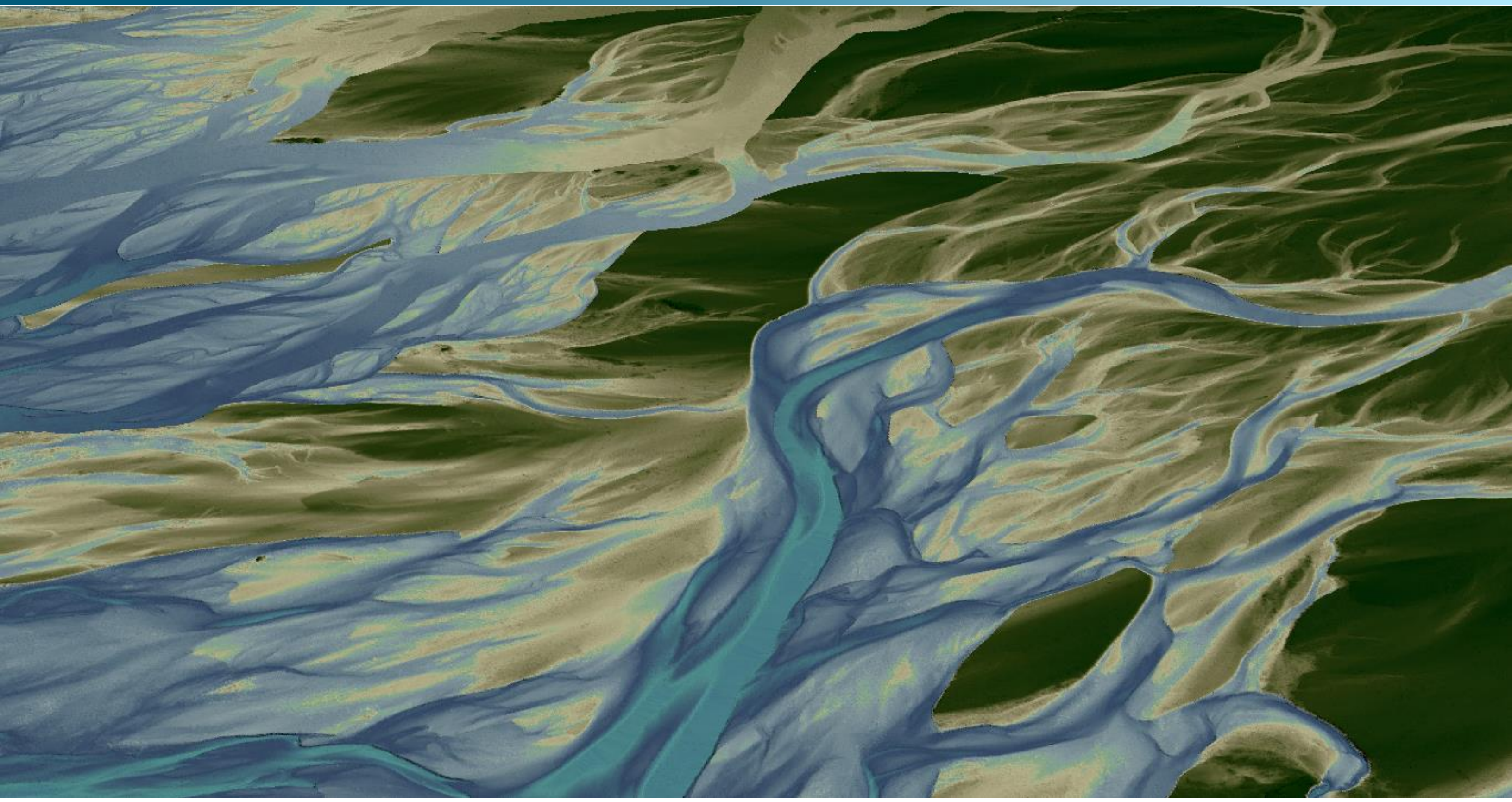
April 20, 2020



MatSu Borough, Alaska Delivery 1

Lidar Technical Data Report

Contract No. G16PC00016, Task Order No. 140G0219F0236

Prepared For:

USGS science for a changing world

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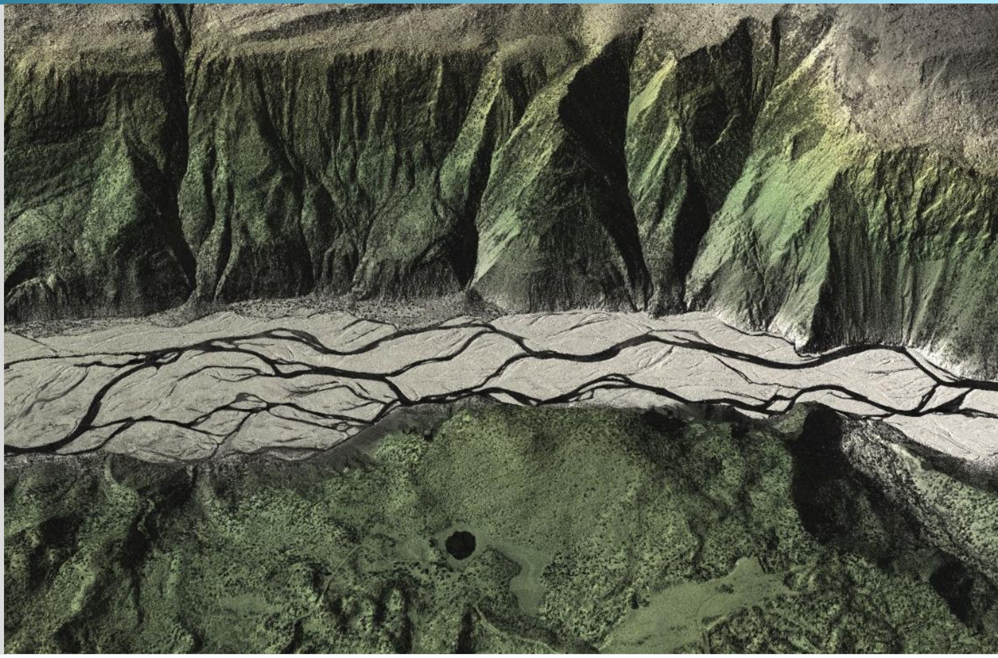
Cover Photo: A view looking south over the Knick River in Alaska. The image was created from the lidar bare earth model colored by elevation.

INTRODUCTION



This image displays the bare earth model of the Matanuska River in the MatSu Borough Delivery 1 site, colored by elevation.

In July 2019, Quantum Spatial was contracted by the United States Geological Survey (USGS) to collect QL2 lidar data in the fall of 2019, over 1,077 square miles of land in the Matanuska-Susitna Valley north of Anchorage, Alaska, under contract no. G16PC00016, task order no. 140G0219F0236. Quantum Spatial was able to acquire and process nearly 87% of the project site before the onset of snow in Alaska halted the 2019 acquisition season. This MatSu Borough Delivery 1 encompasses all 2019 lidar data. Execution of the remaining project area is scheduled to occur in 2020. Data were collected to aid USGS in assessing the topographic and geophysical properties of the study area.

