Tanana River Floodplain Mapping

LiDAR Technical Data Report

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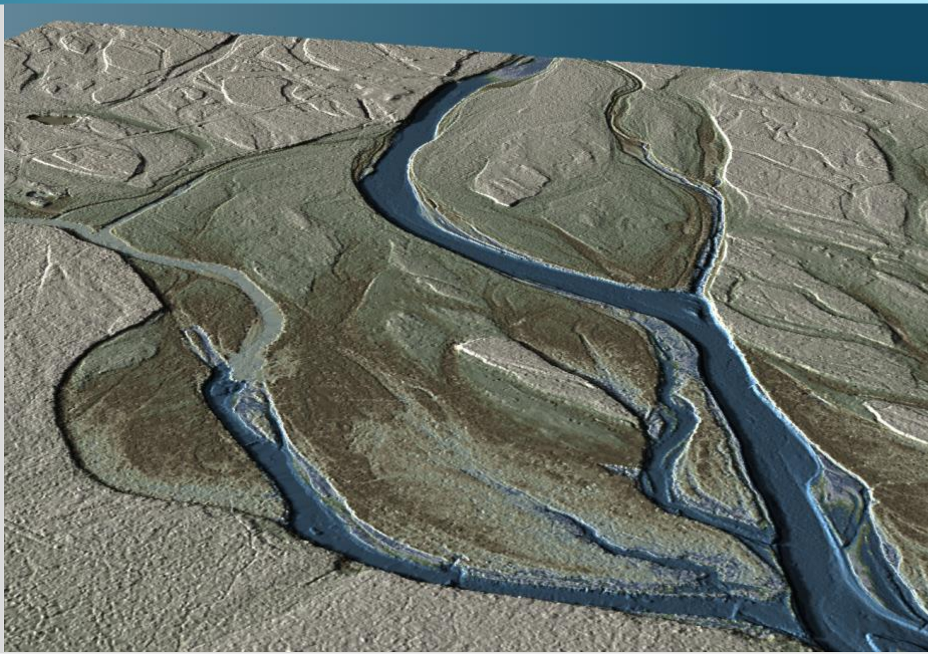
Cover Photo: A view looking southeast over the Tanana River. The image was created from the LiDAR bare earth model overlaid with the above ground point data and colored by elevation.

INTRODUCTION

View of the river channel in the Tanana River Floodplain, Alaska. The bare earth model is created from ground classified LiDAR returns and reveals the landscape with all vegetation removed.



In December 2015, Quantum Spatial (QSI) was contracted by the Fairbanks North Star Borough (FNSB) to collect Light Detection and Ranging (LiDAR) data for the Tanana River Floodplain site near Fairbanks, Alaska. Data were collected to aid FNSB in assessing the topographic and geophysical properties of the study area to aid in HEC-RAS modeling of the Tanana River.

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 FNSB 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 Tanana River Floodplain site

Project Site	Contracted Acres	Buffered Acres	Acquisition Date	Data Type
Tanana River Floodplain	38,400	40,380	April 30th, 2016	LiDAR

Deliverable Products

Table 2: Products delivered to FNSB for the Tanana River Floodplain site

Tanana River Floodplain Mapping Products Projection: Alaska State Plane Zone 3 Horizontal Datum: NAD83 (CORS96) Vertical Datum: NAVD88 (GEOID06) Units: U.S. Survey Feet	
Points	LAS v 1.4 • All Classified Returns • Raw Calibrated Flightline Swaths
Rasters	1.0 Meter ERDAS Imagine Files (*.img) • Bare Earth Model • Hydroflattened & Hydroenforced Bare Earth Model • Hydroflattened & Hydroenforced Bare Earth Model All Sinks Filled
Vectors	Shapefiles (*.shp) • LiDAR Tile Index • LiDAR Project Boundary • Hydro conditioned and flattened breaklines in ESRI Geodatabase file format. (*gdb)

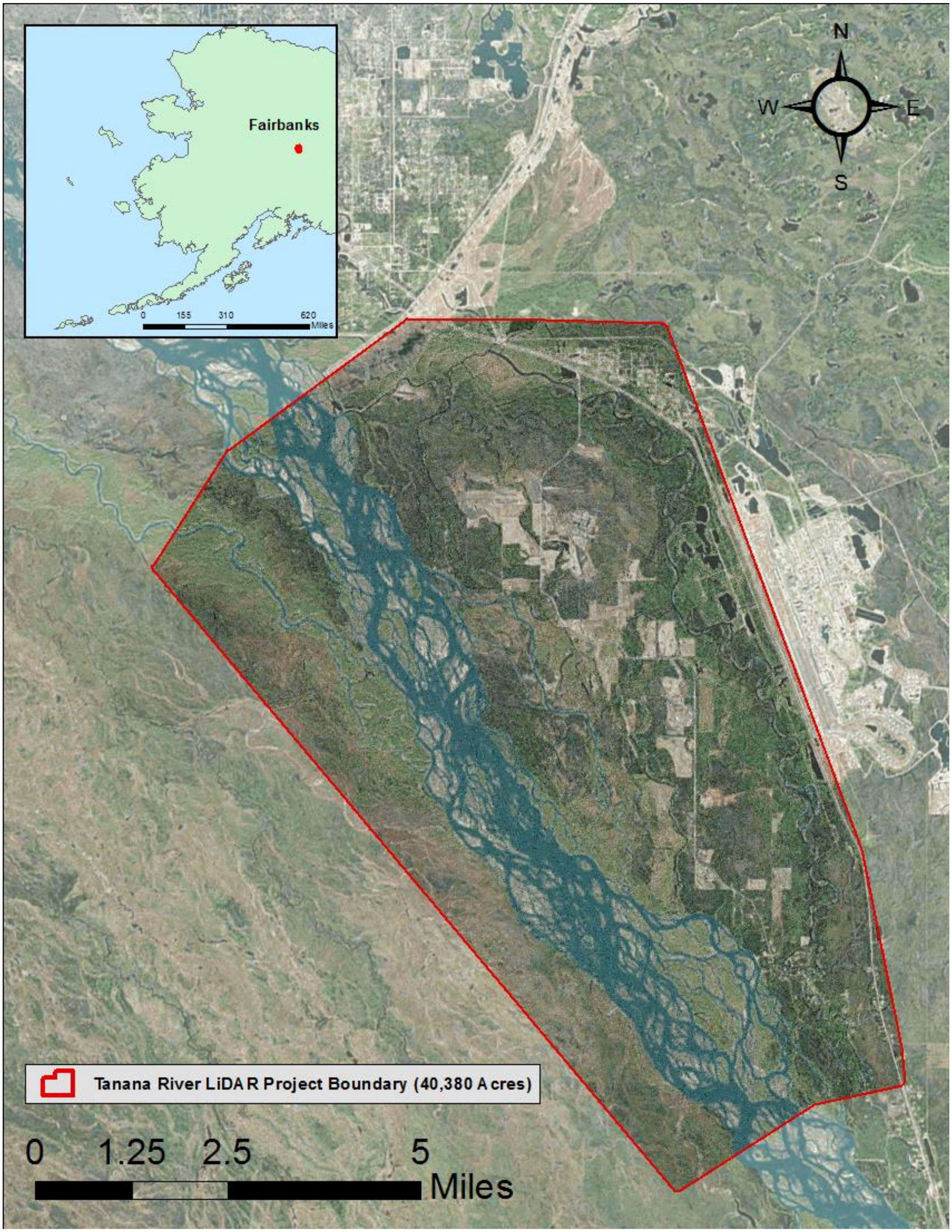


Figure 1: Location map of the Tanana River Floodplain site in Alaska

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 Tanana River Floodplain LiDAR study area at the target point density of ≥2.0 points/m^2 (0.18 points/ft^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.

QSI originally targeted acquisition for October 2015 with leaf-off, no-snow, and low-water conditions; however, acquisition was delayed until April 2016 in order to meet these requirements.

