non-mobile structures such as houses, barns, silos and sheds were classified into the building category (Figure 3).

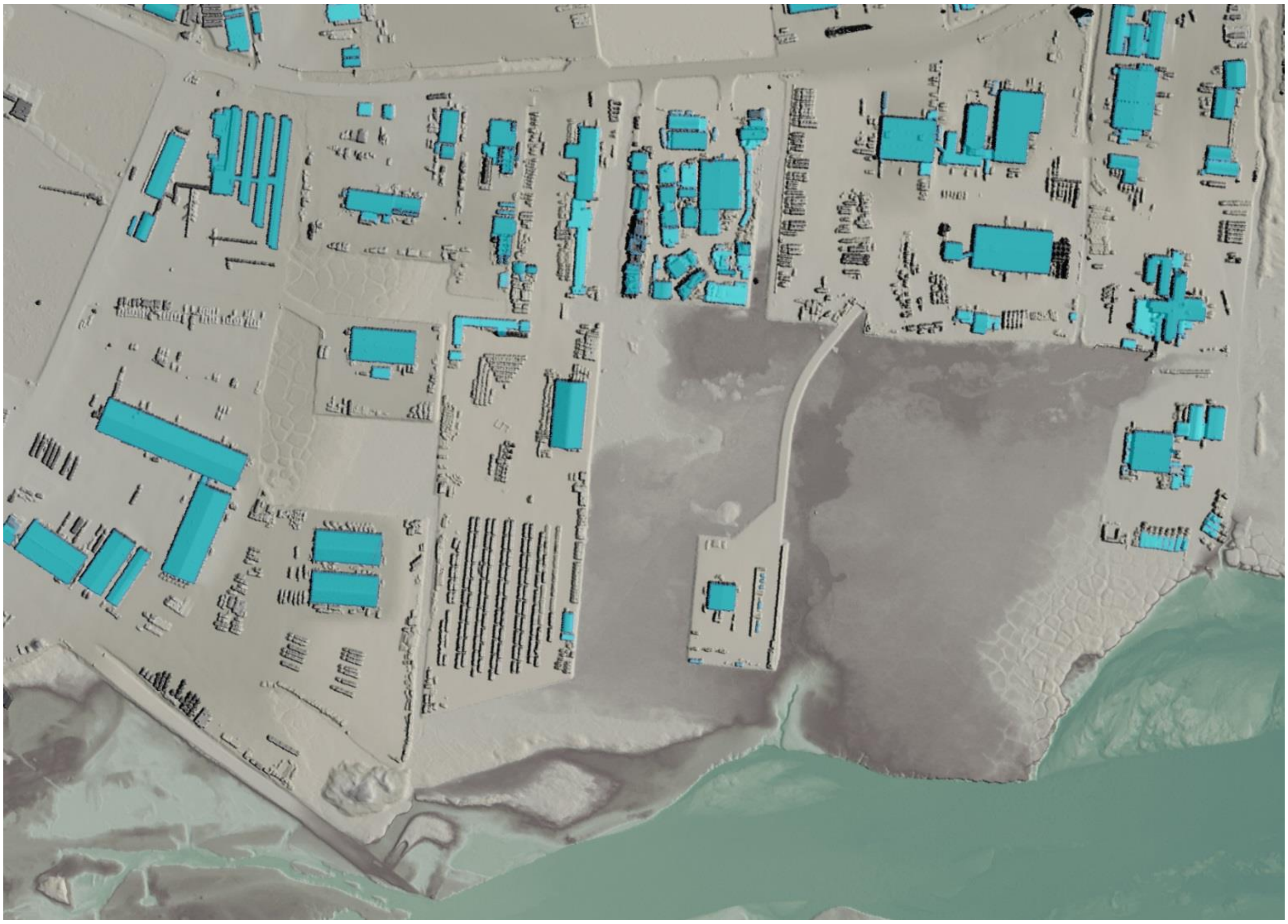
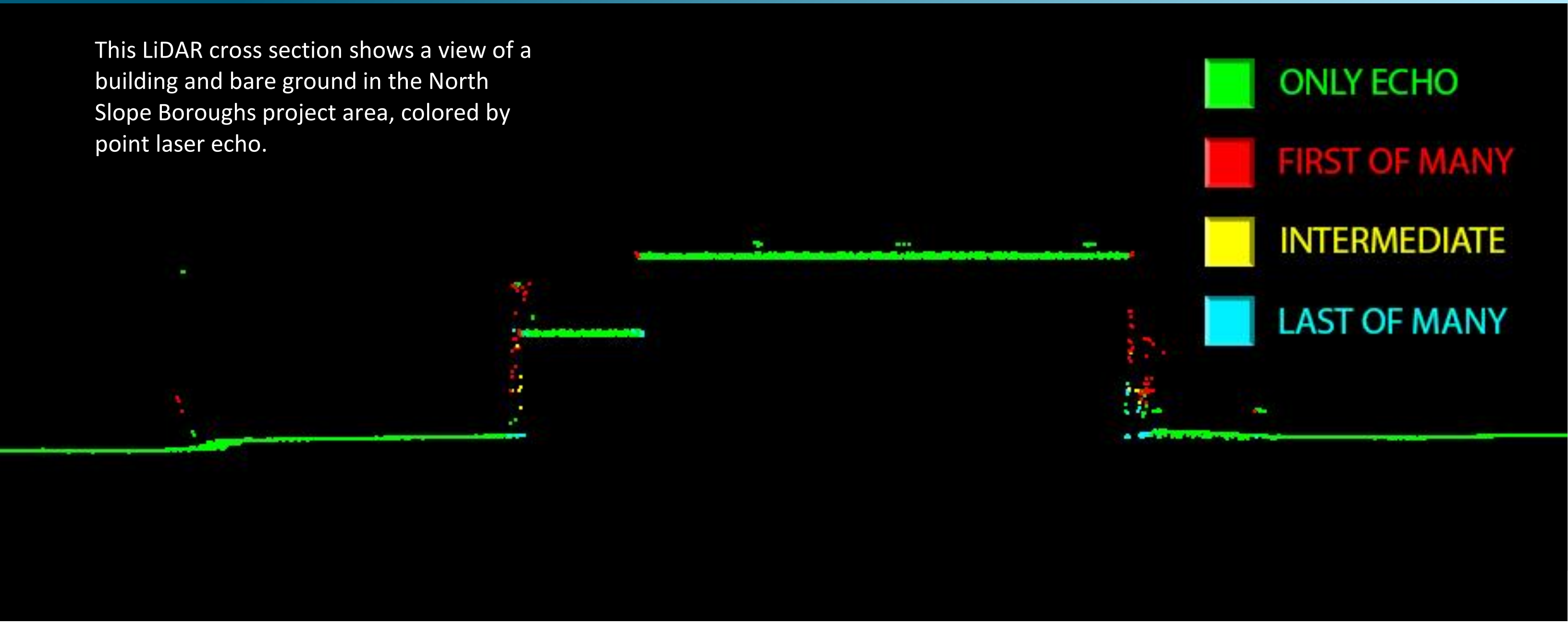