This report accompanies the MatSu Borough, Alaska Delivery 1 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 MatSu Borough, Alaska Delivery 1 site

Project Site	Delivered Acres	Acquisition Dates	Data Type
MatSu Borough, Alaska Delivery 1	608,556	9/13/2019 - 10/7/2019	QL2 NIR Lidar

Deliverable Products

Table 2: Products delivered to USGS for the MatSu Borough, Alaska Delivery 1

MatSu Borough, Alaska Delivery 1 Lidar Products Projection: Alaska State Plane Zone 4 Horizontal Datum: NAD83 (CORS96) Vertical Datum: NAVD88 (GEOID12b) Units: US Survey Feet	
Points	LAS v 1.4 • All Classified Returns
Rasters	3.0 Foot GeoTiffs • Hydroflattened Bare Earth Digital Elevation Model (DEM) • Hydroflattened Bare Earth Shaded Relief Image • Highest Hit Digital Surface Model (DSM) • Highest Hit Shaded Relief Image • Intensity Images • Dz Orthos
Vectors	Shapefiles (*.shp) • Project Boundary • Lidar Tile Index • Ground Survey Shapes • 1 Foot Contours ESRI File Geodatabase (*.gdb) • Flightline Index • Flightline Swath Coverage Extents • Water's Edge Breaklines • Bridge Breaklines • Building Footprints (≥400ft²)

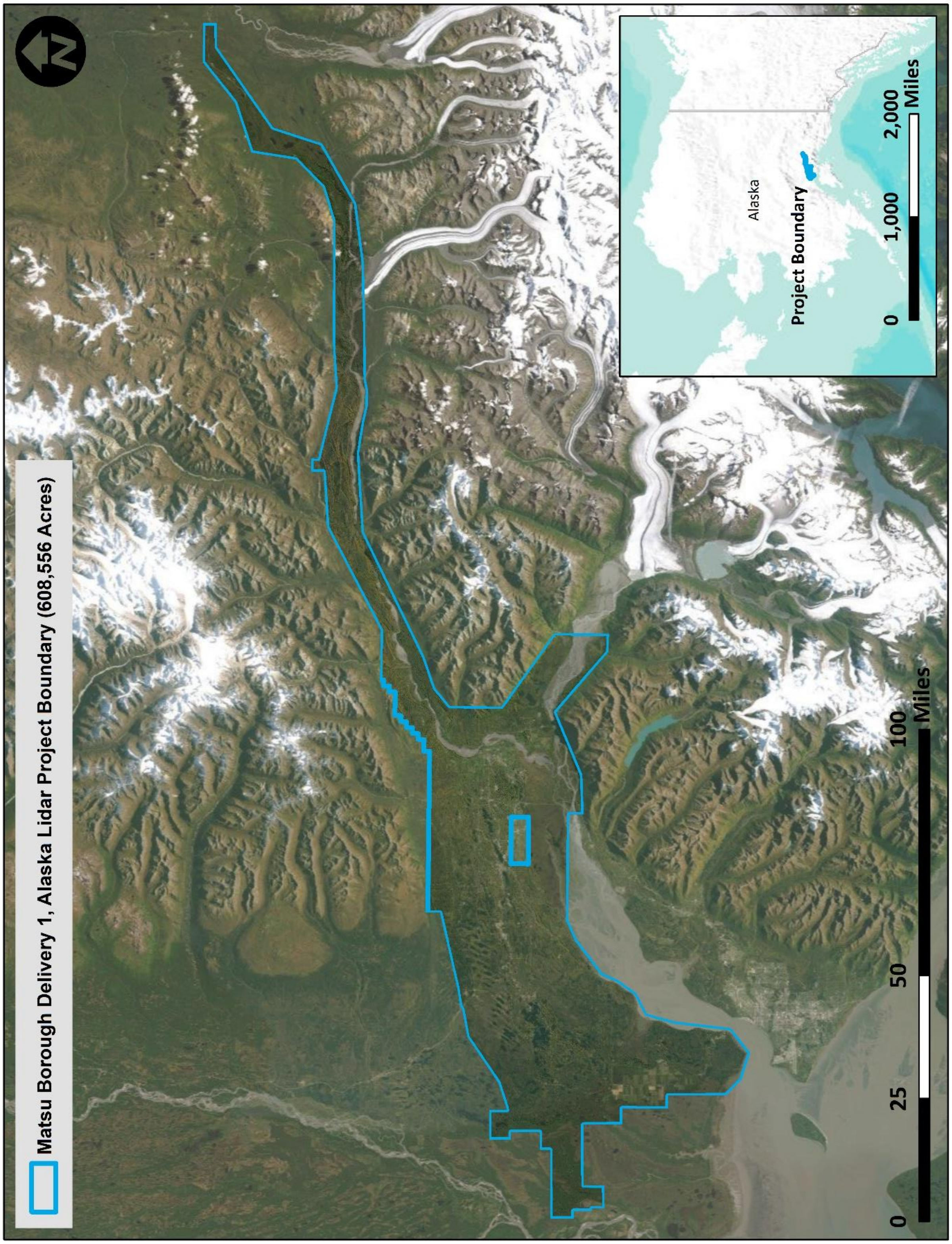


Figure 1: Location map of the MatSu Borough, Alaska Delivery 1 site in Alaska

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 MatSu Borough, Alaska Delivery 1 lidar study area at the target point densities of ≥2.0 points/m^2. 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, tidal conditions, and potential air space restrictions were reviewed.

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 ≥2 pulses/m^2 over the MatSu Borough, Alaska Delivery 1 project area. The Leica ALS80 laser system can record unlimited 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	9/13/2019 - 10/7/2019
Aircraft Used	Cessna Caravan 604MD
Sensor	Leica
Laser	ALS80
Maximum Returns	15
Resolution/Density	Average 2 pulses/m^2
Nominal Pulse Spacing	0.71 m
Survey Altitude (AGL)	1400 m
Survey speed	140 knots
Field of View	40^o
Mirror Scan Rate	52 Hz
Target Pulse Rate	202 kHz
Pulse Length	2.5 ns
Laser Pulse Footprint Diameter	30.8 cm
Central Wavelength	1064 nm
Pulse Mode	Multiple Pulses in Air
Beam Divergence	0.22 mrad
Swath Width	600 m
Swath Overlap	44 %
Intensity	16-bit
Accuracy	$RMSE_Z$ (Non-Vegetated) ≤ 10 cm
	NVA (95% Confidence Level) ≤ 19.6 cm
	VVA (95th Percentile) ≤ 30 cm

Leica ALS80 LiDAR sensor

All areas were surveyed with an opposing flight line side-lap of ≥44% (≥88% 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 Survey

Ground control surveys, including monumentation and ground survey points (GSPs) were conducted 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.

Base Stations

Base stations were utilized for the collection of ground survey points by McClintock Land Associates (MLA). Base station locations included fourteen new monument spikes set by MLA, as well as seven continuously operation reference station (CORS) locations occupied by MLA. Base locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage (Table 4, Figure 2).

Table 4: Base station positions for the MatSu Borough, Alaska Delivery 1 acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Type	Base Station ID	Latitude	Longitude	Ellipsoid (meters)
CORS	AC11	33° 21' 33.55187"	-84° 33' 07.51053"	745.698
CORS	AC53	33° 01' 07.00036"	-85° 02' 51.44287"	20.545
CORS	AKAG	33° 20' 44.82167"	-85° 18' 44.68023"	16.111
CORS	AKER	33° 20' 14.08958"	-85° 08' 38.72193"	72.648
CORS	AKPM	33° 16' 47.16796"	-84° 56' 38.19424"	48.956
CORS	AKPR	33° 18' 08.95011"	-84° 52' 34.59245"	50.099
CORS	ATW2	33° 17' 53.01290"	-84° 52' 56.66781"	57.067
Spike	SALPINE	33° 16' 41.39646"	-84° 45' 08.96788"	214.391
Spike	SBASEFLR	33° 19' 55.41315"	-84° 38' 36.23541"	233.846
Spike	SBASEH2	33° 10' 07.63983"	-84° 47' 50.41418"	918.881
Spike	SBASEP	33° 24' 18.38140"	-84° 29' 19.57687"	665.411
Spike	SBASEV	33° 26' 01.74727"	-84° 27' 28.68444"	459.727
Spike	SBENHUR	33° 24' 04.11047"	-84° 52' 31.22597"	9.494

Type	Base Station ID	Latitude	Longitude	Ellipsoid (meters)
Spike	SBONNIE	33° 21' 51.86640"	-84° 32' 46.39726"	583.865
Spike	SBUFF	33° 15' 12.63106"	-84° 49' 17.56047"	230.444
Spike	SBUFF2	33° 15' 06.88543"	-84° 46' 57.98231"	349.310
Spike	SDANJOE	33° 10' 12.00788"	-84° 58' 32.19831"	152.906
Spike	SE2	33° 31' 21.93059"	-84° 08' 48.95128"	985.707
Spike	SKNIK	33° 26' 14.35326"	-84° 52' 19.72206"	17.234
Spike	SMAUD	33° 21' 09.07464"	-84° 50' 50.89158"	-1.921
Spike	SROSE	33° 14' 21.42856"	-85° 09' 42.81926"	8.131

Monuments were established according to the national standard for geodetic control networks, as specified in the Federal Geographic Data Committee (FGDC) Geospatial Positioning Accuracy Standards for geodetic networks.[1] This standard provides guidelines for classification of monument quality at the 95% confidence interval as a basis for comparing the quality of one control network to another. The monument rating for this project is shown in Table 5.

