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Nenana-Totchaket Aerial Survey & Mapping

Technical Data Report

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INTRODUCTION

This photo taken by Quantum Spatial acquisition staff shows a view of the Nenana-Totchaket project area

In June 2020, Quantum Spatial was contracted by Alaska Department of Natural Resources (AKDNR) to collect Light Detection and Ranging (lidar) data and digital imagery in the fall of 2020 for the Nenana-Totchaket site in Alaska. Data were collected to aid AKDNR in outlining agricultural, commercial and residential parcels.

This report accompanies the delivered lidar data and imagery, 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 AKDNR 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 Nenana-Totchaket site

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
Nenana-Totchaket	155,647	160,089	07/11/2020-07/31/2020	Lidar
			08/13/2020-08/14/2020	4 band (RGB-NIR) Digital Imagery

Deliverable Products

Table 2: Products delivered to AKDNR for the Nenana-Totchaket site

Nenana-Totchaket Products		
Projection:	**UTM Zone 6 North**	**Alaska State Plane FIPS 5004**
Horizontal Datum:	**NAD83 (2011)**	**NAD83 (2011)**
Vertical Datum:	**NAVD88 (GEOID12B)**	**NAVD88 (GEOID12B)**
Units:	**Meters**	**US Survey Feet**
Points	LAS v 1.4 • All Classified Returns	LAS v 1.4 • All Classified Returns
Rasters	1.0 Meter GeoTiffs • Hydroflattened Bare Earth Model (DEM) • Highest Hit Digital Surface Model (DSM) • > 3.0 m Canopy Height Model 0.5 Meter GeoTiffs • Intensity Images	3.0 Foot GeoTiffs • Hydroflattened Bare Earth Model (DEM) • Highest Hit Digital Surface Model (DSM) • > 9.0 ft Canopy Height Model 1.5 Foot GeoTiffs • Intensity Images
Vectors	Shapefiles (*.shp) • Area of Interest** • Lidar Tile Index** • Water's Edge Breaklines** • Ground Survey Shapes** AutoDesk Civil 3D • Bare Earth Surface Model (DTM) AutoCAD Drawing Files • Contours (0.5m) • Planimetric Data	Shapefiles (*.shp) • Area of Interest** • Lidar Tile Index** • Water's Edge Breaklines** • Ground Survey Shapes** AutoDesk Civil 3D • Bare Earth Surface Model (DTM) AutoCAD Drawing Files • Contours (2ft) • Planimetric Data
Digital Imagery	30-cm GeoTiff • Tiled Imagery (RGB, NIR) 30-cm GeoTiff • Tiled NDVI Imagery (RGB)	1-ft GeoTiff • Tiled Imagery (RGB, NIR) 1-ft GeoTiff • Tiled NDVI Imagery (RGB)

***Quantum Spatial delivered these lidar-derived products in addition to contracted deliverables in order to provide a more complete and versatile dataset to AKDNR.*