Figure 3: An aerial view of the Deadhorse community, created from the highest hit digital surface model colored by elevation, overlaid with the building footprint colored in blue.



This LiDAR cross section shows a view of a building and bare ground in the North Slope Boroughs 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 (0.74 points/ft^2) for QL1 areas, and ≥2 points/ m^2 (0.19 points/ft^2) for the QL2 areas. 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 North Slope Borough Communities QL1 project areas was 1.12 points/ft^2 (12.10 points/m^2), while the average first-return density of LiDAR data for the QL2 project areas was 0.43 points/ft^2 (4.61 points/m^2) (Table 7).

Ground classified density of LiDAR data for the North Slope Borough Communities QL1 project areas was 0.37 points/ft^2 (3.99 points/m^2), while the ground classified density for the QL2 project areas was 0.23 points/ft^2 (2.46 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 4 through Figure 9.

Table 7: Average LiDAR point density results

Classification	QL1 Point Density	QL2 Point Density
First-Return	1.12 points/ft^2 12.10 points/m^2	0.43 points/ft^2 4.61 points/m^2
Ground Classified	0.37 points/ft^2 3.99 points/m^2	0.23 points/ft^2 2.46 points/m^2

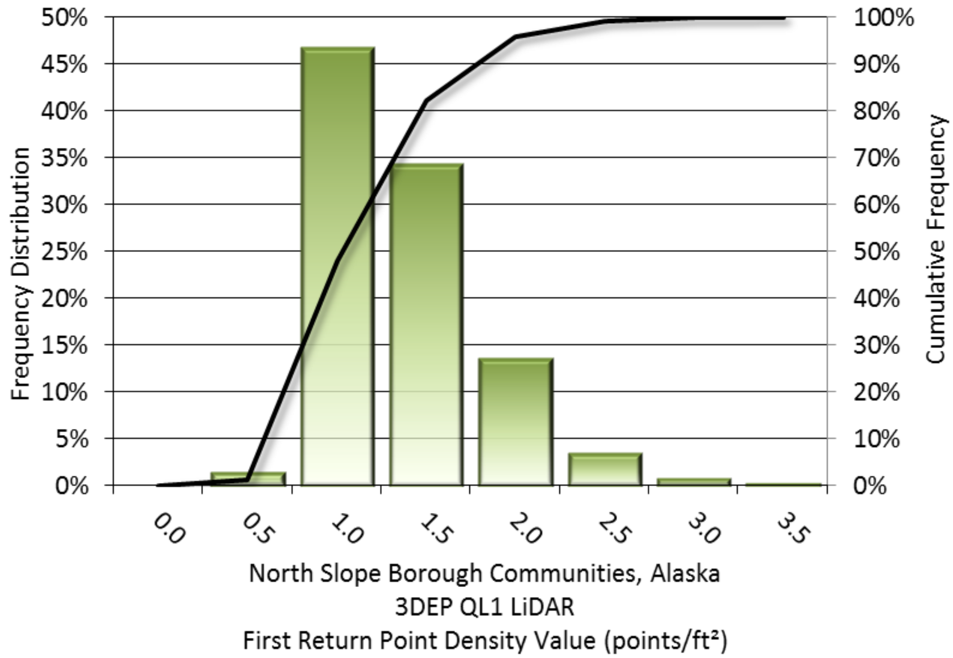


Figure 4: Frequency distribution of QL1 LiDAR first return point density values per 100 x 100 m cell