Table 5: Federal Geographic Data Committee monument rating for network accuracy

Direction	Rating
1.96 * St Dev $_{NE}$:	0.020 m
1.96 * St Dev $_{z}$:	0.020 m

For the MatSu Borough, Alaska Delivery 1 lidar project, the monument coordinates contributed no more than 2.8 cm of positional error to the geolocation of the final ground survey points and lidar, with 95% confidence.

Ground Survey Points (GSPs)

Ground survey points were collected by MLA and provided to QSI to be used in lidar calibration and post-processing, and for accuracy assessment. MLA provided ground control point data for lidar calibration, in addition to non-vegetated (NVA) and vegetated (VVA) check point data for accuracy assessment.

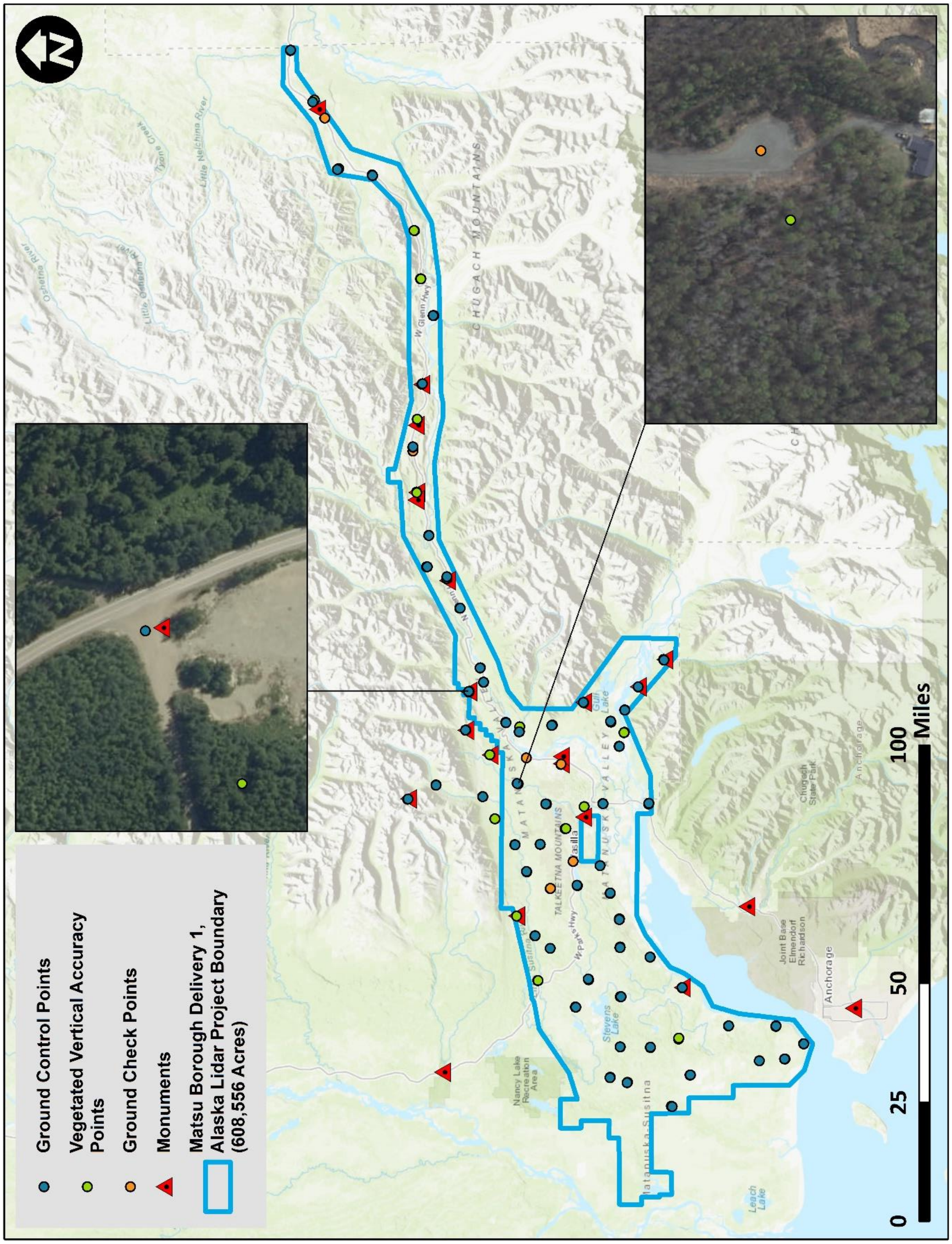
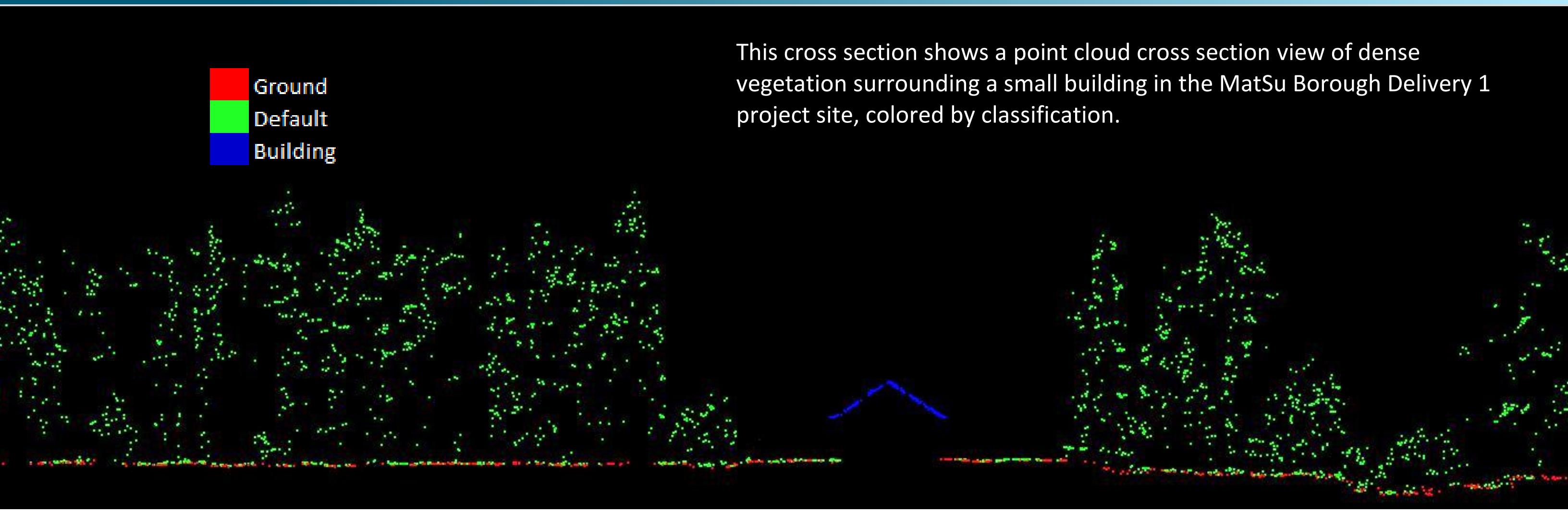


Figure 2: Ground survey location



This cross section shows a point cloud cross section view of dense vegetation surrounding a small building in the MatSu Borough Delivery 1 project site, colored by classification.

Lidar Data Processing

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 6). Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 7.