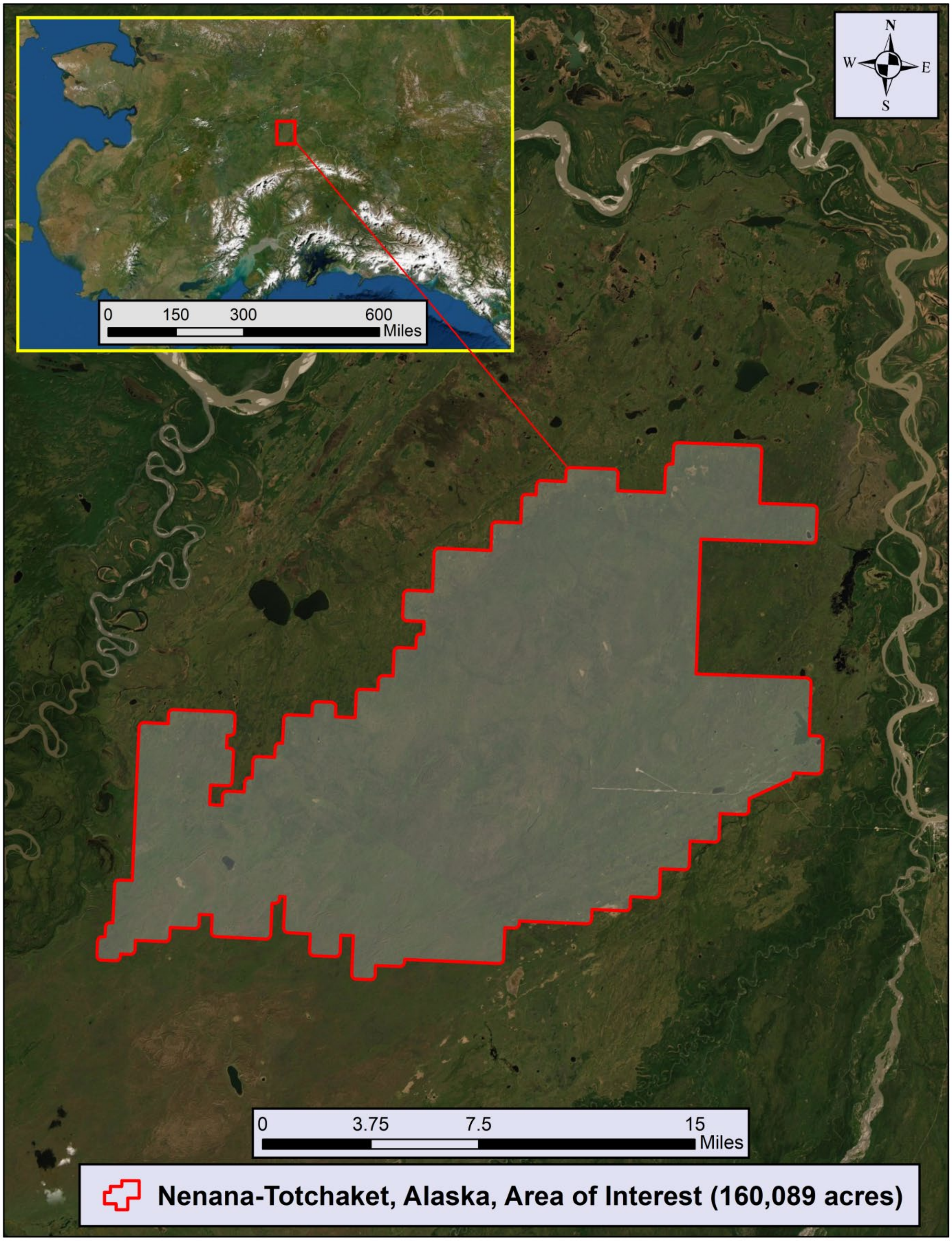


Figure 1: Location map of the Nenana-Totchaket site in Alaska

ACQUISITION

Quantum Spatial's ground acquisition equipment set up in the Nenana-Totchaket Lidar study area.

Planning

In preparation for data collection, Quantum Spatial reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Nenana-Totchaket Lidar study area at the target point density of ≥8.0 points/m^2 (0.74 points/ft^2) for lidar collection and 1-ft resolution for imagery. Acquisition parameters including orientation relative to terrain, flight altitude, pulse rate, scan angle, and ground speed were adapted to optimize flight paths and flight times while meeting all contract specifications.

Factors such as satellite constellation availability and weather windows must be considered during the planning stage. Any weather hazards or conditions affecting the flight were continuously monitored due to their potential impact on the daily success of airborne and ground operations. In addition, logistical considerations including private property access and potential air space restrictions were reviewed.

Airborne Survey

Lidar

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 Nenana-Totchaket project area. The Leica ALS80 laser system can record unlimited range measurements (returns) per pulse, however only 15 returns can be stored due to LAS 1.4 file limitations. 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	July 11 - 31, 2020
Aircraft Used	Cessna Caravan
Sensor	Leica
Laser	ALS80
Maximum Returns	15
Resolution/Density	Average 8 pulses/m^2
Nominal Pulse Spacing	0.353 m
Survey Altitude (AGL)	1900 m
Survey speed	140 knots
Field of View	40º
Mirror Scan Rate	52 Hz
Target Pulse Rate	579 kHz
Pulse Length	2.5 ns
Laser Pulse Footprint Diameter	32 cm
Central Wavelength	1064 nm
Pulse Mode	Multiple Pulses in Air (MPiA)
Beam Divergence	0.22 mrad
Swath Width	1383 m
Swath Overlap	60 %
Intensity	8-bit scaled to 16-bit
Horizontal Accuracy	$RMSE_Z$ (Non-Vegetated) ≤ 30 cm
Vertical Accuracy	$RMSE_Z$ (Non-Vegetated) ≤ 10 cm
Relative Accuracy	$RMSE_Z$ (Non-Vegetated) ≤ 6 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.

Photo taken within the Nenana-Totchaket project boundary.