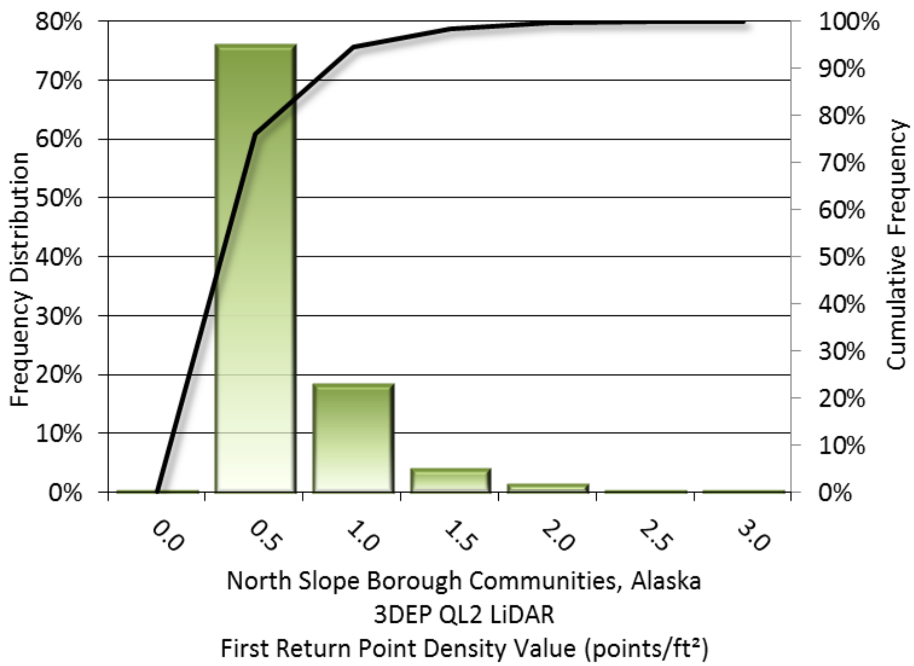


Figure 5: Frequency distribution of QL2 LiDAR first return point density values per 100 x 100 m cell

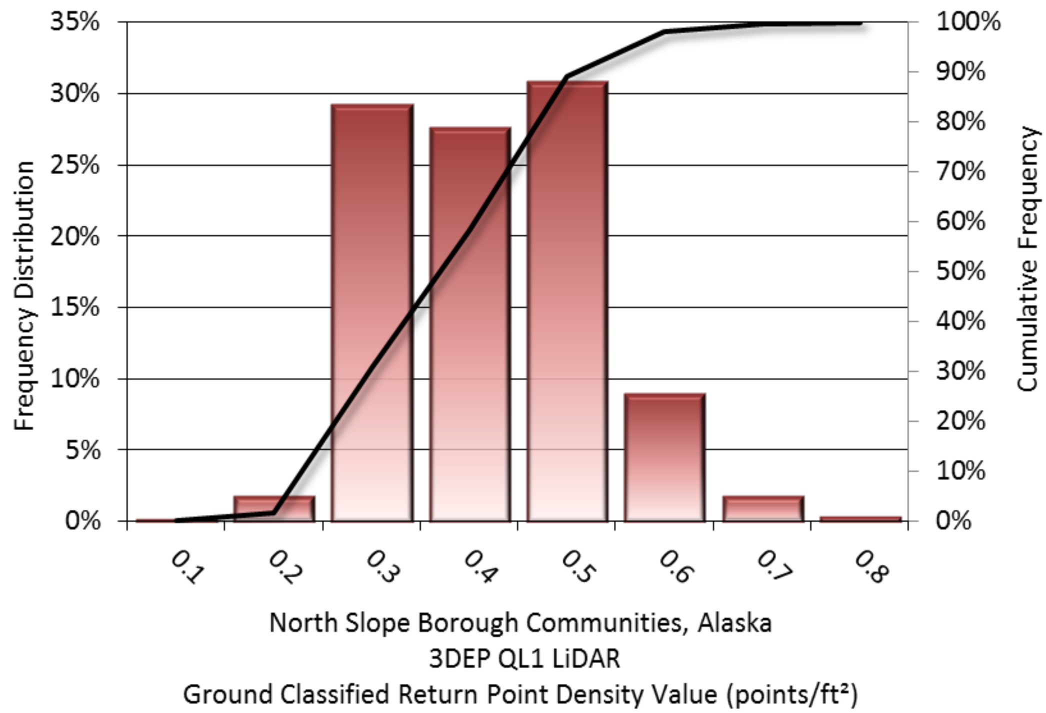


Figure 6: Frequency distribution of QL1 LiDAR ground classified point density values per 100 x 100 m cell