Table 6: ASPRS LAS classification standards applied to the MatSu Borough, Alaska Delivery 1 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
2	Ground	Laser returns that are determined to be ground using automated and manual cleaning algorithms
6	Buildings and Bridges	Permanent structures such as buildings and bridges
7	Low Noise	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
18	High Noise	Above-ground laser returns that are often associated with birds, scattering from reflective surfaces, or atmospheric noise
20	Ignored Ground	Ground points proximate to water’s edge breaklines; ignored for correct model creation

Table 7: 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.	Waypoint Inertial Explorer v.8.8
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.	Waypoint Inertial Explorer v.8.8 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.19
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.19
Classify resulting data to ground and other client designated ASPRS classifications (Table 6). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.19 TerraModeler v.19
Export intensity images as GeoTIFFs at a half meter pixel resolution for QL1 areas and a 1-meter pixel resolution for QL2 areas.	Las Monkey 2.4 (QSI proprietary) LAS Product Creator 3.0 (QSI proprietary) ArcMap v. 10.3.1
Generate hydroflattened bare earth models as triangulated surfaces. Generate highest hit models as a surface expression of all classified points. Export all surface models as Geotiff format at a 3.0 foot pixel resolution.	LAS Product Creator 3.0 (QSI proprietary)

Lidar Feature Extraction

Hydroflattening and Water's Edge Breaklines

Hydroflattening was performed for all rivers, lakes, and tidal waters within the MatSu Borough, Alaska Delivery 1 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.

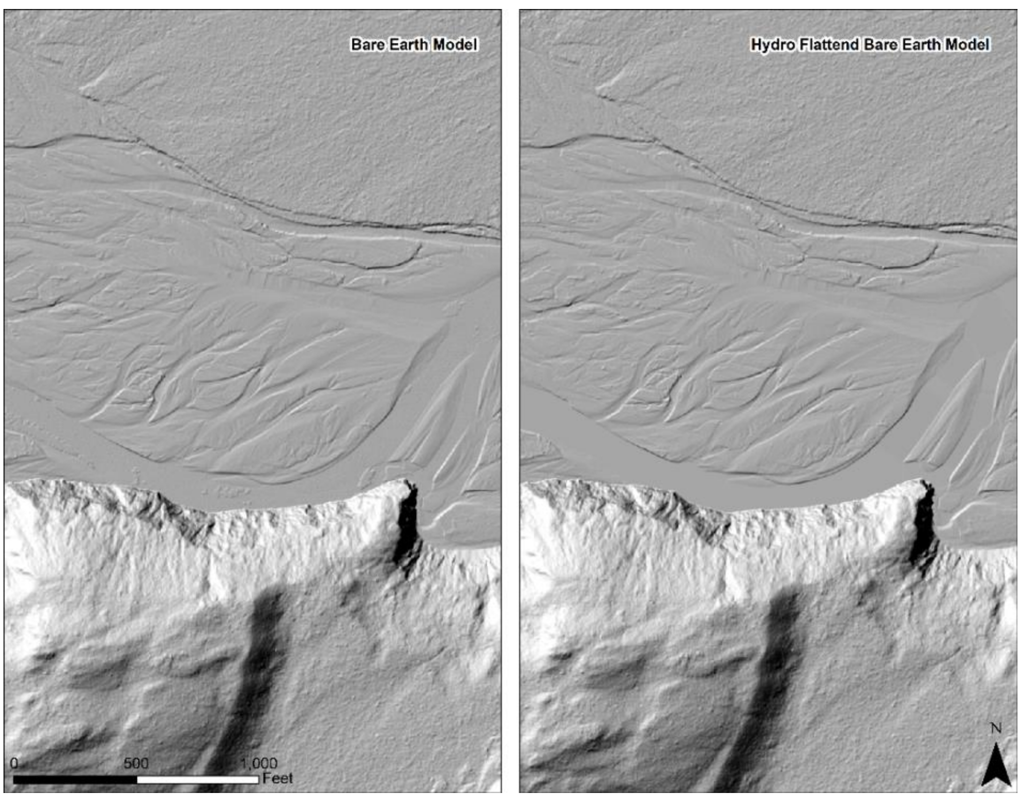


Figure 3: Example ground surface models along the MatSu Borough, Alaska Delivery 1: lidar bare earth and hydroflattened bare earth

Contour Generation

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 keypoints were selected from the ground model every foot 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 1-foot elevation increments (Figure 4).

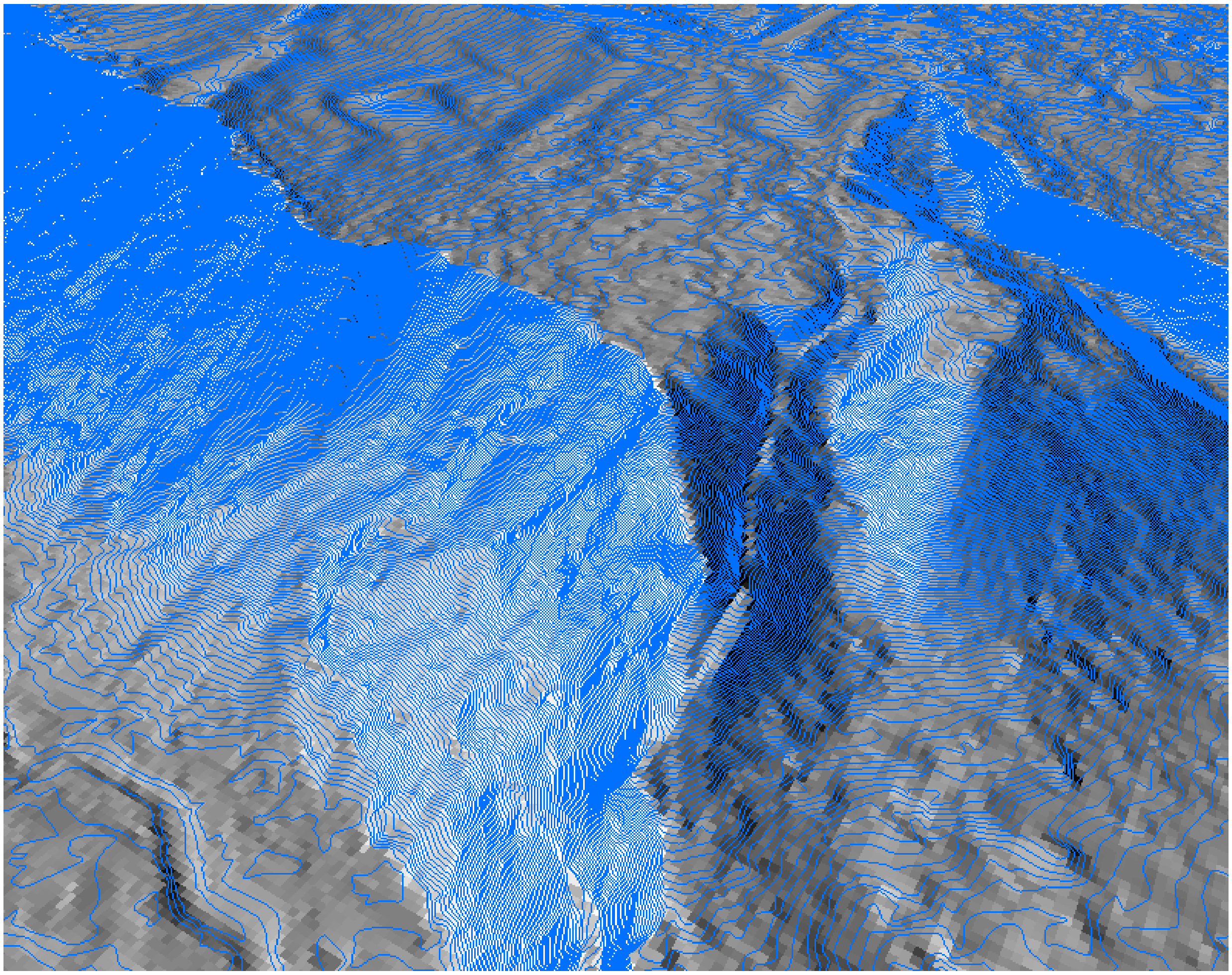


Figure 4: Contours draped over the MatSu Borough, Alaska Delivery 1 bare earth digital elevation model.

Building Footprints

Building classification was performed through a combination of automated algorithms and manual classification. All non-mobile structures such as houses, barns, silos and sheds were classified into the building category. Once classification was complete, automated routines were used generate the polygon shapefile representing building and bridge footprints. Building features are reviewed and additional manual editing of the building classification was performed as necessary where dense canopy was immediately proximate to features. A total of 49,552 buildings were classed in the data (Figure 5).