Factors such as satellite constellation availability, weather windows, and specific client requirements must be considered during the planning stage. Any weather hazards or conditions affecting the flight or data 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 due to the sites close proximity to a populated locality and military establishment.

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 Tanana River Floodplain 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	April 30, 2016
Aircraft Used	Cessna Caravan
Sensor	Leica ALS80
Survey Altitude (AGL)	1700 m
Swath Width	977 m
Target Pulse Rate	324.80 kHz
Pulse Mode	Dual Pulse in Air (2PiA)
Laser Pulse Diameter	37.4 cm
Mirror Scan Rate	48 Hz
Field of View	32^{o}
GPS Baselines	≤13 nm
GPS PDOP	≤3.0
GPS Satellite Constellation	≥6
Maximum Returns	Unlimited
Intensity	16-bit
Resolution/Density	Average 8 pulses/m^2
Accuracy	$RMSE_Z \leq 15$ cm

Leica ALS80 LiDAR sensor

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. Figure 2 below displays the flightlines for the Tanana River LiDAR site, and Table 4 details flight line start and stop times.

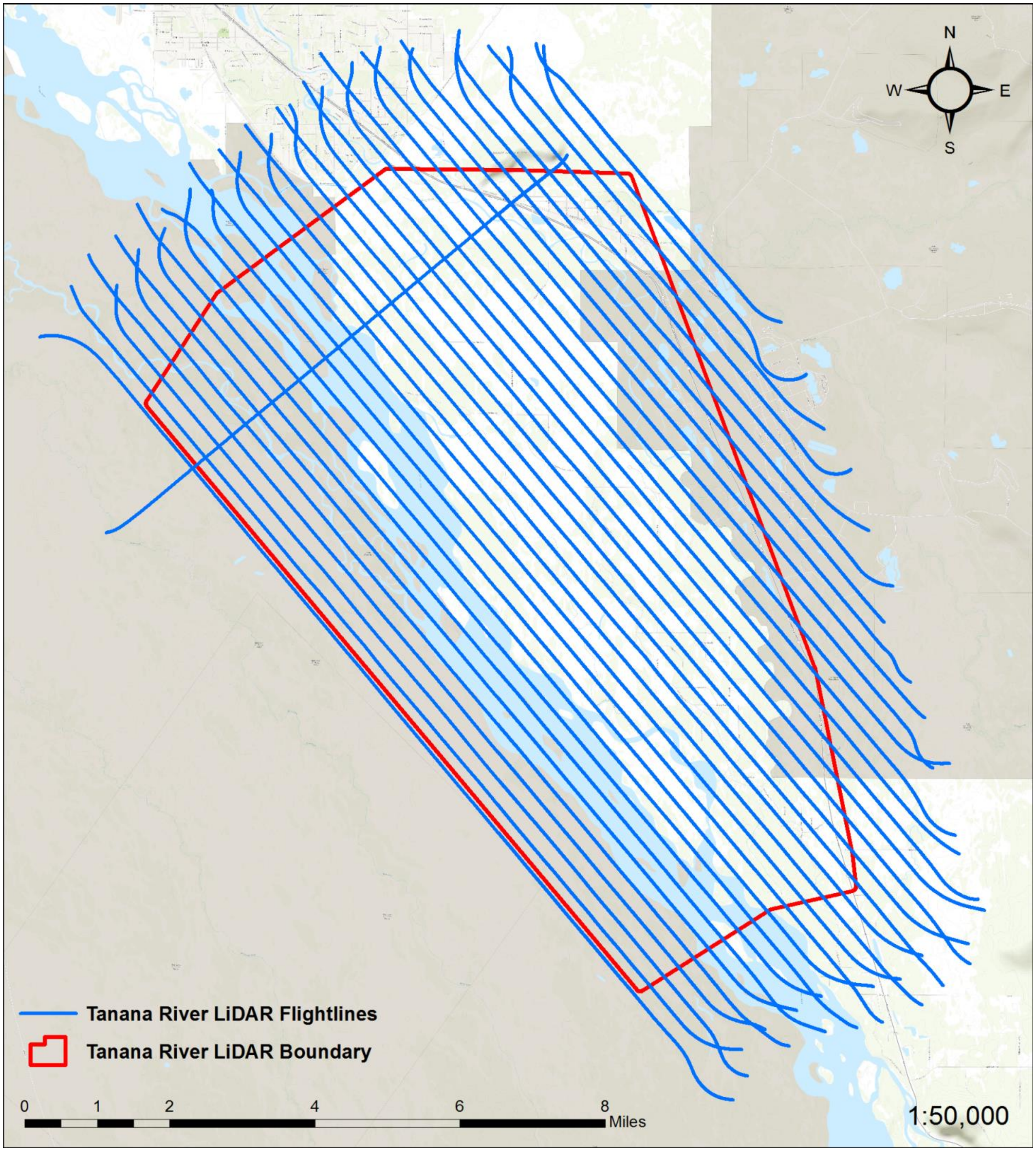


Figure 2: Tanana River LiDAR flightline map

Table 4: Flight details

April 30th Flight Details				
	Greenwich Meridian Time		Local Alaska Time	
Flightline ID	Start Time	End Time	Start Time	End Time
135	17:16:54	17:19:00	9:16:54	9:19:00
136	17:19:42	17:22:06	9:19:42	9:22:06
137	17:22:46	17:25:34	9:22:46	9:25:34
138	17:26:02	17:29:02	9:26:02	9:29:02
139	17:29:28	17:32:52	9:29:28	9:32:52
140	17:33:31	17:37:07	9:33:31	9:37:07
141	17:38:16	17:42:16	9:38:16	9:42:16
142	17:43:14	17:47:20	9:43:14	9:47:20
143	17:48:23	17:52:59	9:48:23	9:52:59
144	17:53:46	17:58:22	9:53:46	9:58:22
145	17:59:16	18:04:04	9:59:16	10:04:04
146	18:04:50	18:09:44	10:04:50	10:09:44
147	18:10:31	18:15:43	10:10:31	10:15:43
148	18:16:17	18:21:35	10:16:17	10:21:35
149	18:22:29	18:27:59	10:22:29	10:27:59
150	18:28:44	18:34:08	10:28:44	10:34:08
151	18:34:46	18:39:42	10:34:46	10:39:42
115	19:05:43	19:11:13	11:05:43	11:11:13
116	19:12:05	19:17:41	11:12:05	11:17:41
117	19:18:24	19:23:48	11:18:24	11:23:48
118	19:24:39	19:30:09	11:24:39	11:30:09
119	19:30:49	19:36:14	11:30:49	11:36:14
120	19:36:54	19:42:24	11:36:54	11:42:24
121	19:42:58	19:48:22	11:42:58	11:48:22
122	19:49:07	19:54:25	11:49:07	11:54:25
123	19:55:09	20:00:21	11:55:09	12:00:21
124	20:01:08	20:06:32	12:01:08	12:06:32
125	20:07:01	20:12:13	12:07:01	12:12:13
126	20:12:58	20:18:16	12:12:58	12:18:16
127	20:18:46	20:23:58	12:18:46	12:23:58
128	20:24:44	20:30:02	12:24:44	12:30:02
129	20:30:37	20:35:43	12:30:37	12:35:43
130	20:37:11	20:40:35	12:37:11	12:40:35

Ground Control

Ground control surveys, including monumentation, collection of ground control points (GCPs) and land cover class check points (LCPs), were conducted on behalf of QSI by DOWL 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.

Monumentation

QSI used static GNSS data provided by DOWL from base stations set up over three monument locations for the Tanana River Floodplain LiDAR project (Table 5, Figure 3). Horizontal coordinates are based on the NAD83(NSRS2007) ASPC Zone 3 position of the NGS Primary Airport Control Station “FAI A”, PID DF3640, as retrieved from the NGS database on July 1, 2008. NAD83(NSRS2007) and NAD83(CORS96) were held equivalent for the project area. Vertical coordinates are based on the USC&GS Benchmark “G 121”, PID TT2770, as retrieved from the NGS database on July 1, 2008. Further detail on the basis or coordinates and calculation of monument positions can be found in DOWL’s survey report in Appendix B.