Digital Imagery

Aerial imagery was collected using an UltraCam Eagle 260 megapixel digital camera (Table 4) mounted in a Piper Navajo. The UltraCam Eagle is a large format digital aerial camera manufactured by Microsoft Corporation. The system is gyro-stabilized and simultaneously collects panchromatic and multispectral (RGB, NIR) imagery. Panchromatic lenses collect high resolution imagery by illuminating nine charge coupled device (CCD) arrays, writing nine raw image files. RGB and NIR lenses collect lower resolution imagery, written as four individual raw image files. Level 2 images are created by stitching together raw image data from the nine panchromatic CCDs and are ultimately combined with the multispectral image data to yield Level 3 pan-sharpened TIFFs.

Table 4: Camera manufacturer's specifications

UltraCam Eagle	
Focal Length	80 mm
Data Format	RGB NIR
Pixel Size	5.2 µm
Image Size	20,010 x 13,080 pixels
Frame Rate	1.8 seconds
FOV	66° x 46°

For the Nenana-Totchaket site, images were collected in four spectral bands (red, green, blue, and NIR) with 60% along track overlap and 30% sidelap between frames. The acquisition flight parameters were designed to yield a native pixel resolution of ≤ 30-cm. Orthoimagery specifications particular to the Nenana-Totchaket project are in Table 5.

Table 5: Project-specific orthoimagery specifications

Digital Orthoimagery Specifications	
Equipment	UltraCam Eagle
Spectral Bands	Red, Green, Blue, NIR
Resolution	1-ft pixel size (30-cm)
Along Track Overlap	≥60%
Flight Altitude (MSL)	2,200 meters
GPS Baselines	≤25 nm
GPS PDOP	≤3.0
GPS Satellite Constellation	≥6
Horizontal Accuracy	0.06 m
Image	8-bit GeoTiff

Ground Survey

Ground control surveys, including monumentation, aerial targets 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 and orthoimagery products.

Base Stations

Base stations were utilized for collection of ground survey points using real time kinematic (RTK), and fast-static (FS) survey technique.

Monument locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage. Quantum Spatial utilized one existing monument for the Nenana-Totchaket lidar project (Table 6, Figure 2). Quantum Spatial's professional land surveyor, Evon Silvia (AKPLS#119313) oversaw and certified the occupation of all monuments.

Table 6: Monument positions for the Nenana-Totchaket acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Monument ID	Latitude	Longitude	Ellipsoid (meters)
NENANA_01	64° 35' 07.07405"	-149° 18' 49.45633"	138.127

Quantum Spatial utilized static Global Navigation Satellite System (GNSS) data collected at 1 Hz recording frequency for each base station. During post-processing, the static GNSS data were triangulated with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS[1]) for precise positioning. Multiple independent sessions over the same monument were processed to confirm antenna height measurements and to refine position accuracy.

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.[2] 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 7.

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

[2] Federal Geographic Data Committee, Geospatial Positioning Accuracy Standards (FGDC-STD-007.2-1998). Part 2: Standards for Geodetic Networks, Table 2.1, page 2-3. http://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part2/chapter2

Table 7: 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 Nenana-Totchaket 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 using real time kinematic (RTK) and fast-static (FS) survey techniques. For RTK surveys, a roving receiver receives corrections from a nearby base station or Real-Time Network (RTN) via radio or cellular network, enabling rapid collection of points with relative errors less than 1.5 cm horizontal and 2.0 cm vertical. FS surveys compute these corrections during post-processing to achieve comparable accuracy. RTK surveys record data while stationary for at least five seconds, calculating the position using at least three one-second epochs. FS surveys record observations for up to fifteen minutes on each GSP in order to support longer baselines. All GSP measurements were made during periods with a Position Dilution of Precision (PDOP) of ≤ 3.0 with at least six satellites in view of the stationary and roving receivers. See Table 8 for Trimble unit specifications.

GSPs were collected in areas where good satellite visibility was achieved on paved roads and other hard surfaces such as gravel or packed dirt roads. GSP measurements were not taken on highly reflective surfaces such as center line stripes or lane markings on roads due to the increased noise seen in the laser returns over these surfaces. GSPs were collected within as many flightlines as possible; however, the distribution of GSPs depended on ground access constraints and monument locations and may not be equitably distributed throughout the study area (Figure 2).

Table 8: Quantum Spatial ground survey equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R10	Integrated Antenna	TRMR10	Static, Rover

Aerial Targets

Aerial targets were placed throughout the project area prior to imagery acquisition in order to geo-spatially correct the orthoimagery. Located within RTK range of the ground survey monuments, the targets were secured with surveyor's nails and routinely checked for disturbance (Figure 2).

The air targets used for the Nenana-Totchaket project were white vinyl squares. In addition, existing permanent photo-identifiable features painted on asphalt were also utilized as air targets, such as handicap parking signs, stop bars, drainage pipes and turn lane arrows.