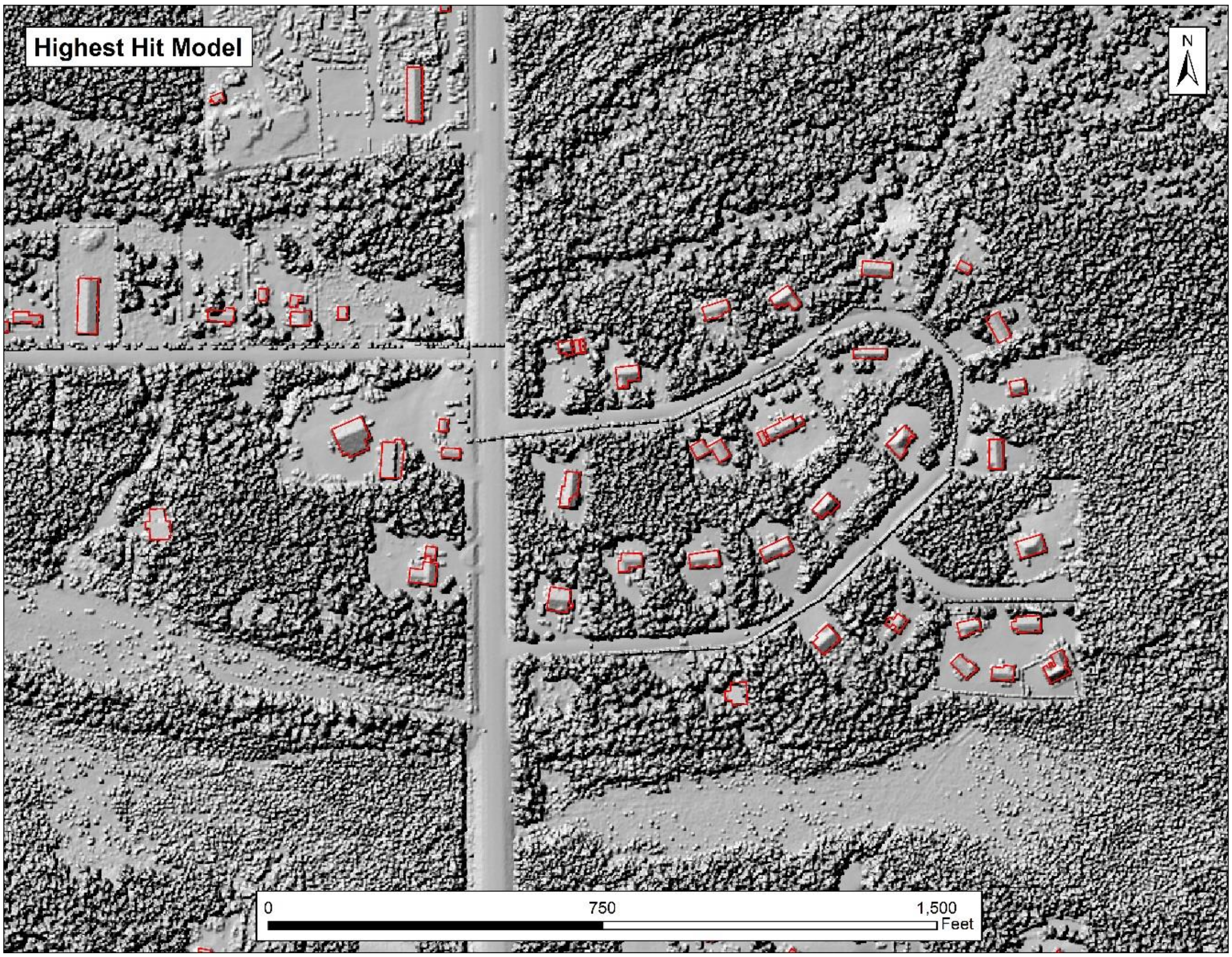
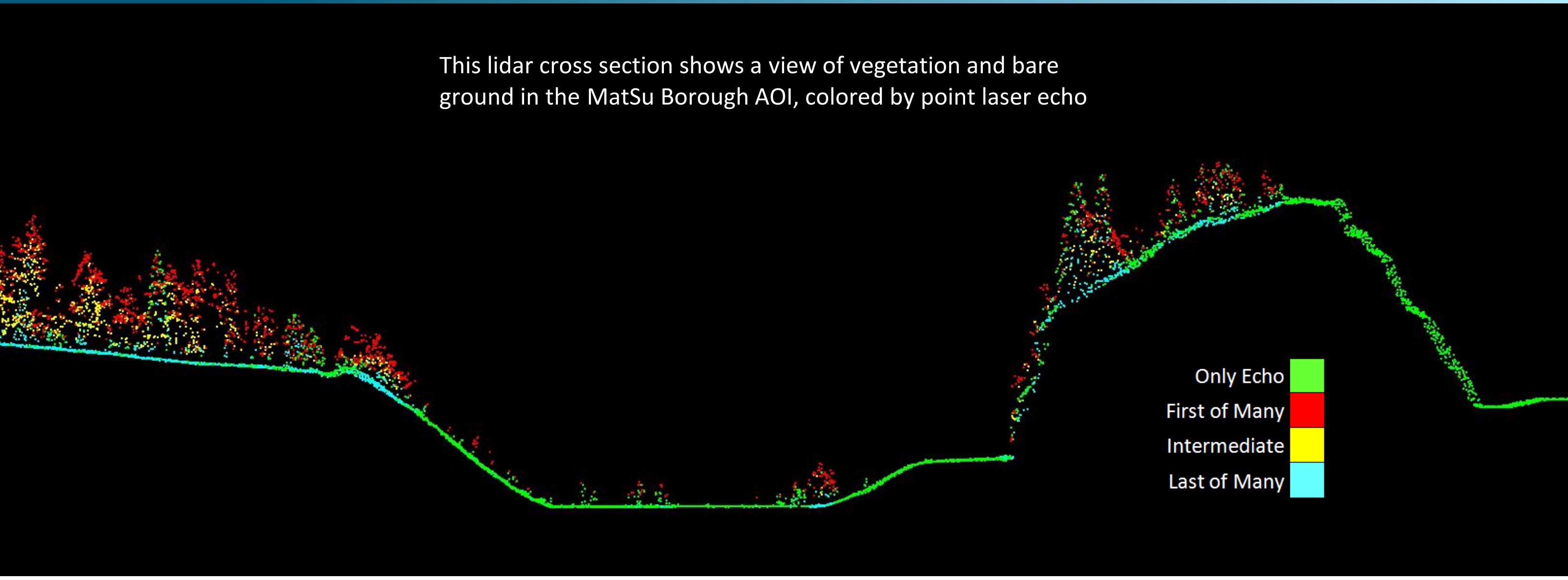


Figure 5: Sample image of building and bridge footprints in the MatSu Borough, Alaska Delivery 1 dataset



Lidar Density

The acquisition parameters were designed to acquire an average first-return density of 2 points/m^2 (0.19 points/ft^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 MatSu Borough, Alaska Delivery 1 project was 4.64 points/m^2 (0.43 points/ft^2) while the average ground classified density was 1.73 points/m^2 (0.16 points/ft^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 6 through Figure 8.