All survey data were reviewed by QSI staff upon receipt, and monument positions were verified by processing static GNSS data against nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS[1]).

Table 4: Monuments established for the Tanana River Floodplain acquisition. Coordinates are on the NAD83 (CORS96) datum, epoch 2002.00

Monument ID	Latitude	Longitude	Ellipsoid (meters)
BUNKER	64° 45’ 28.83429”	-147° 13’ 16.86350”	167.723
PC 112_12.17	64° 43’ 25.09176”	-147° 16’ 22.58805”	169.841
GATE	64° 41’ 26.19583”	-147° 07’ 27.06874”	172.251

The spatial configuration of ground survey monuments provided redundant control within 13 nautical miles of the mission areas for LiDAR flights. Monuments were also used for collection of ground survey points using real time kinematic (RTK) survey techniques.

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

Ground Control Points (GCPs)

Ground control points were collected on behalf of QSI by DOWL using real time kinematic survey techniques and supplied to QSI for LiDAR calibration.

Land Cover Class Check Points (LCPs)

In addition to ground survey points, land cover class check points were collected and provided by DOWL throughout the study area. Land cover types were compared to the LiDAR dataset in order to assess confidence in the LiDAR-derived ground models across land cover classes. Land cover types and descriptions are shown in Table 5.

Table 5: Land Cover Types and Descriptions

Land cover type	Land cover code	Description
Shrub	SH	Landscape with short vegetation as seen in grazing lands
Forested	FO	Tree-dominated landscape where trees are large enough to produce timber
Bare Earth	BE	Areas characterized by bare rock, gravel, sand, silt, clay, or other earthen material, with little or no "green" vegetation present regardless of its inherent ability to support life.
Urban Area	UA	Areas dominated by urban development or human-made features.
Tall Grass	TG	Areas dominated by upland grasses and forbs, characterized by natural or semi-natural herbaceous vegetation.

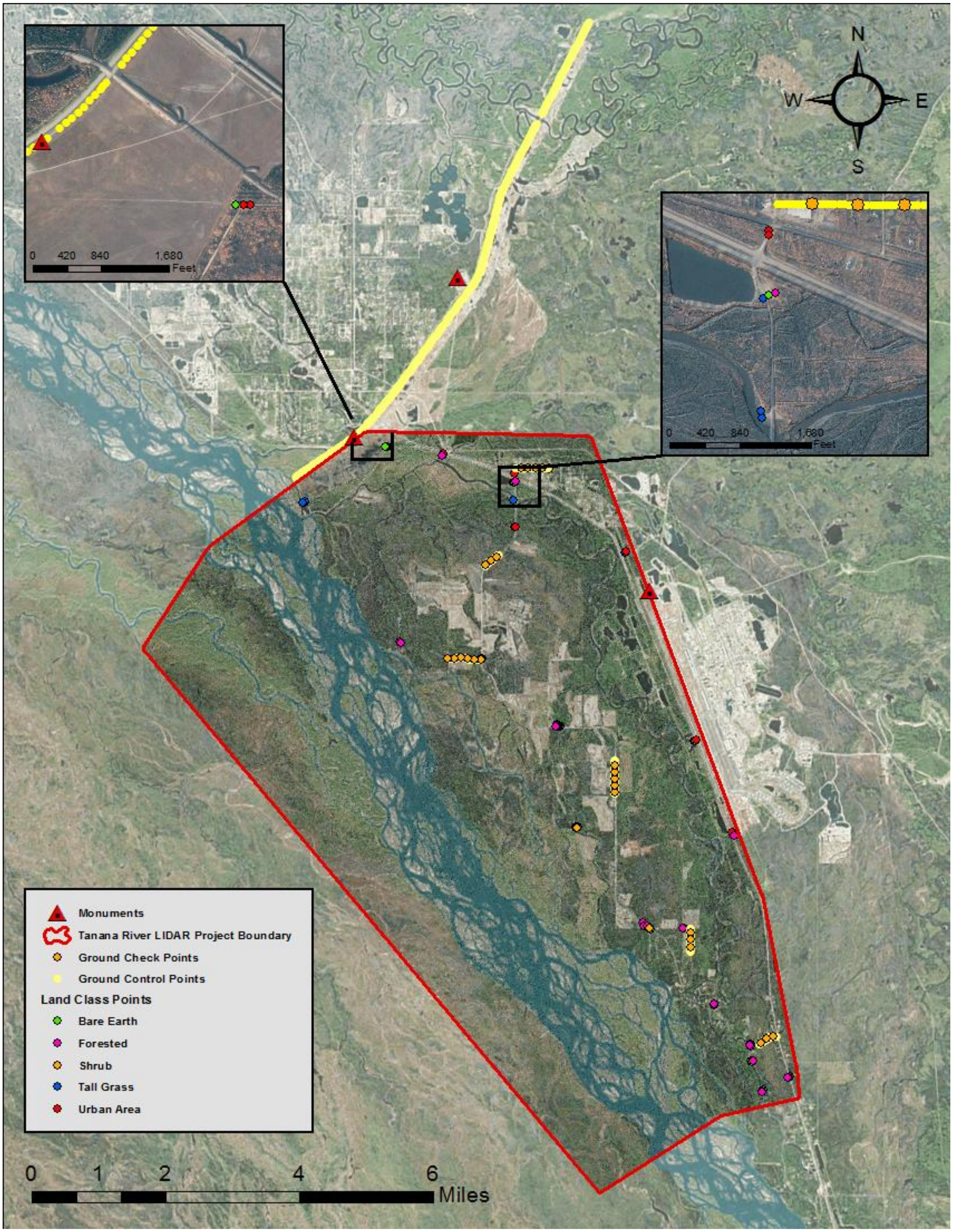
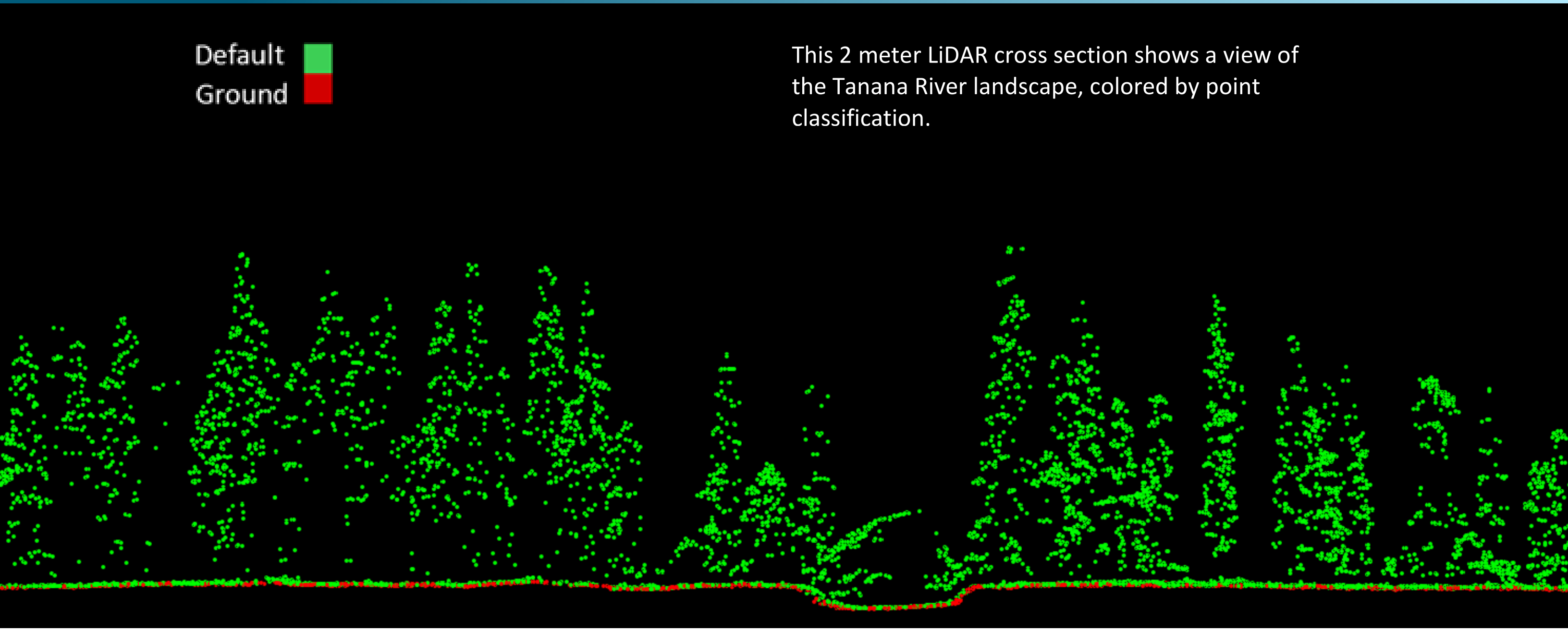