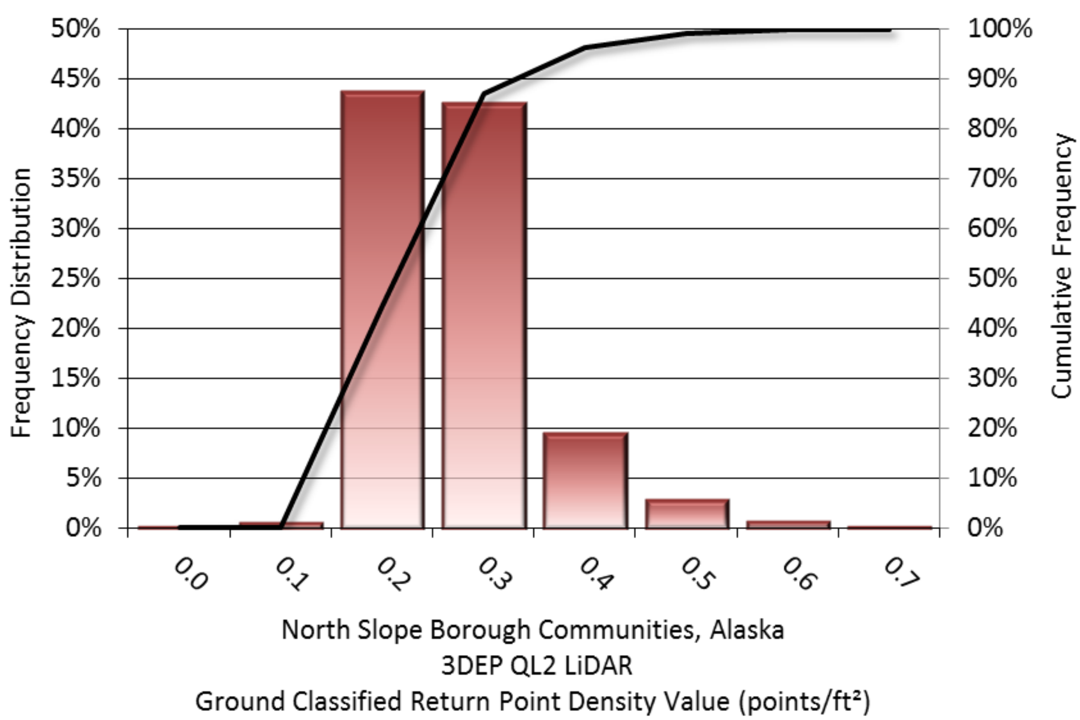


Figure 7: Frequency distribution of QL2 LiDAR ground classified point density values per 100 x 100 m cell

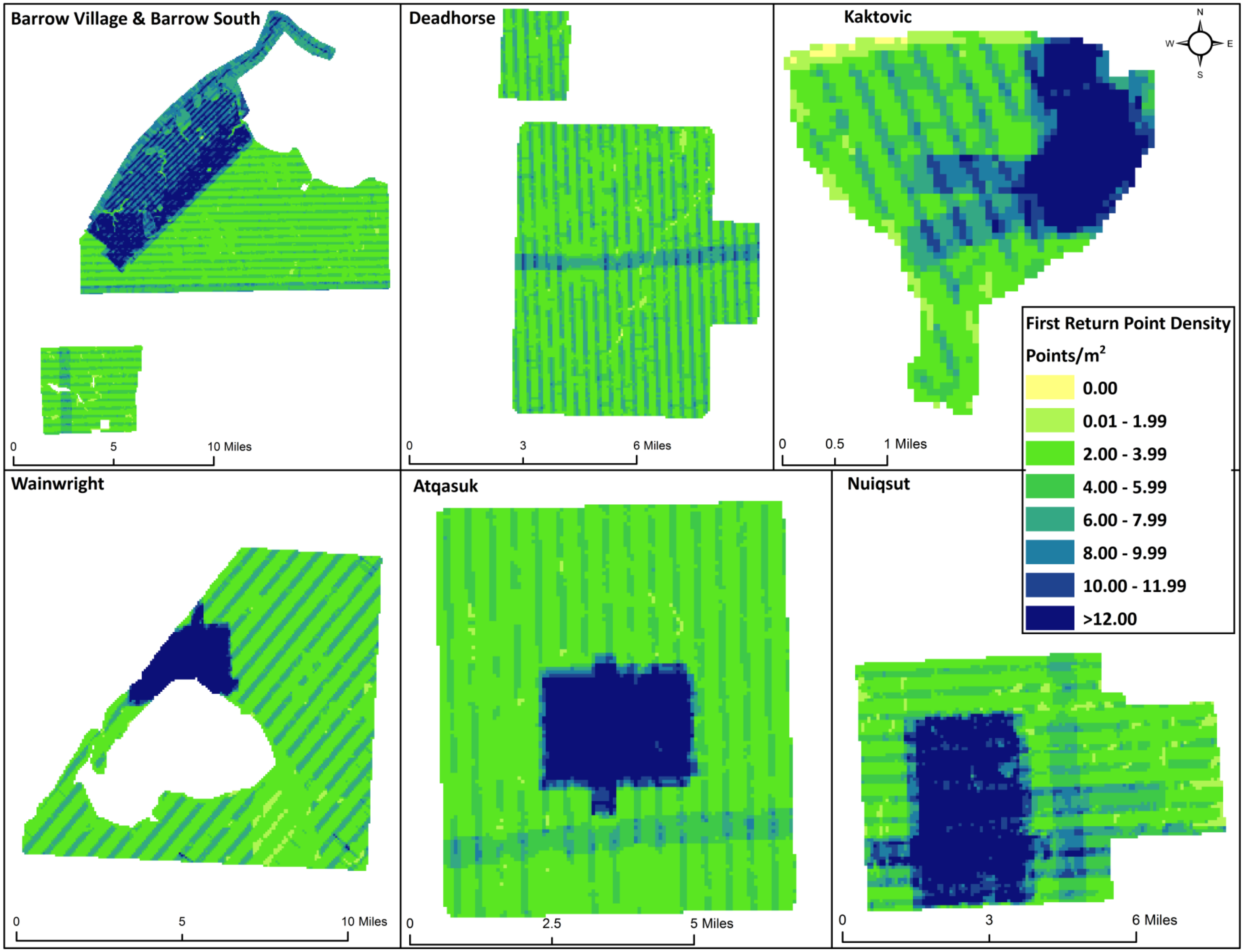


Figure 8: First return point density map for the North Slope Borough Communities site (100 m x 100 m cells)