Table 8: Average lidar point densities

Classification	Point Density
First-Return	4.64 points/m^2 0.43 points/ft^2
Ground Classified	1.73 points/m^2 0.16 points/ft^2

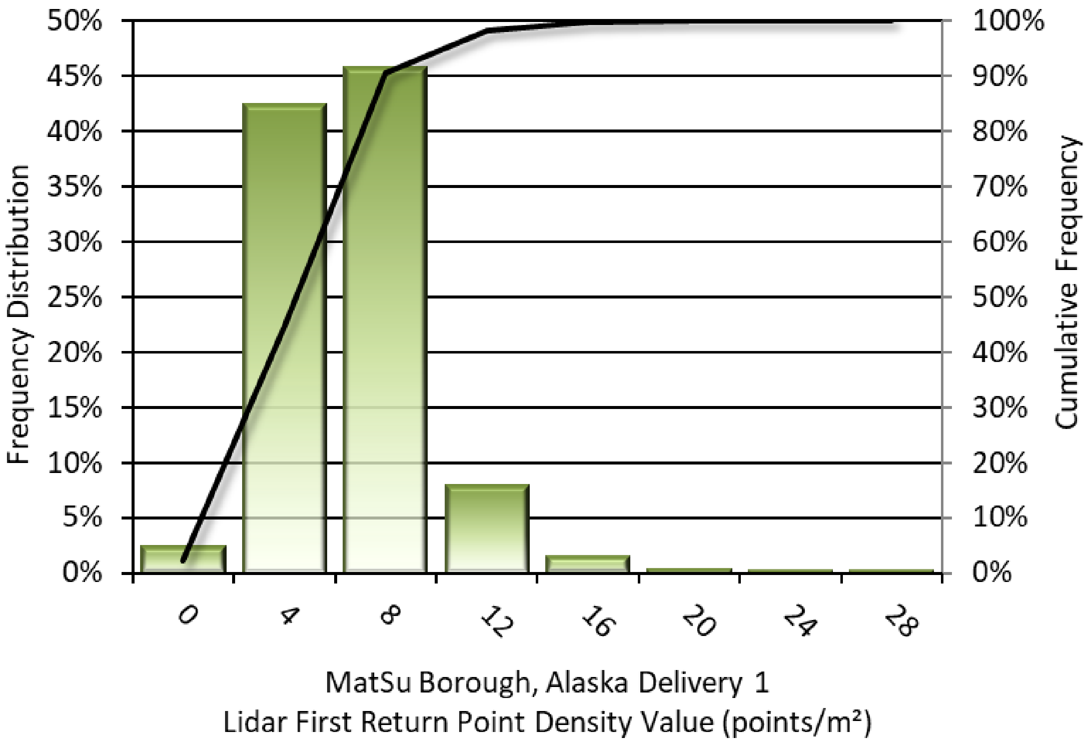


Figure 6: Frequency distribution of first return point density values per 100 x 100 m cell

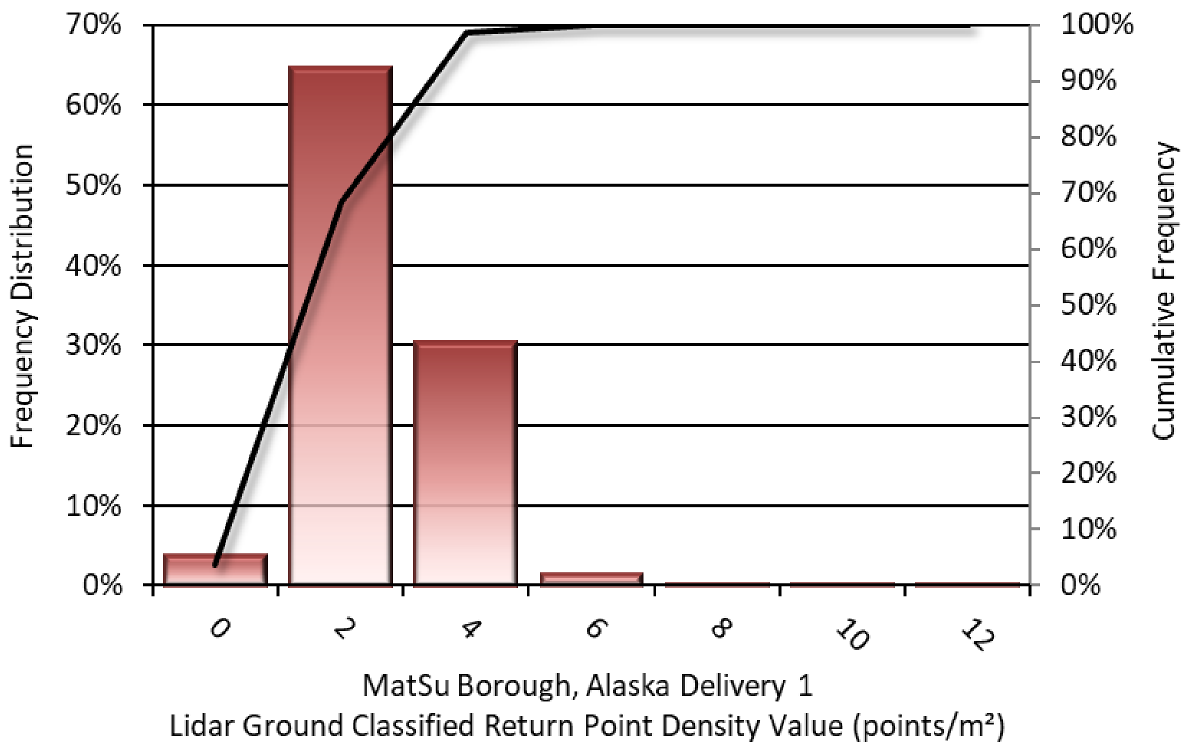


Figure 7: Frequency distribution of ground-classified return point density values per 100 x 100 m cell

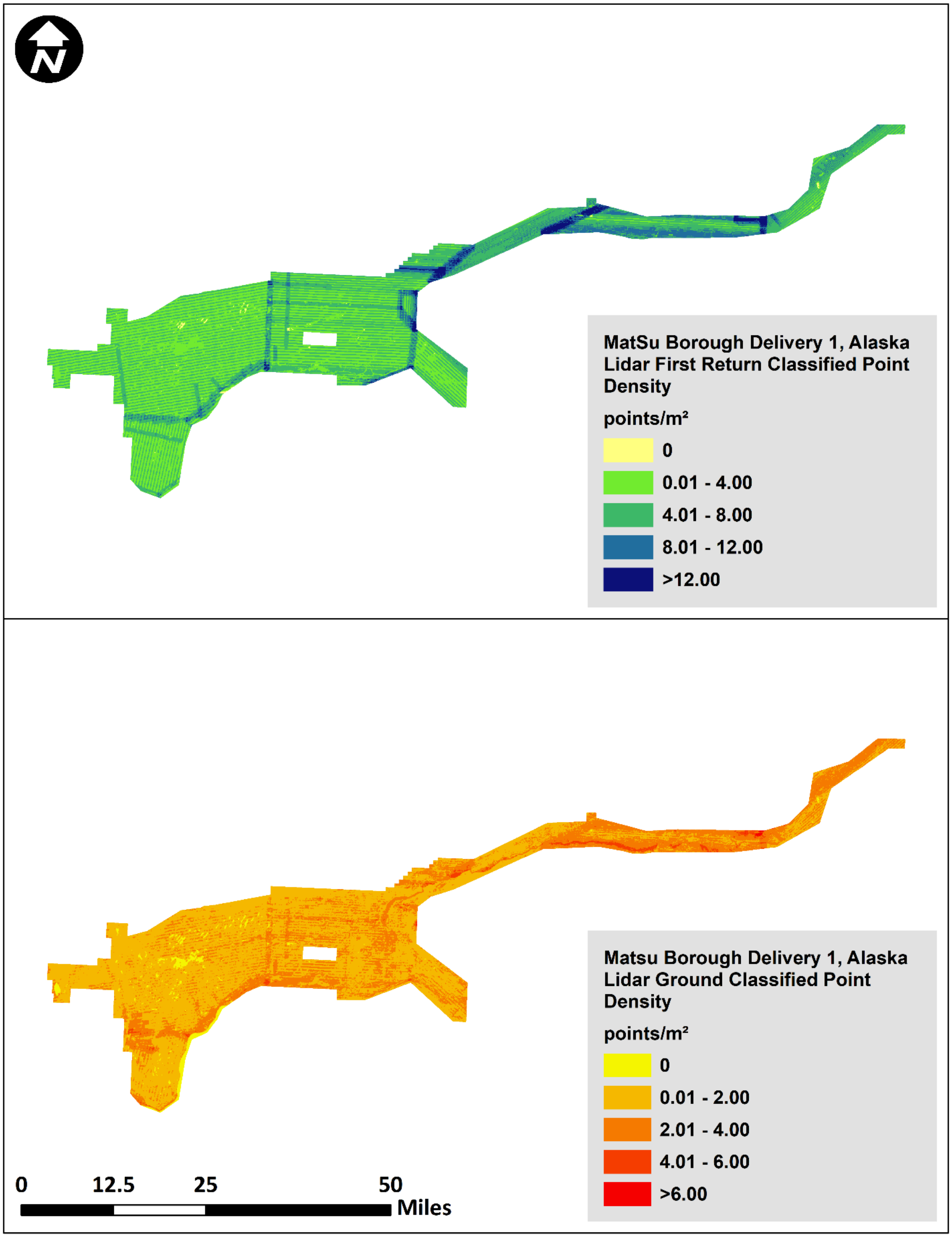


Figure 8: First return and ground-classified point density map for the MatSu Borough, Alaska Delivery 1 site (100 m x 100 m cells)

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[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 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 MatSu Borough, Alaska Delivery 1 survey, 52 ground check points were withheld from the calibration and post processing of the lidar point cloud, with resulting non-vegetated vertical accuracy of 0.070 meters (0.228 feet) as compared to unclassified LAS, and 0.068 meters (0.223 feet) as compared to the bare earth DEM, with 95% confidence (Figure 9, Figure 10).