Figure 3: Ground survey location map



This 2 meter LiDAR cross section shows a view of the Tanana River 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 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 Tanana River Floodplain dataset

Classification Number	Classification Name	Classification Description
1	Default/Unclassified	Laser returns that are not included in the ground class, composed of vegetation and human-made structures
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.
9	Water	Laser returns that are determined to be water using automated and manual cleaning algorithms
10	Ignored Ground	Ground points proximate to water's edge breaklines; ignored for correct model creation
17	Bridge Decks	A structure carrying a road, path, railroad, canal, aircraft taxiway, or any other transit between two locations of higher elevation over an area of lower elevation.
18	Culverts	Ignored ground around Hydro-Enforcement 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.8.6
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 geoid06 correction.	Waypoint Inertial Explorer v.8.6 Leica Cloudpro v. 1.2.2
Import raw laser points into manageable blocks (less than 500 MB) to perform manual relative accuracy calibration and filter erroneous points. Classify ground points for individual flight lines.	TerraScan v.16
Using ground classified points per each flight line, test the relative accuracy. Perform automated line-to-line calibrations for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calculate calibrations on ground classified points from paired flight lines and apply results to all points in a flight line. Use every flight line for relative accuracy calibration.	TerraMatch v.16
Classify resulting data to ground and other client designated ASPRS classifications (Table). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.16 TerraModeler v.16
Generate bare earth models as triangulated surfaces. Generate highest hit models as a surface expression of all classified points. Export all surface models in EDRAS Imagine (.img) format at a 3.0 foot pixel resolution.	TerraScan v.16 TerraModeler v.156 ArcMap v. 10.2

Feature Extraction

Hydroflattening and Water's edge breaklines

To support the hydraulic modeling use of the data the bare earth model was hydro-flattened and hydro-enforced. The Tanana River and other water bodies with within the project area were flattened to consistent water levels. Bodies of water that were flattened include lakes and other closed water bodies with a surface area greater than 2 acres and all streams and rivers that are nominally wider than 30 meters. The hydro-flattening 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. Hydro-flattening 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.

Enforcement lines to direct surface flow were also incorporated into the DEM. To identify areas needing enforcement, all sinks (depressions) in the model were filled and using ArcHydro 2.0, all paths of flow with an accumulation threshold of at least 2.5 acres were identified. The model was then inspected for artificial obstructions to the flow (e.g., culverts beneath roads that allow flow but are not reflected in the normal bare earth model) and small enforcement lines were placed at these locations. Elevations for enforcements lines were initially derived from the LiDAR data and then forced down by 3ft to ensure the obstruction to flow was removed.

The hydro-flattening and hydro-enforcement breaklines were then incorporated into the hydroflattened and enforced bare earth model by enforcing triangle edges (adjacent to the breakline) to the elevation values of the breakline (Figure 4). This implementation corrected interpolation along the hard edge. Lastly, two hydro-flattened and enforced models are being provided to add flexibility for the intended further analysis. One DEM version has had no sinks/depressions filled and one model version has had all sinks/depressions filled.

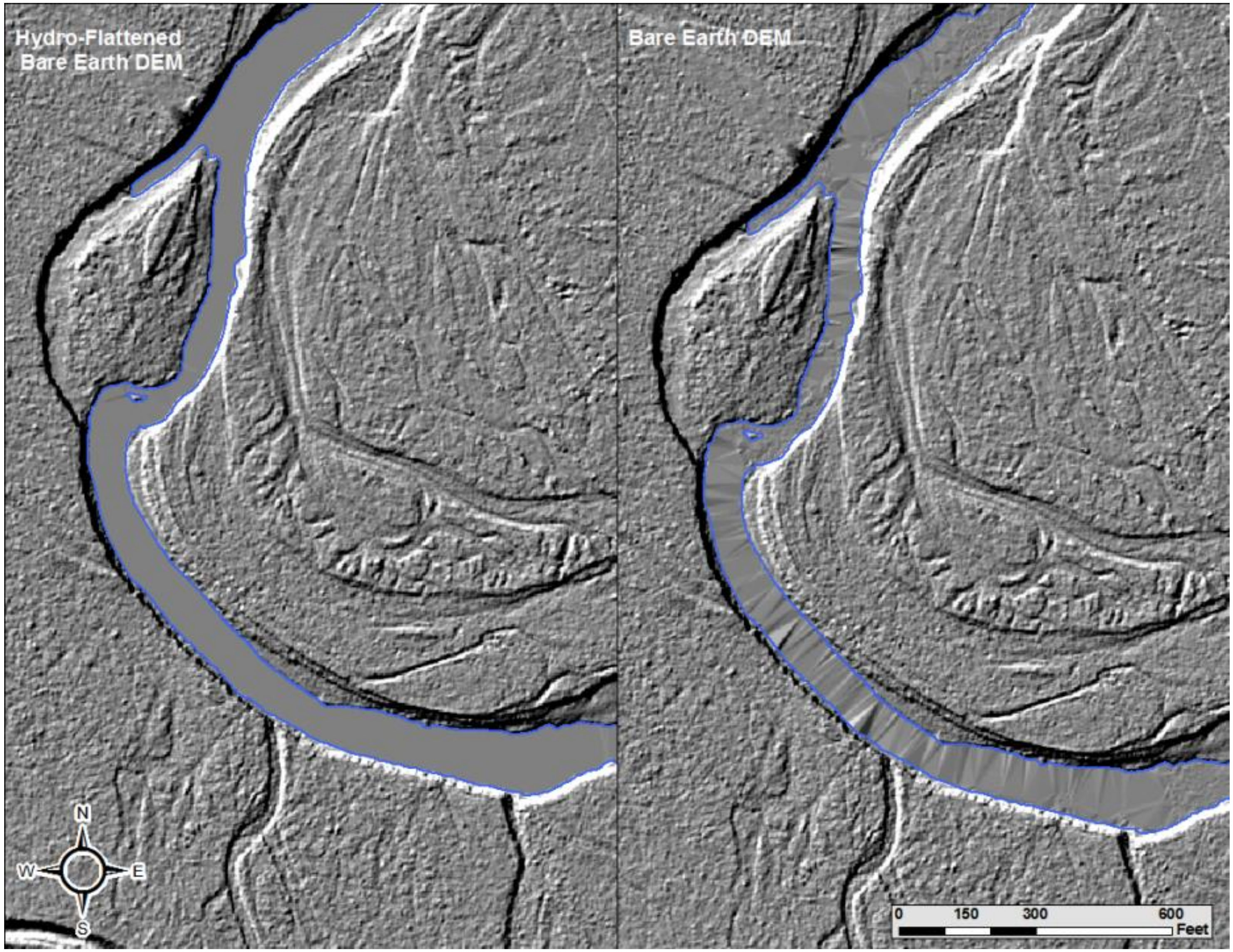
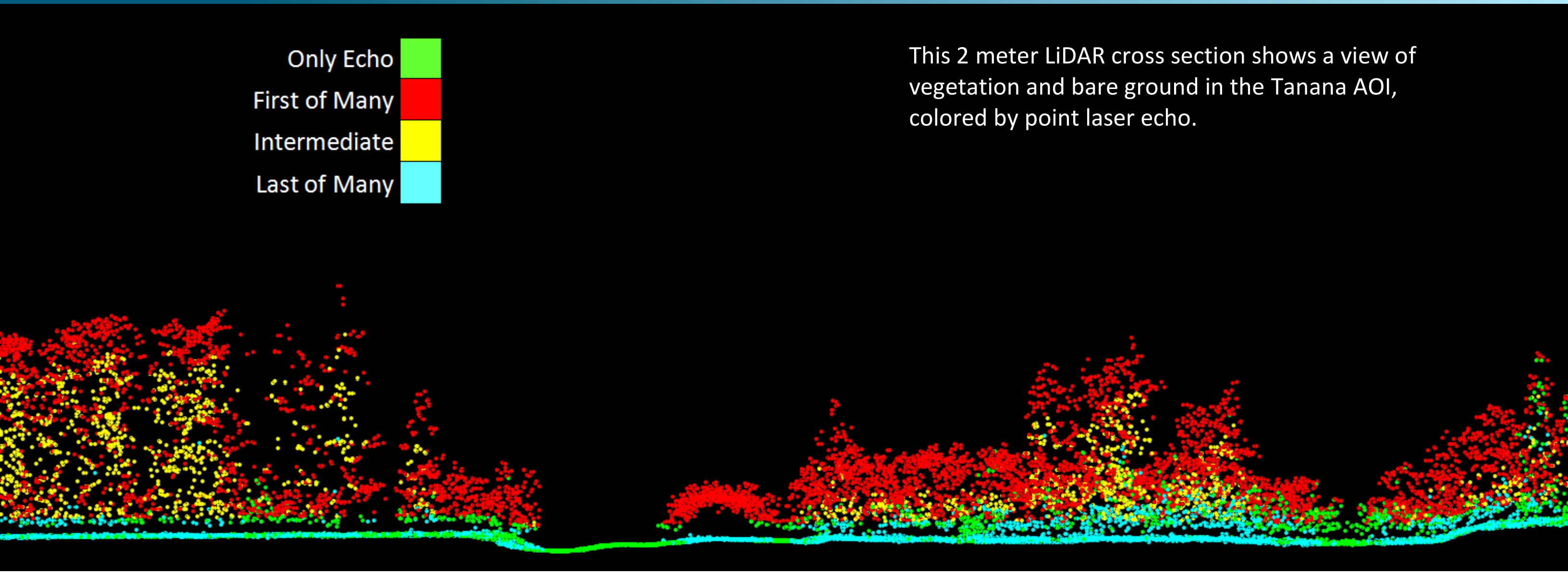