Land Cover Class

In addition to ground survey points, land cover class check points were collected throughout the study area to evaluate vertical accuracy. Vertical accuracy statistics were calculated for all land cover types to assess confidence in the Lidar derived ground models across land cover classes (Table 9, see Lidar Accuracy Assessments, page 22).

Table 9: Land Cover Types and Descriptions

Land cover type	Land cover code	Example	Description	Accuracy Assessment Type
Bare Earth	BE		Areas of bare earth surface	NVA
Shrub	SH		Maintained or low growth herbaceous shrub	VVA
Tall Grass	TG		Herbaceous grasslands in advanced stages of growth	VVA

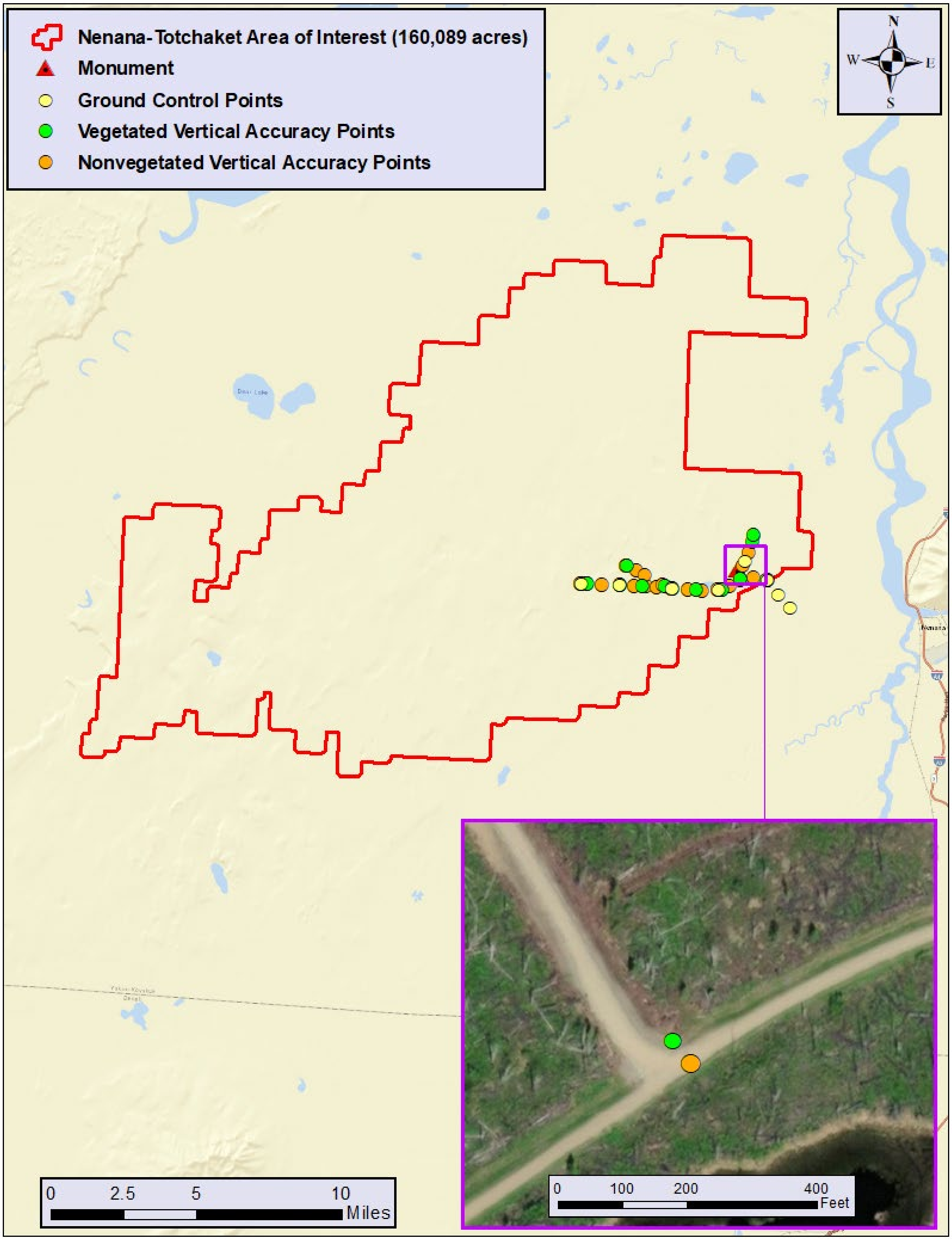
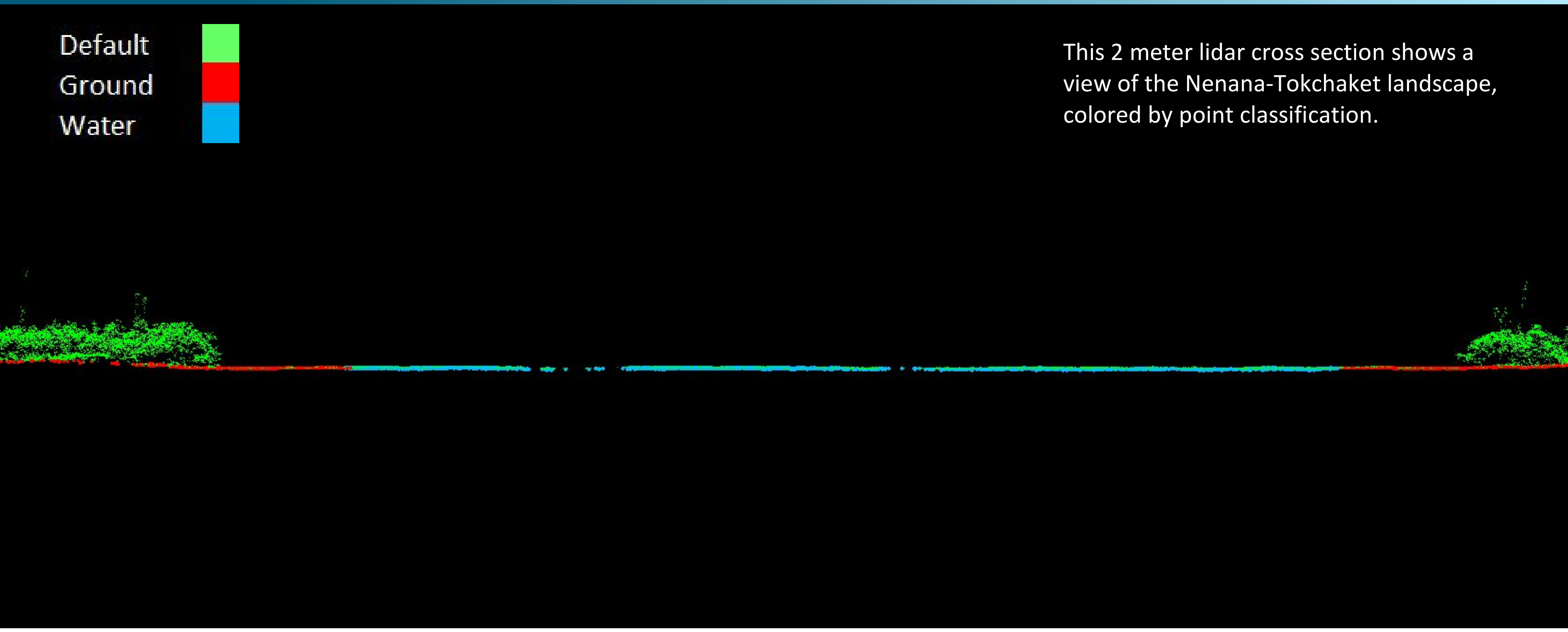