QSI also assessed absolute accuracy using 53 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 9 and Figure 11.

[2] Federal Geographic Data Committee, ASPRS POSITIONAL ACCURACY STANDARDS FOR DIGITAL GEOSPATIAL DATA EDITION 1, Version 1.0, NOVEMBER 2014. https://www.asprs.org/a/society/committees/standards/Positional_Accuracy_Standards.pdf.

Table 9: Absolute accuracy results

Absolute Vertical Accuracy			
	NVA, as compared to unclassified LAS	NVA, as compared to bare earth DEM	Ground Control Points
Sample	52 points	52 points	53 points
95% Confidence (1.96*RMSE)	0.228 ft 0.070 m	0.223 ft 0.068 m	0.274 ft 0.084 m
Average	0.015 ft 0.004 m	0.007 ft 0.002 m	0.004 ft 0.001 m
Median	0.007 ft 0.002 m	-0.003 ft -0.001 m	0.013 ft 0.004 m
RMSE	0.116 ft 0.035 m	0.114 ft 0.035 m	0.140 ft 0.043 m
Standard Deviation (1σ)	0.117 ft 0.036 m	0.115 ft 0.035 m	0.141 ft 0.043 m

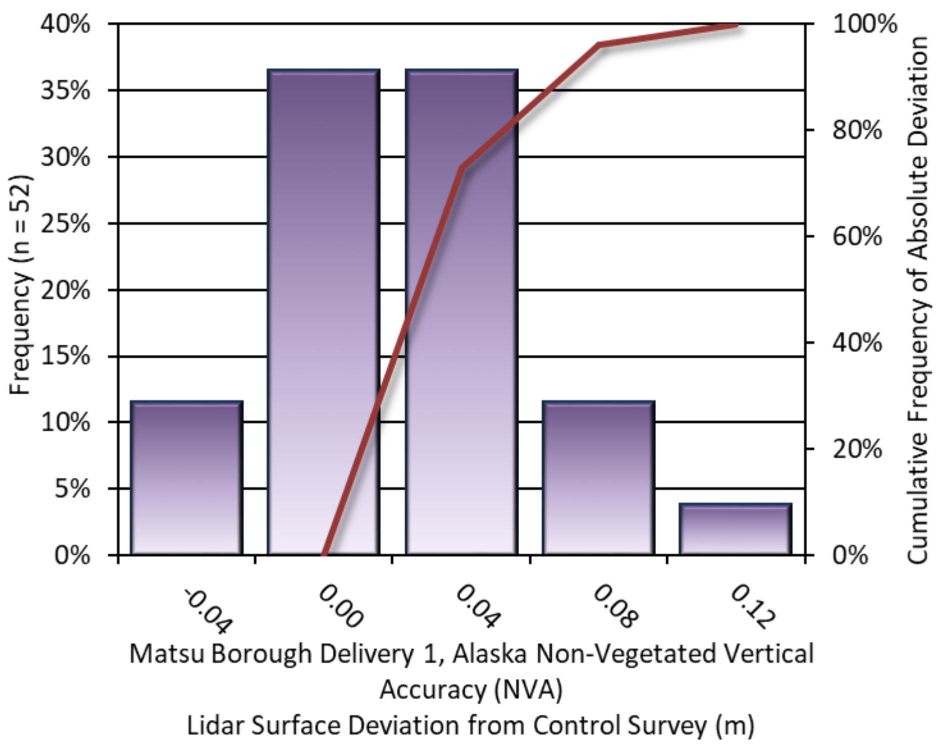


Figure 9: Frequency histogram for lidar unclassified LAS deviation from ground check point values (NVA)

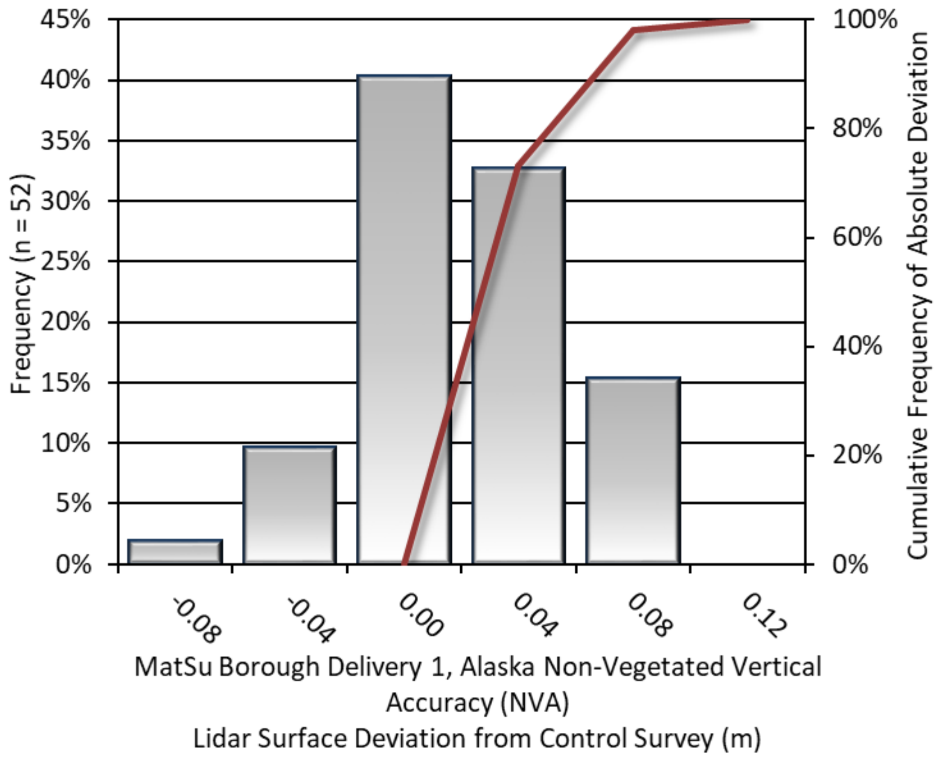


Figure 10: Frequency histogram for lidar bare earth DEM surface deviation from ground check point values (NVA)