Figure 4: Example of hydro-flattening in the Tanana River Floodplain LiDAR dataset.



This 2 meter LiDAR cross section shows a view of vegetation and bare ground in the Tanana AOI, colored by point laser echo.

LiDAR Density

The acquisition parameters were designed to acquire an average first-return density of 2 points/m^2 (0.18 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 Tanana River Floodplain project was 0.80 points/ft^2 while the average ground classified density was 0.25 points/ft^2 (Table 6). 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 5 through figure 8.

Table 6: Average LiDAR point densities

Classification	Point Density
First-Return	0.80 points/ft^2 8.61 points/m^2
Ground Classified	0.25 points/ft^2 2.72 points/m^2

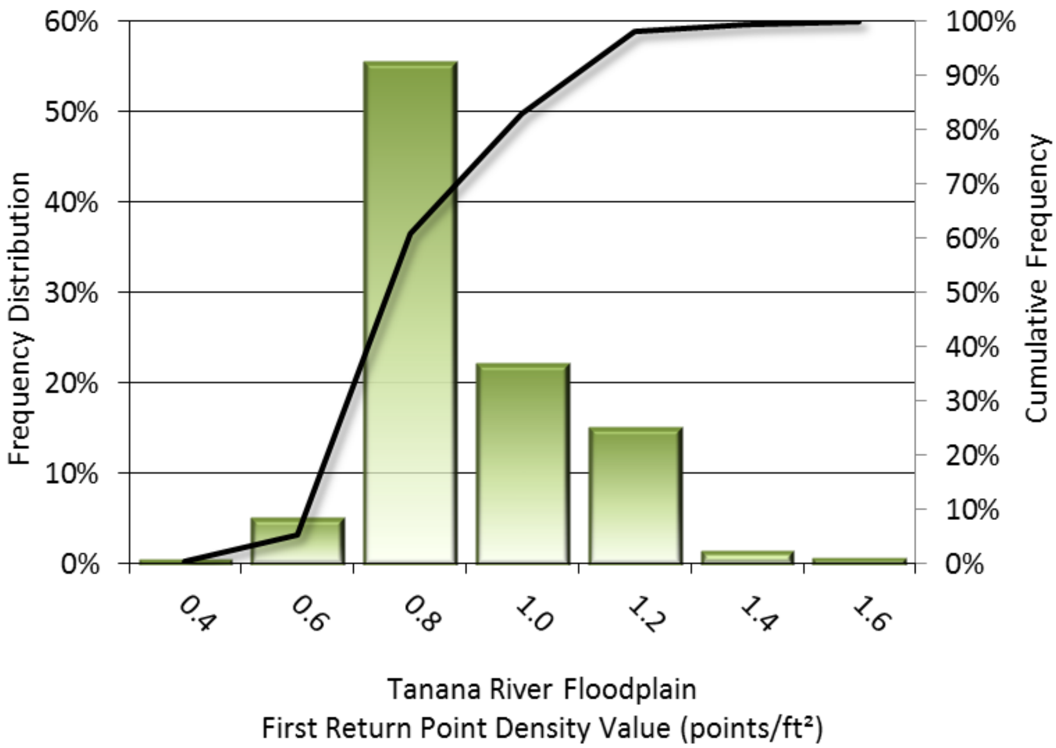


Figure 5: Frequency distribution of first return point density values per 100 x 100 m cell

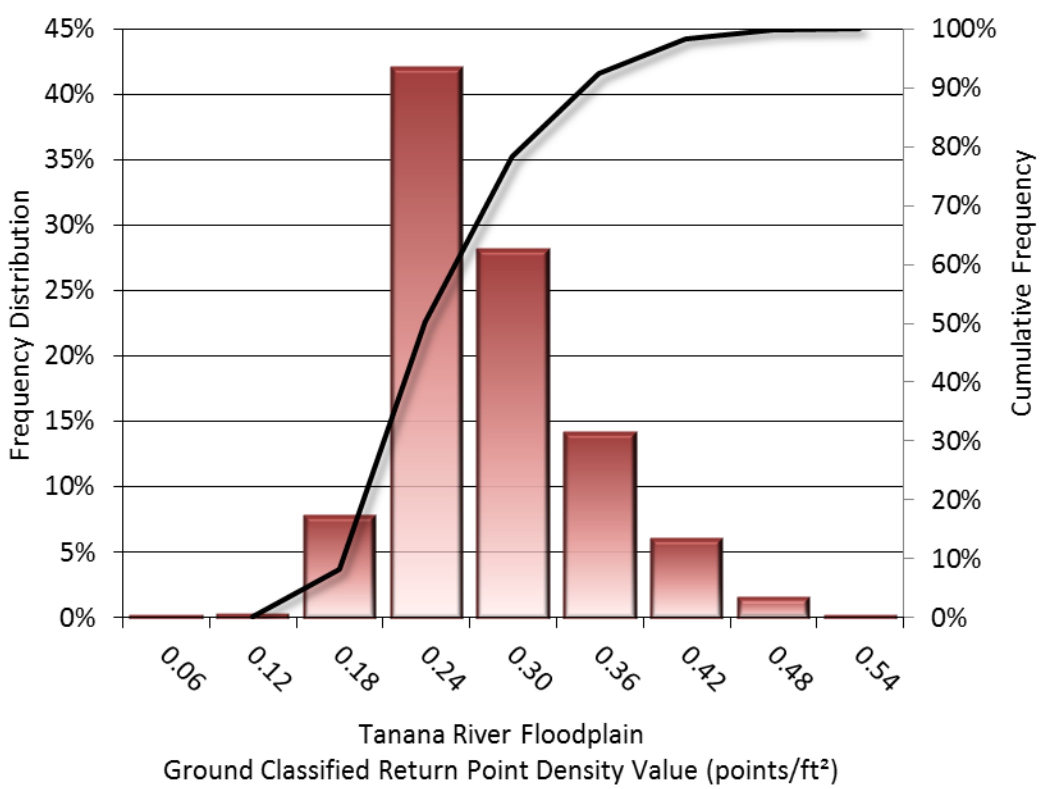


Figure 6: Frequency distribution of ground-classified return point density values per 100 x 100 m cell