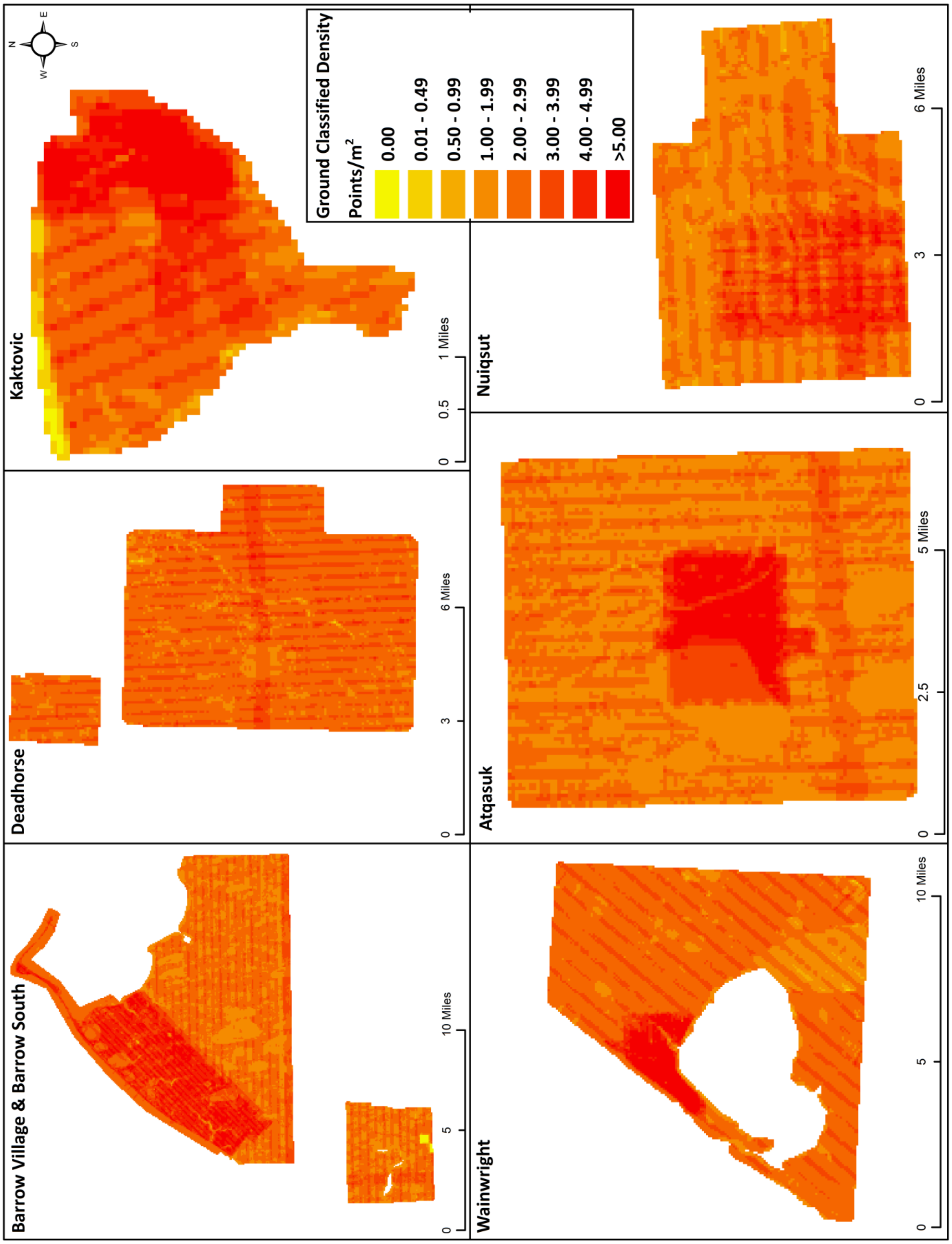


Figure 9: Ground point density map for the North Slope Borough Communities site (100 m x 100 m cells)

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[1]. 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 North Slope Borough Communities survey, 45 ground check points were withheld from the calibration and post processing of the LiDAR point cloud, with resulting non-vegetated vertical accuracy of 0.138 feet (0.042 meters) as compared to unclassified LAS, and 0.137 feet (0.042 meters) as compared to the bare earth DEM, with 95% confidence (Figure 10, Figure 11).

QSI also assessed absolute accuracy using 29 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 12.

[1] 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

Absolute Vertical Accuracy			
	NVA, as compared to unclassified LAS	NVA, as compared to bare earth DEM	Ground Control Points
Sample	45 points	45 points	29 points
95% Confidence (1.96*RMSE)	0.138 ft 0.042 m	0.137 ft 0.042 m	0.127 ft 0.039 m
Average	0.017 ft 0.005 m	0.013 ft 0.004 m	0.009 ft 0.003 m
Median	0.010 ft 0.003 m	0.016 ft 0.005 m	0.003 ft 0.001 m
RMSE	0.070 ft 0.021 m	0.070 ft 0.021 m	0.065 ft 0.020 m
Standard Deviation (1σ)	0.069 ft 0.021 m	0.070 ft 0.021 m	0.065 ft 0.020 m