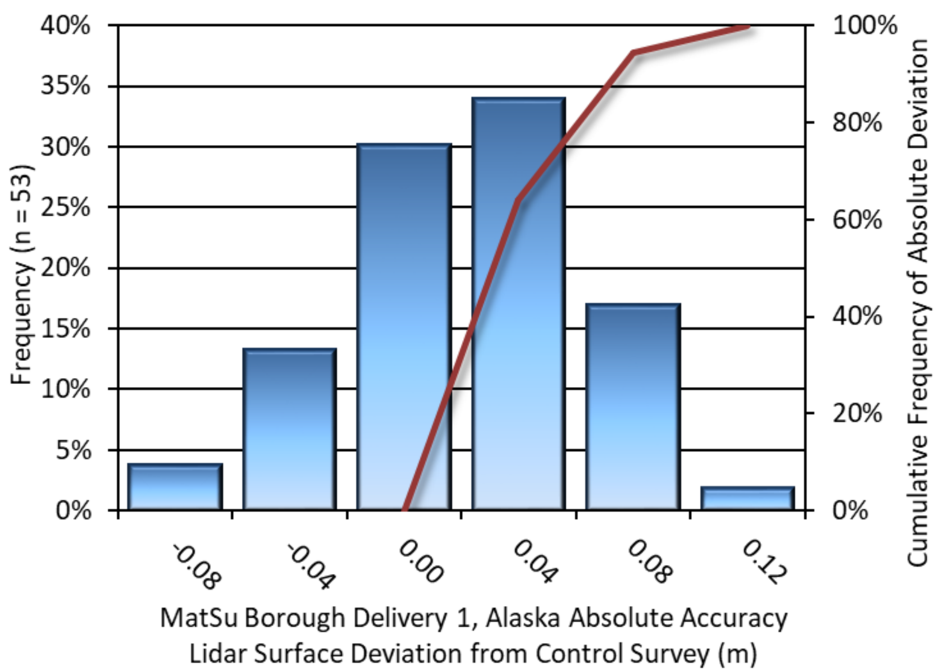


Figure 11: Frequency histogram for lidar surface deviation from ground control point values

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 MatSu Borough, Alaska Delivery 1 survey, 41 vegetated check points were collected, with resulting vegetated vertical accuracy of 0.242 meters (0.794 feet) as compared to the bare earth DEM, evaluated at the 95th percentile (Table 10, Figure 12).

Table 10: Vegetated vertical accuracy results

Vegetated Vertical Accuracy	
Sample	41 points
95th Percentile	0.794 ft 0.242 m
Average	-0.292 ft -0.089 m
Median	-0.227 ft -0.069 m
RMSE	0.438 ft 0.133 m
Standard Deviation (1σ)	0.330 ft 0.101 m

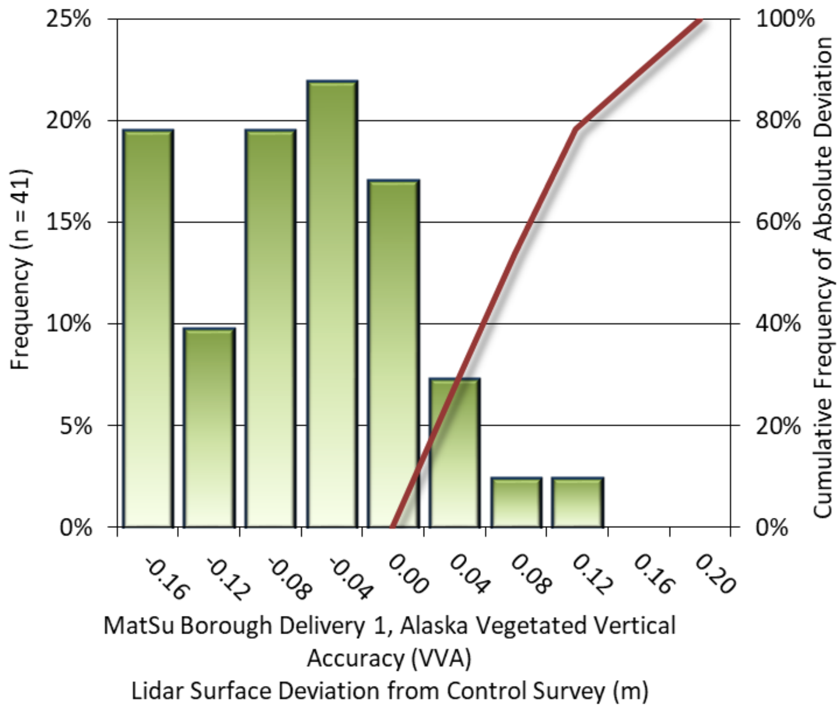


Figure 12: Frequency histogram for lidar surface deviation from vegetated check point values (VVA)

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 MatSu Borough, Alaska Delivery 1 lidar project was 0.039 meters (-0.002 feet) (Table 11, Figure 13).

Table 11: Relative accuracy results

Relative Accuracy	
Sample	253 surfaces
Average	-0.002 ft 0.039 m
Median	-0.001 ft 0.036 m
RMSE	0.008 ft 0.040 m
Standard Deviation (1σ)	0.008 ft 0.010 m
1.96σ	0.015 ft 0.020 m

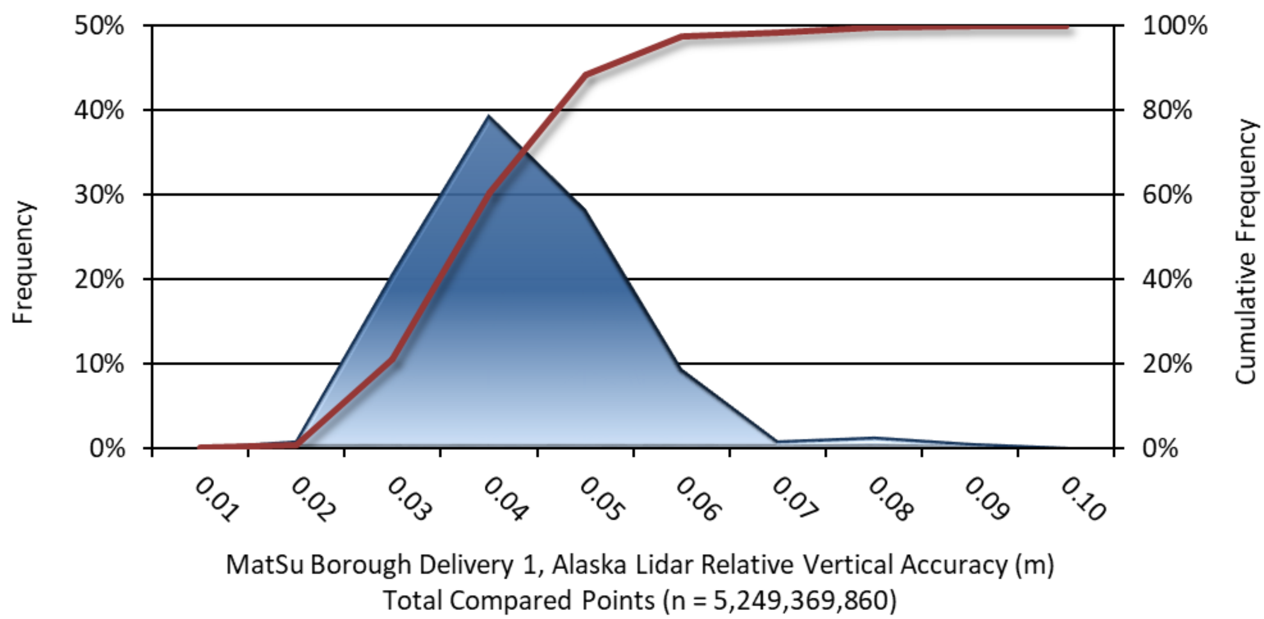


Figure 13: Frequency plot for relative vertical accuracy between flight lines

Lidar Horizontal Accuracy

Lidar horizontal accuracy is a function of Global Navigation Satellite System (GNSS) derived positional error, flying altitude, and INS derived attitude error. The obtained $RMSE_r$ value is multiplied by a conversion factor of 1.7308 to yield the horizontal component of the National Standards for Spatial Data Accuracy (NSSDA) reporting standard where a theoretical point will fall within the obtained radius 95 percent of the time. Based on a flying altitude of 1,750 meters, an IMU error of 0.002 decimal degrees, and a GNSS positional error of 0.070 meters, this project was compiled to meet 0.0008 meters (0.0029 ft) horizontal accuracy at the 95% confidence level.

Table 12: Horizontal Accuracy

Horizontal Accuracy	
$RMSE_r$	0.0029 ft 0.0008 m
ACC_r	0.0050 ft 0.0015 m

CERTIFICATIONS

Quantum Spatial, Inc. provided LiDAR services for the MatSu Borough, Alaska Delivery 1 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 (Apr 20, 2020)

Tucker Selko
Project Manager
Quantum Spatial, Inc.

Figure 14: View looking east over MatSu Borough, Alaska Delivery 1. The image was created from the lidar bare earth model overlaid colored by elevation and point intensity.

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.
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> **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).
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> **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 ±20^{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.