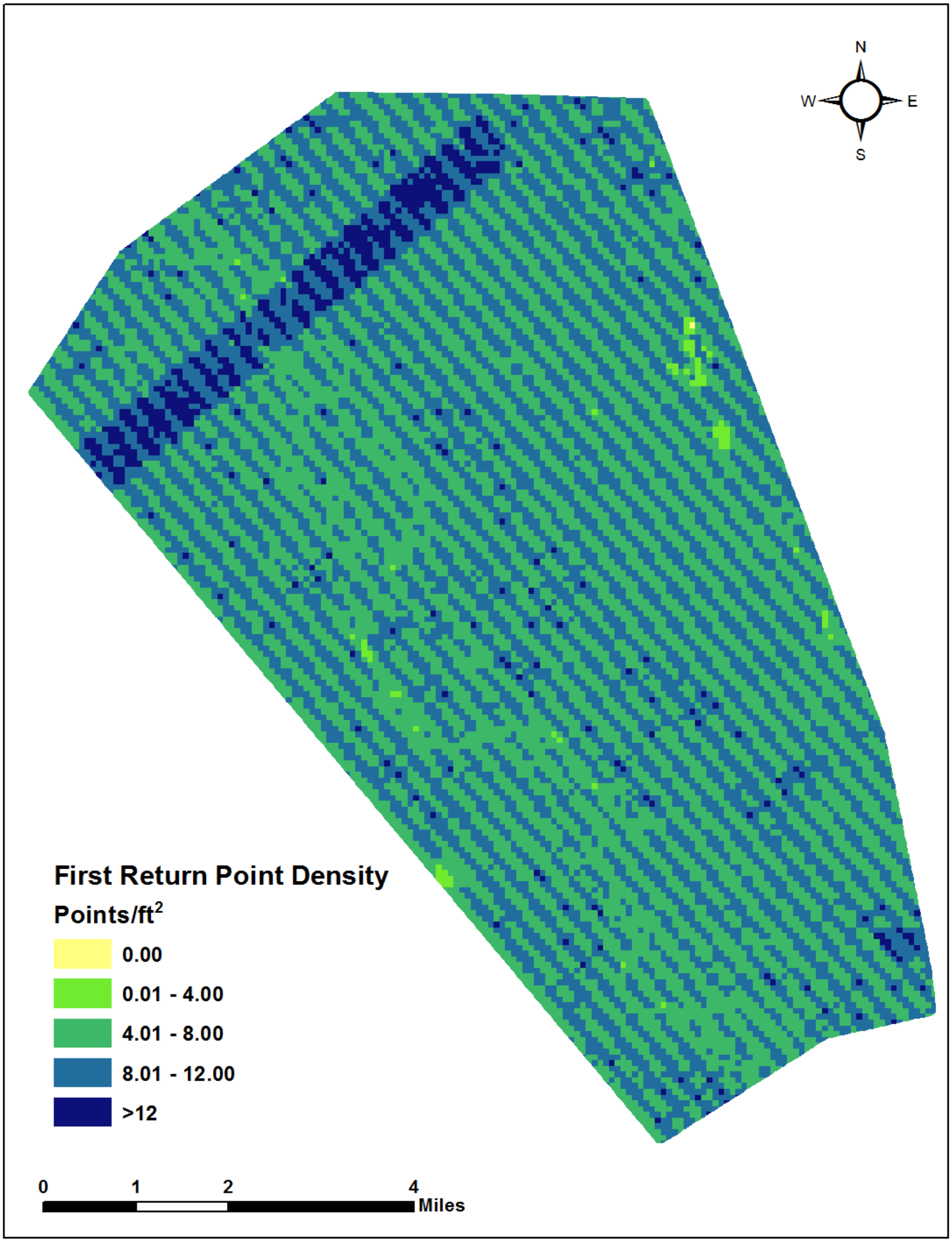


Figure 7: First return point density map for the Tanana River Floodplain site (100 m x 100 m cells)

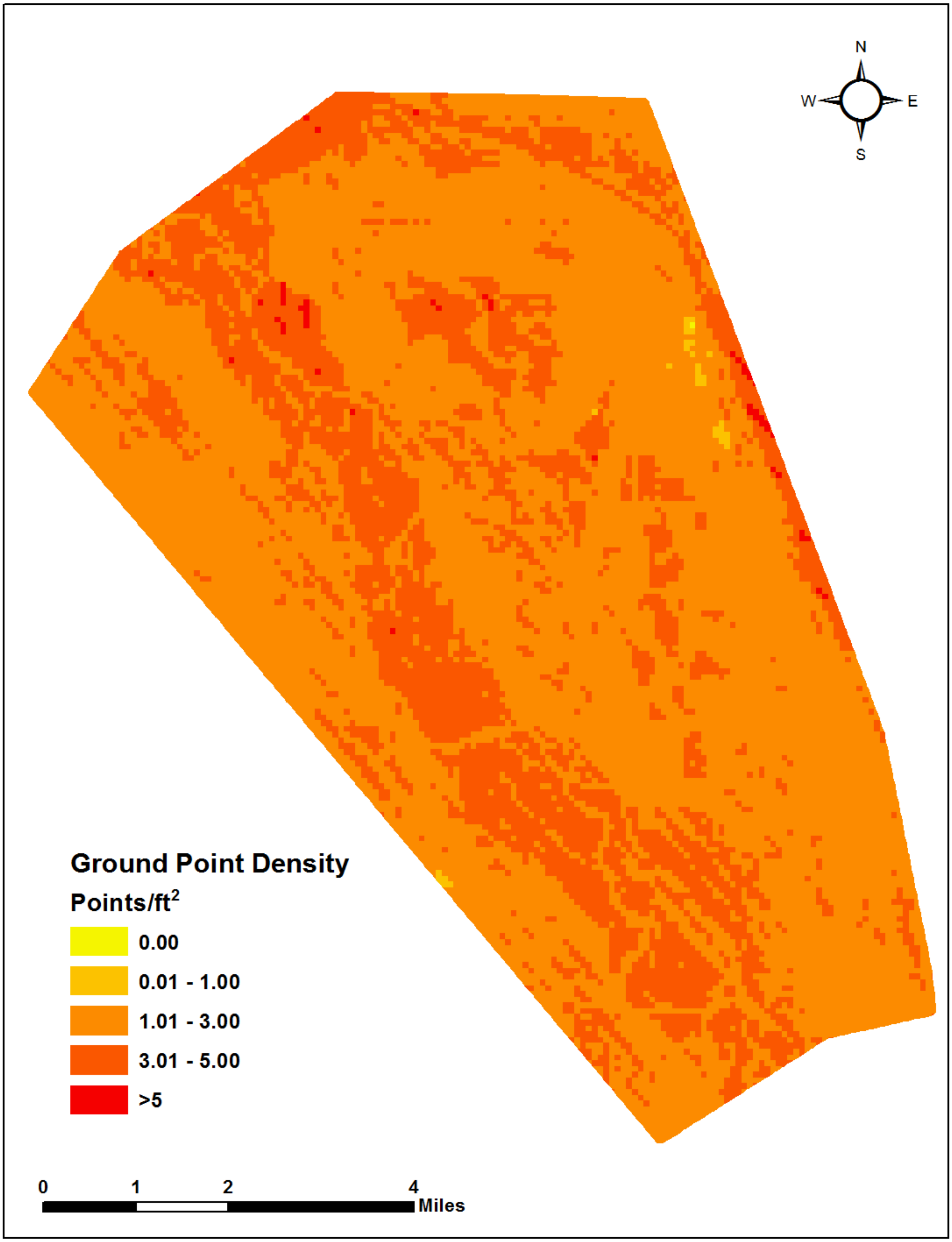


Figure 8: Ground point density map for the Tanana River Floodplain site (100 m x 100 m cells)

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 Absolute 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 quality assurance point data collected on open, bare earth surfaces with level slope (<20°) to the triangulated surface generated by the LiDAR points. 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 7.