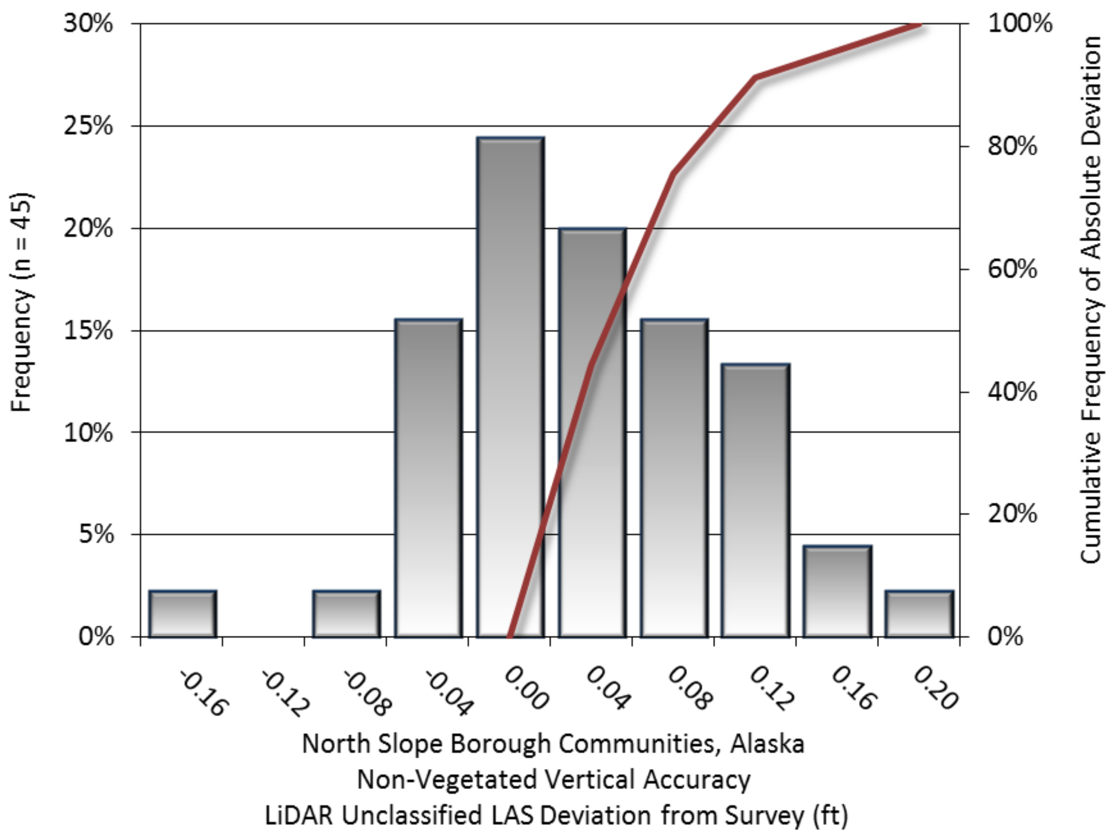


Figure 10: Frequency histogram for LiDAR unclassified LAS deviation from ground check point values (NVA)

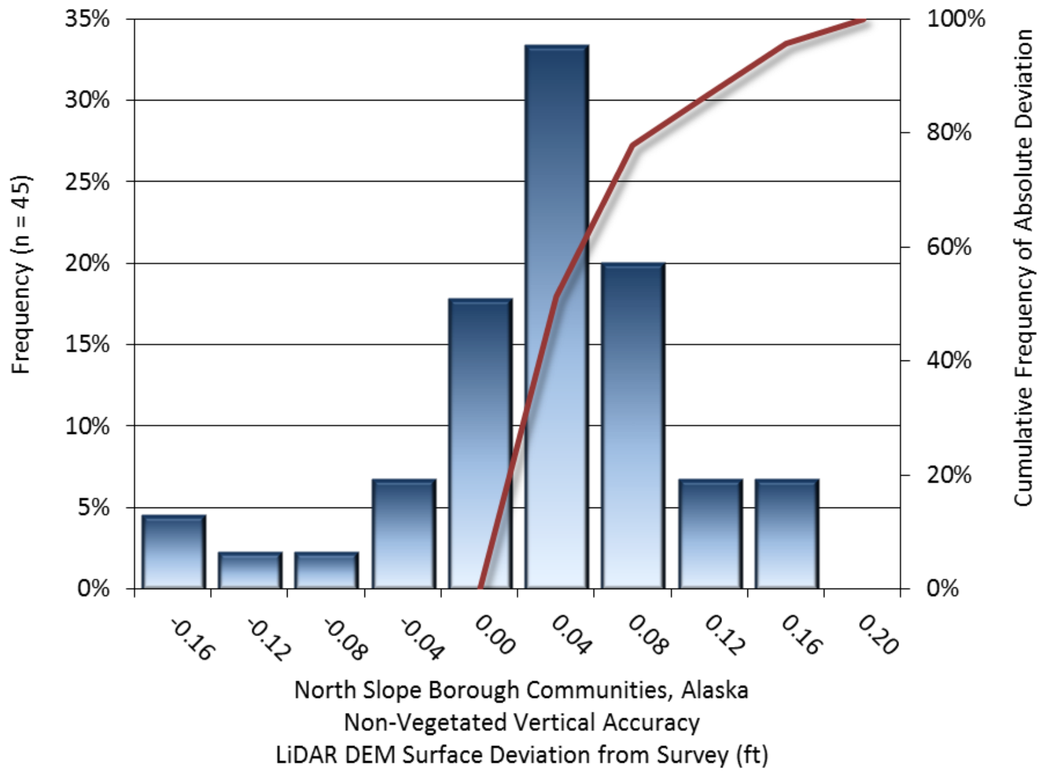


Figure 11: Frequency histogram for LiDAR bare earth DEM surface deviation from ground check point values (NVA)