Figure 2: Ground survey location map



This 2 meter lidar cross section shows a view of the Nenana-Tokchaket landscape, colored by point classification.

Lidar Data

Upon completion of data acquisition, Quantum Spatial 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 10). Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 11.

Table 10: ASPRS LAS classification standards applied to the Nenana-Totchaket 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
9	Water	Laser returns that are determined to be water using automated and manual cleaning algorithms

Table 11: 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 TerraPOS v.2.5.0
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.20
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.20
Classify resulting data to ground and other client designated ASPRS classifications (Table 10). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.20 TerraModeler v.20
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 (1 meter) pixel resolution.	LAS Product Creator 3.4 (proprietary)
Correct intensity values for variability and export intensity images as GeoTIFFs at a 1.5 foot (0.5 meter) pixel resolution.	LAS Product Creator 3.4 (proprietary) TerraScan v.20

Feature Extraction

Hydroflattening and Water's Edge Breaklines

The Nenana-Totchaket River and other water bodies within the project area were flattened to a consistent water level. 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 non-tidal 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 manually digitized to define 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. Water surfaces were obtained from a TIN of the 3-D water edge breaklines resulting in the final hydroflattened model (Figure 3).

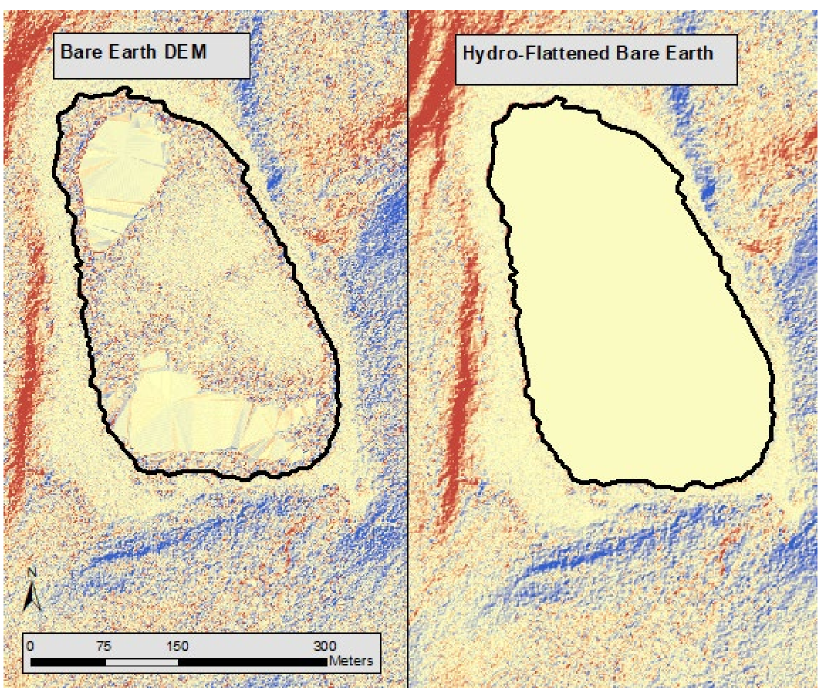


Figure 3: Example of hydroflattening in the Nenana-Totchaket lidar dataset

AutoCAD Civil 3D Surface Model and Contours

Surface model generation from Lidar ground point data required a thinning operation to reduce redundant detail in terrain representation, particularly where topographic change is minimal (i.e., flat surfaces), while preserving resolution where topographic change was present. These Model Key Points were selected from the ground points with a nominal 20 foot (6.09 meters) spacing that increased in regions with high surface curvature.

AutoCAD .DWG files contains one (1) surface each built from the Lidar LAS files. Model Key points are extracted from each LAS files in the form of an ASCII XYZ text files and are added to the surface to create a TIN. Next, 3D breaklines are added to ensure z-values along linear features and water surfaces are maintained in the surface TIN. The surface TIN is displayed using the surface style “Contour 1' and 5' (Existing)” and “Contour 0.5m and 2.5m (Existing)” for State Plane and UTM respectively.

Table 12: Surface Model processing workflow

AutoCAD C3D Processing Steps	Software Used
Model Key Points are extracted to a comma-delimited ascii X,Y,Z file from the LAS (class 8) files per sheet tile (50’ outer boundary buffer)	TerraScan v.20
The ascii XYZ points are added to the surface model, followed by breaklines. The surface is clipped to the boundary polygon	AutoCAD Civil 3d v.2018
The surface is “promoted” which embeds the point and breakline elements into an independent TIN object	AutoCAD Civil 3d v.2018