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 Tanana River Floodplain survey, 61 quality assurance points were withheld in total resulting in a non-vegetated vertical accuracy of 0.295 feet (0.090 meters) (Figure 9).

QSI also assessed absolute accuracy using 331 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 Figure 10.

Table 7: Absolute accuracy results

Absolute Accuracy		
	Quality Assurance Points (NVA)	**Ground Control Points**
Sample	61 points	331 points
NVA (1.96*RMSE)	0.295 ft 0.090 m	0.184 ft 0.056 m
Average	-0.016 ft -0.005 m	-0.033 ft -0.010 m
Median	0.000 ft 0.000 m	-0.033 ft -0.10 m
RMSE	0.151 ft 0.046 m	0.094 ft 0.029 m
Standard Deviation (1σ)	0.151 ft 0.046 m	0.088 ft 0.027 m

[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.

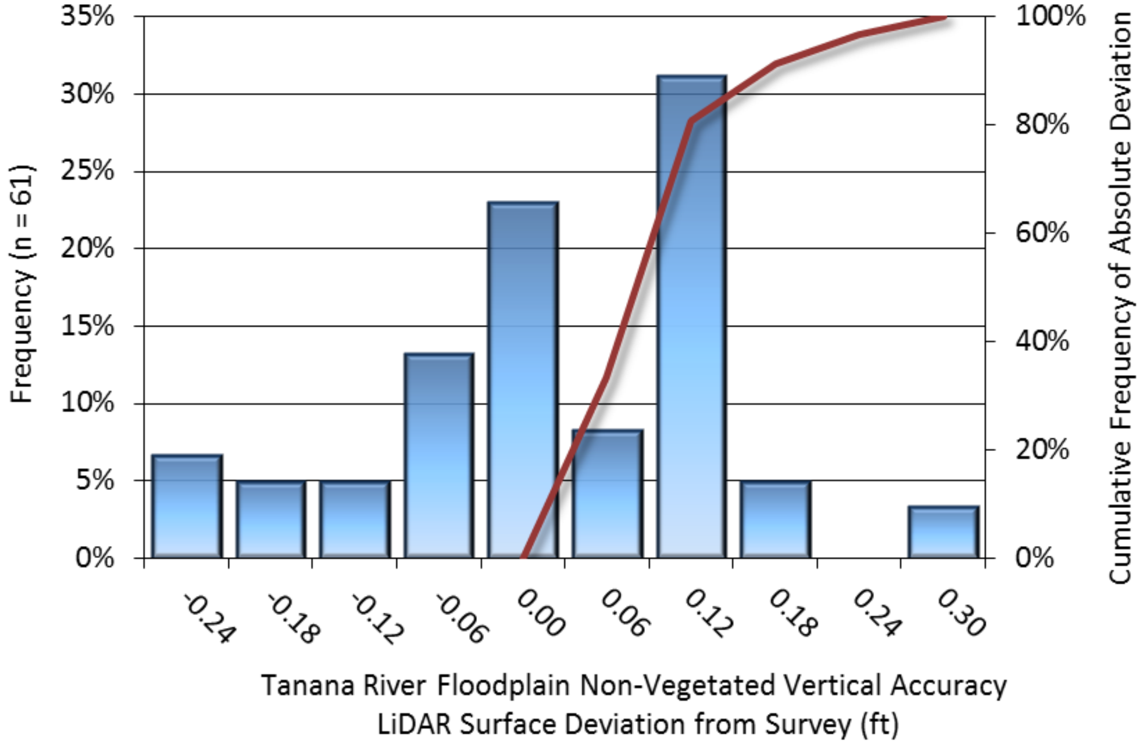


Figure 9: Frequency histogram for LiDAR surface deviation from quality assurance point values

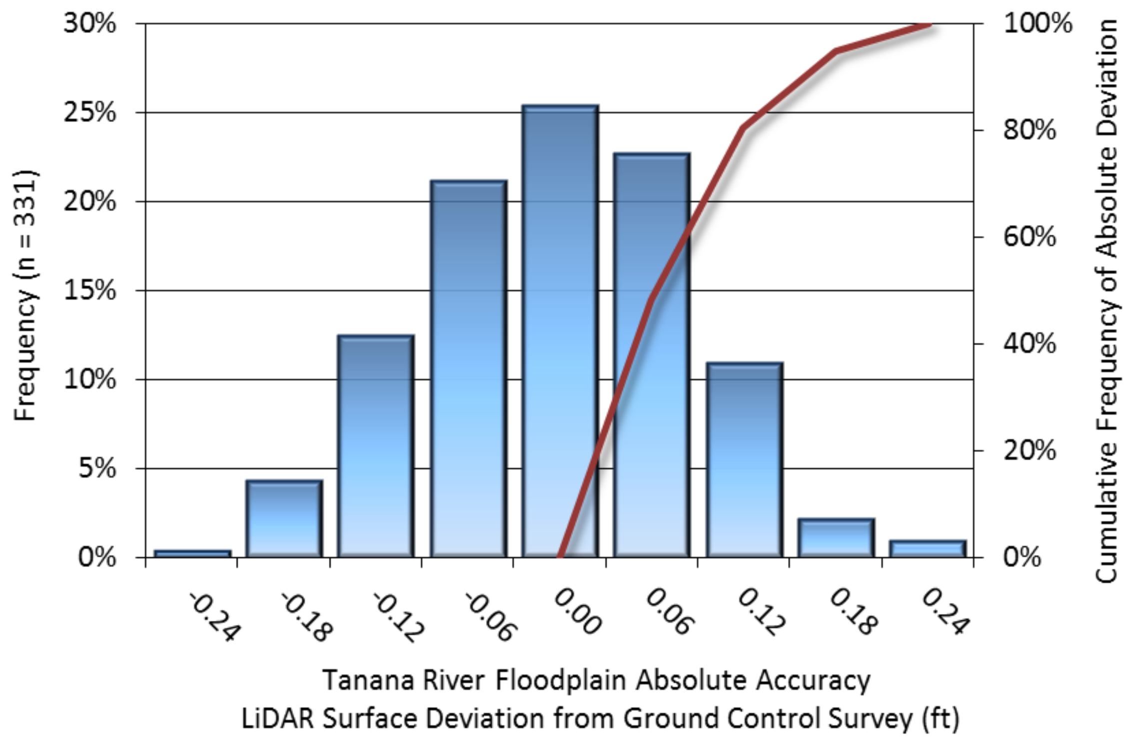


Figure 10: Frequency histogram for LiDAR surface deviation from ground control point values

LiDAR Vegetated Vertical Accuracies

QSI also assessed vertical accuracy using Vegetated Vertical Accuracy (VVA) reporting. VVA compares known ground quality assurance point data collected over vegetated surfaces using land class descriptions to the triangulated ground surface generated by the ground classified LiDAR points. VVA is evaluated at the 95th percentile (Table 8, Figure 11.)