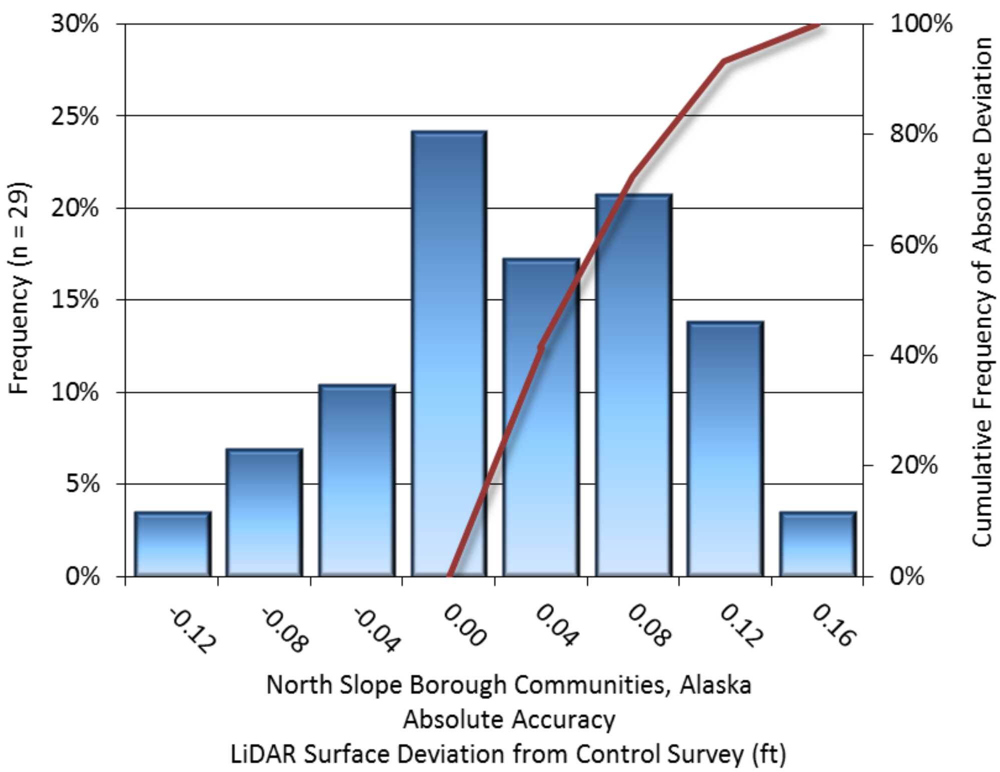


Figure 12: Frequency histogram for LiDAR surface deviation from ground control point values

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 North Slope Borough Communities survey, 24 vegetated check points were collected, with resulting vegetated vertical accuracy of 0.506 feet (0.154 meters) as compared to the bare earth DEM, evaluated at the 95th percentile (Table 9, Figure 13).

Table 9: Vegetated vertical accuracy results

Vegetated Vertical Accuracy	
Sample	24 points
95th Percentile	0.506 ft 0.154 m
Average	-0.048 ft -0.015 m
Median	-0.015 ft -0.004 m
RMSE	0.242 ft 0.074 m
Standard Deviation (1σ)	0.243 ft 0.074 m