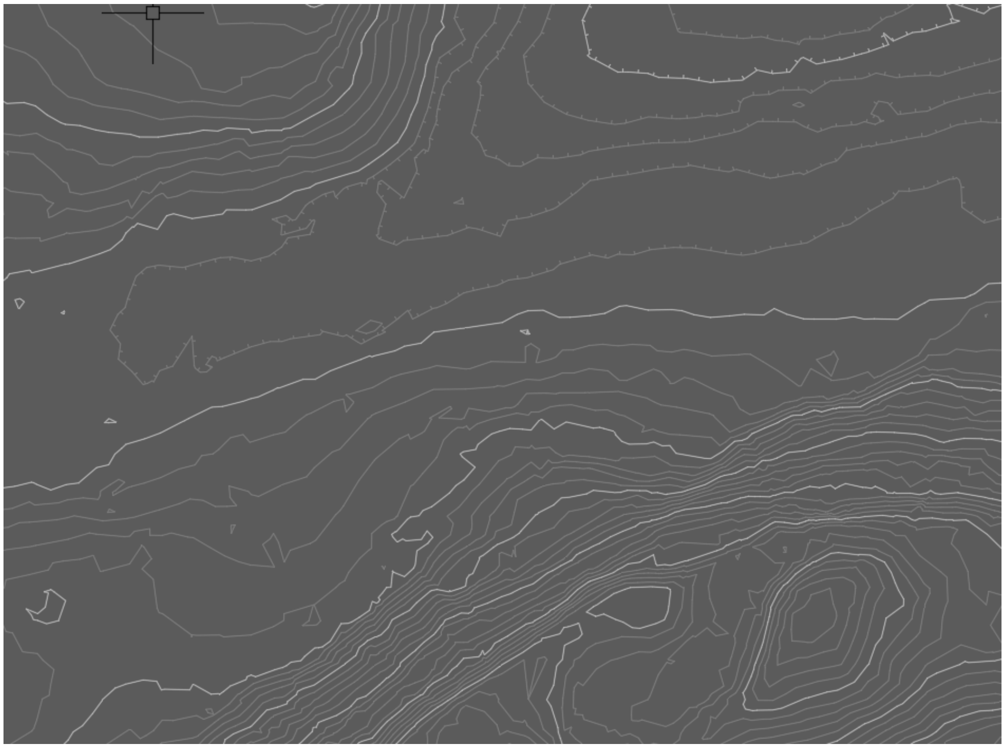


Figure 4: Contour lines of the Nenana-Totchaket LiDAR dataset

Digital Imagery

As with the NIR Lidar, the collected digital photographs went through multiple processing steps to create final orthophoto products. Initially, image radiometric values were calibrated to specific gain and exposure settings and photo position and orientation were calculated by linking the time of image capture to the smoothed best estimate of trajectory (SBET). Within Inpho's Match-AT, the exterior orientation derived from the SBET was applied to the aerial images, photo-identifiable aerial targets were measured, and the interior orientation of the camera was defined.

Adjusted images were orthorectified using the Lidar-derived ground model to remove displacement effects from topographic relief inherent in the imagery and individual orthorectified TIFFs were blended together to remove seams. The final mosaics were corrected for any remaining radiometric differences between images using Inpho's OrthoVista and Photoshop. The processing workflow for orthoimages is summarized in Table 13.

Table 13: Orthoimagery processing workflow

Orthoimagery Processing Step	Software Used
Resolve GPS kinematic corrections for the aircraft position data using kinematic aircraft GPS (collected at 2 Hz), onboard IMU (collected at 200 Hz) and Applanix virtual SmartBase.	POSPac MMS v. 8.4
Develop a smooth best estimate trajectory (SBET) file that blends post-processed aircraft position with attitude data. Sensor heading, position, and attitude are calculated throughout the survey.	POSPac MMS v 8.4
Create an exterior orientation file (EO) for each image with omega, phi, and kappa.	POSPac MMS v. 8.4
Convert camera raw imagery data into usable image files.	PPS 6.2
Apply EO to image, measure ground control points and perform aerial triangulation.	Inpho Match-AT 10.1
Import DEM and generate individual ortho frames.	Inpho OrthoMaster 10.1
Mosaic orthorectified imagery, blending seams between individual images and correcting for radiometric differences between images.	OrthoVista v. 10.1
Review and edit in Photoshop.	Adobe Photoshop CS6
Declare GeoTiff header projection and set 'NoData' value to zero.	GDAL 2.201.1 - Geospatial Data Abstraction Library