Table 8: Vegetated Vertical Accuracy for the Tanana River Floodplain Project

Vegetated Vertical Accuracy (VVA)	
Sample	37 points
Average Dz	0.159 ft 0.048 m
Median	0.164 ft 0.050 m
RMSE	0.229 ft 0.070 m
Standard Deviation (1σ)	0.167 ft 0.051 m
95th Percentile	0.492 ft 0.150 m

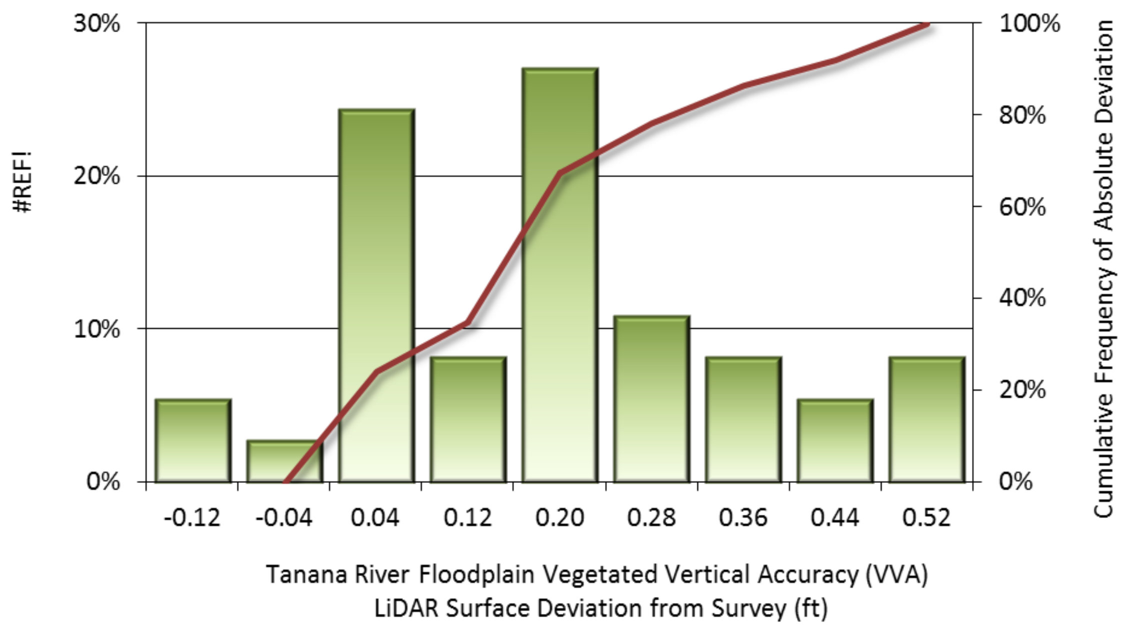


Figure 11: Frequency histogram for LiDAR surface deviation from all land cover class point values (VVA)

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 Tanana River Floodplain LiDAR project was 0.049 feet (0.015 meters) (Table 9, Figure 12).

Table 9: Relative accuracy results

Relative Accuracy	
Sample	33 surfaces
Average	0.049 ft 0.015 m
Median	0.049 ft 0.015 m
RMSE	0.049 ft 0.015 m
Standard Deviation (1σ)	0.004 ft 0.001 m
1.96σ	0.008 ft 0.002 m

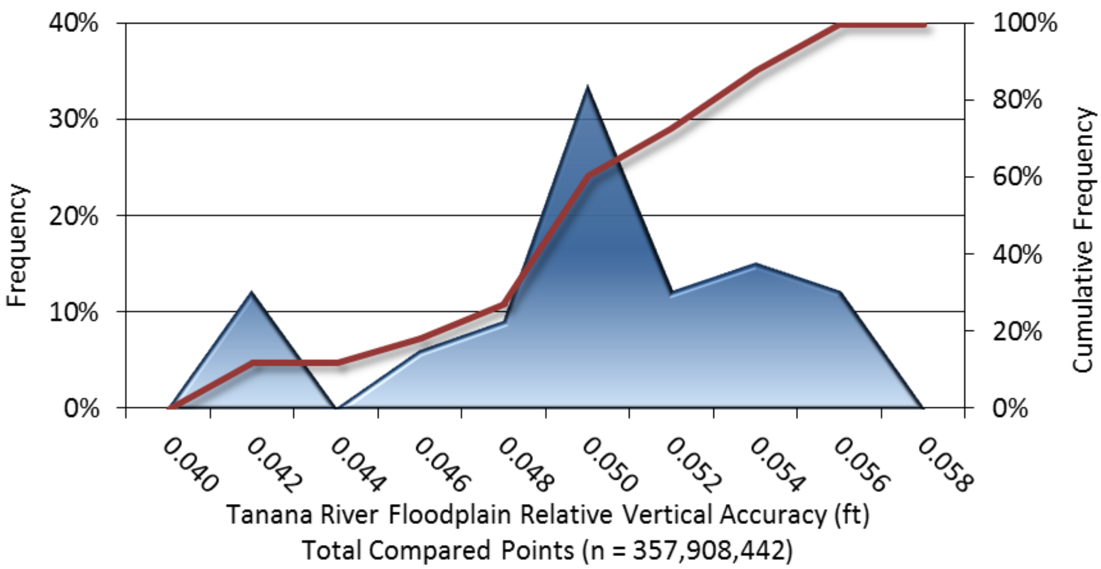


Figure 12: Frequency plot for relative vertical accuracy between flight lines

Figure 13: View looking east over Tanana River Floodplain. The image was created from the LiDAR bare earth model overlaid with the above-ground point cloud.

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 Fundamental Vertical Accuracy (FVA) 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., echos) reflected back to the sensor. Portions of the wave form that return first are the highest element in multi-tiered surfaces such as vegetation. Portions of the wave form that return last are the lowest element in multi-tiered surfaces.

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 $\pm 16^{o}$ 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.

Horizontal Control - NAD83(2007.00) Alaska State Plane Coordinates, Zone 3, USFeet

Coordinates are NAD83(2007.00) Alaska State Plane Coordinates, Zone 3, in US Feet. The Basis of Coordinates is the NAD83(2007.00) ASPC Zone 3 position of NGS Primary Airport Control Station "FAI A", PID DF3640 as retrieved from the NGS database on July 1, 2008, a 3-1/4" brass cap pipe monument, having coordinates of N=3956198.10967, E=1351803.19115 US Feet. Other horizontal positions shown hereon were determined by differential static GPS observations using Leica dual frequency receivers during the period of July 2008 and May 2010.

Scale Factor

The Project Combined Scale Factor is 0.99991512162. To convert ground distances to Alaska State Plane Zone 3 (ASPCZ3) grid distances, multiply by a combined scale factor of 0.99991512162. To convert ASPZ3 grid distances to ground distances, multiply by a combined scale factor of 100000000000/99991512162.

Vertical Control - NAVD88, US Feet

Elevations are NAVD88 in US Feet. The Basis of Elevations are USC&GS Bench Mark "G 121", PID TT2770, a 3-3/4" brass cap on stainless steel rod monument, having a value of 499.66 US Feet and USEO Bench Mark "DIKE 23 USE", PID TT2766, a brass cap having a value of 490.90 US Feet; as retreived from the NGS database on July 1, 2008. Other elevations are derived from differential leveling using a Leica DNA10 digital level with fiberglass barcode rod (Lev.), or differential static GPS observations using Leica dual frequency GPS receivers (GPS), or real time kinematic GPS positioning using the same receivers (RTK), as noted, during the period of July 27 through August 15, 2008, and during the period of April 19 through May 22, 2010. Elevations derived from differential static GPS observations or RTK GPS positioning were computed using GEOID06 orthometric heights.

Point No.	Northing	Easting	Elevation	Description
1	3933338.50	1449701.88	519.03	BCMON.BUNKER
708	3920927.56	1441394.27	525.87	ALMON.PC STA 112+13.17
734	3908409.98	1464435.64	533.45	ALMON.GATE