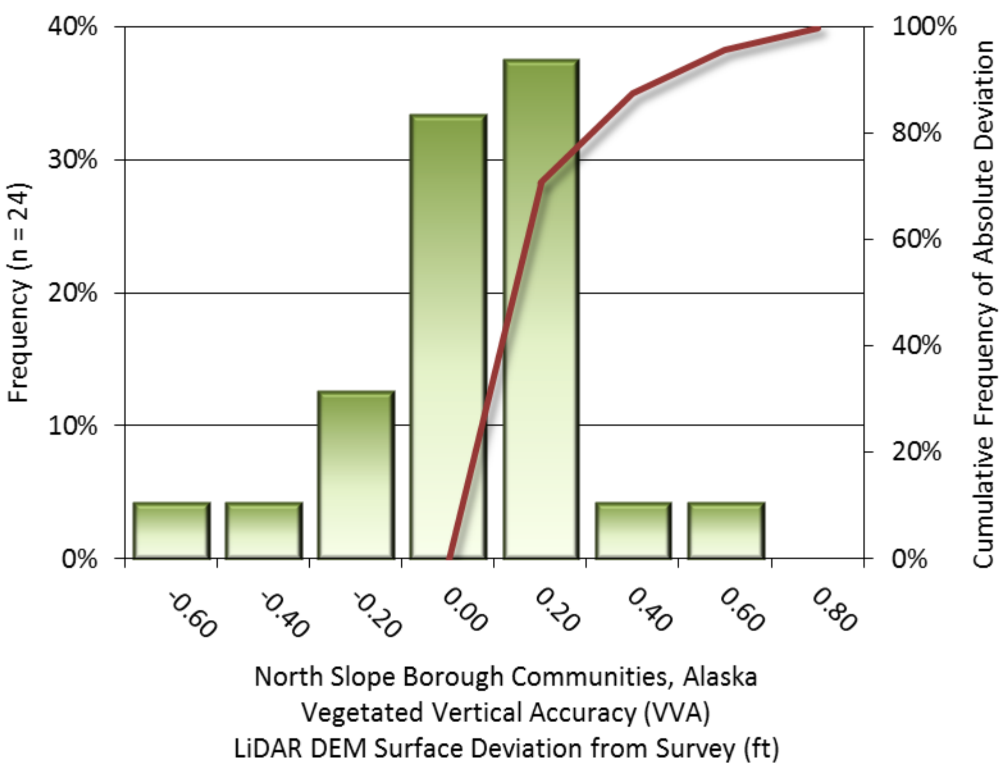


Figure 13: Frequency histogram for LiDAR surface deviation from vegetated check point values (VVA)

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 North Slope Borough Communities LiDAR project was 0.064 feet (0.019 meters) (Table 10, Figure 14).

Table 10: Relative accuracy results

Relative Accuracy	
Sample	192 surfaces
Average	0.064 ft 0.019 m
Median	0.046 ft 0.014 m
RMSE	0.052 ft 0.016 m
Standard Deviation (1σ)	0.013 ft 0.004 m
1.96σ	0.025 ft 0.008 m

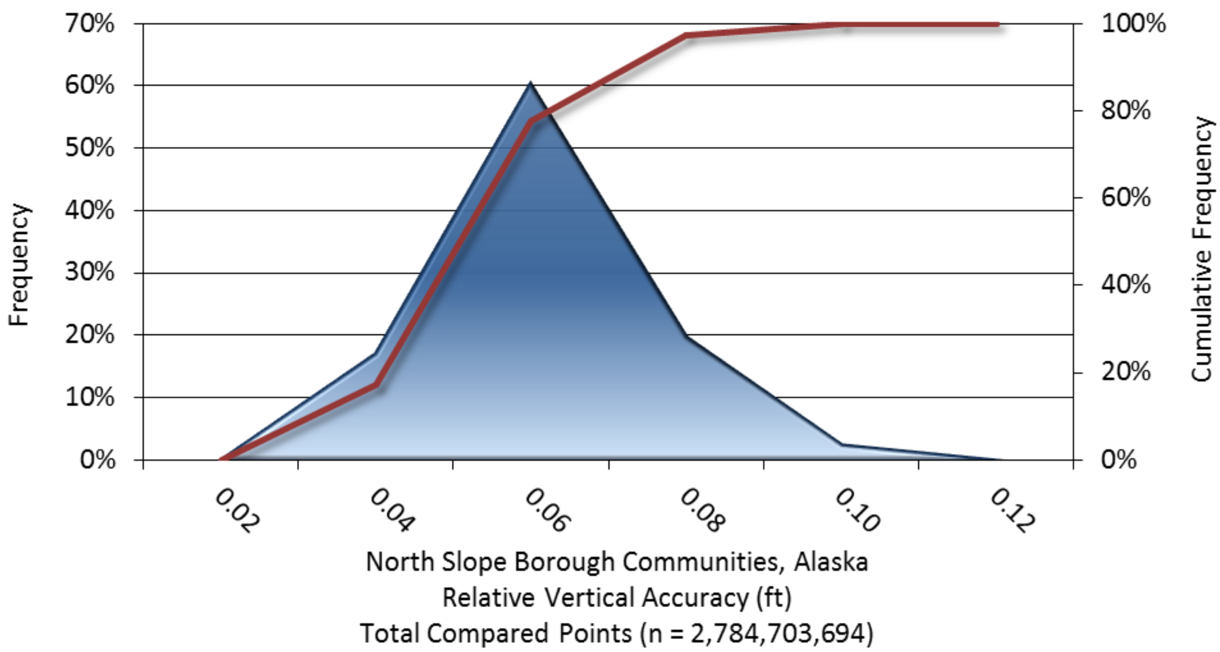


Figure 14: Frequency plot for relative vertical accuracy between flight lines

CERTIFICATIONS

Quantum Spatial, Inc. provided LiDAR services for the North Slope Borough Communities project as described in this report.

I, Tucker Selko, have reviewed the attached report for completeness and hereby state that it is a complete and accurate report of this project.

Tucker Selko
Tucker Selko (May 3, 2019)

May 3, 2019

Tucker Selko, PMP
Project Manager
Quantum Spatial, Inc.

I, Evon P. Silvia, PLS, being duly registered as a Professional Land Surveyor in and by the state of Alaska, hereby certify that the methodologies, static GNSS occupations used during airborne flights, and ground survey point collection were performed using commonly accepted Standard Practices. Airborne survey field work conducted for this report was conducted between July 14th and September 29th, 2018. The ground survey was conducted by Umiaq and under the supervision of its staff surveyors.

Accuracy statistics shown in the Accuracy Section of this Report have been reviewed by me and found to meet the "National Standard for Spatial Data Accuracy".

Evon P. Silvia

May 3, 2019

Evon P. Silvia, PLS
Quantum Spatial, Inc.
Corvallis, OR 97330

Signed: May 3, 2019
COA: 125659

Figure 15: A view the Meade River and surrounding tundra landscape in the Atqasuk area of interest. This image was created from the LiDAR-derived bare earth model colored by elevation.

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.

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 ±15-17^{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.