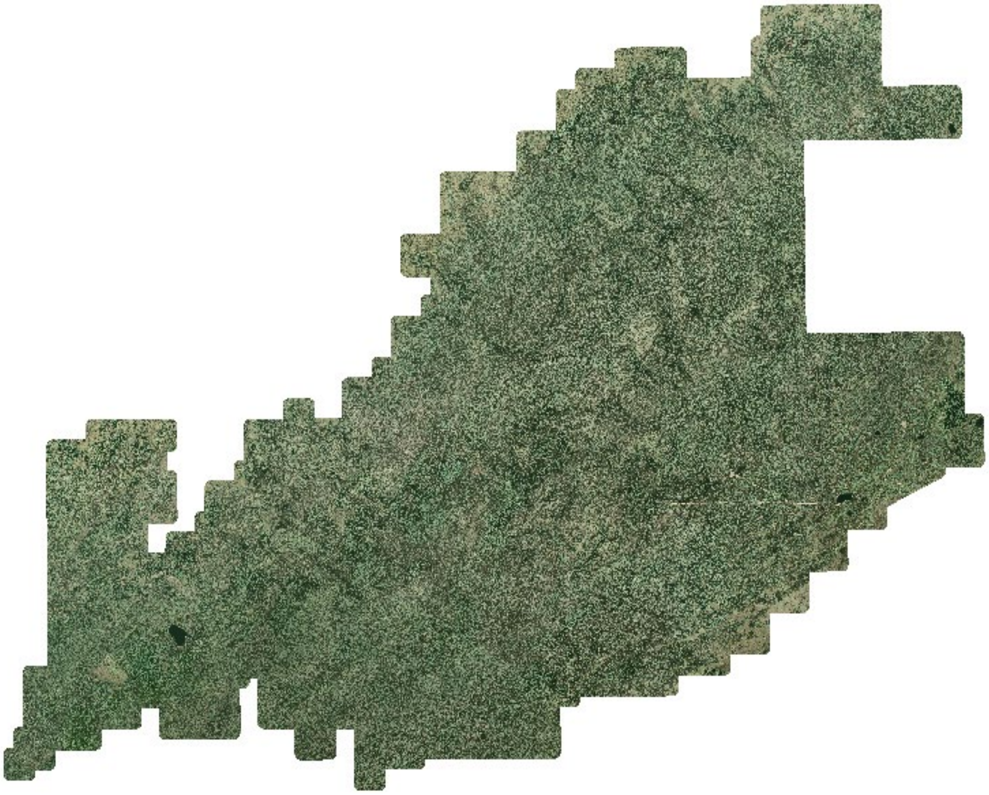


Figure 5: Natural Color composite orthoimagery of the Nenana-Totchaket dataset

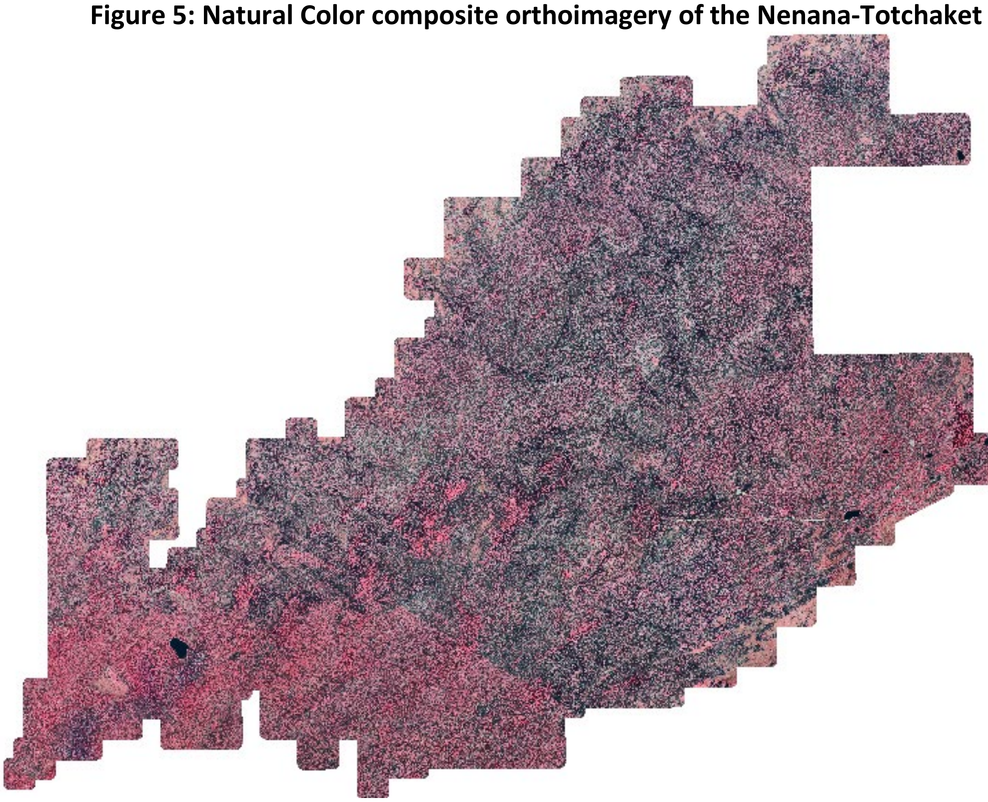


Figure 6: False-color Infrared composite orthoimagery of the Nenana-Totchaket dataset

Planimetric Feature Extraction

Technicians view each image stereo pair in 3-D with our DAT/EM Summit Evolution softcopy workstations. Using a precise 3-D cursor and stereo-mapping techniques, planimetric features are digitized directly into a vector mapping application, such as AutoCAD. As features are placed, they are superimposed on a background image screen to assure their location. Similar features are grouped into layers with attributes such as color and line styles.

Normalized Difference Vegetation Index (NDVI)

The **normalized difference vegetation index** (**NDVI**) is a simple indicator that can be used to analyze vegetation vigor. The NDVI is calculated from individual from the image pixel measurements as follows:

NVDI = (NIR – Red) / (NIR + Red)

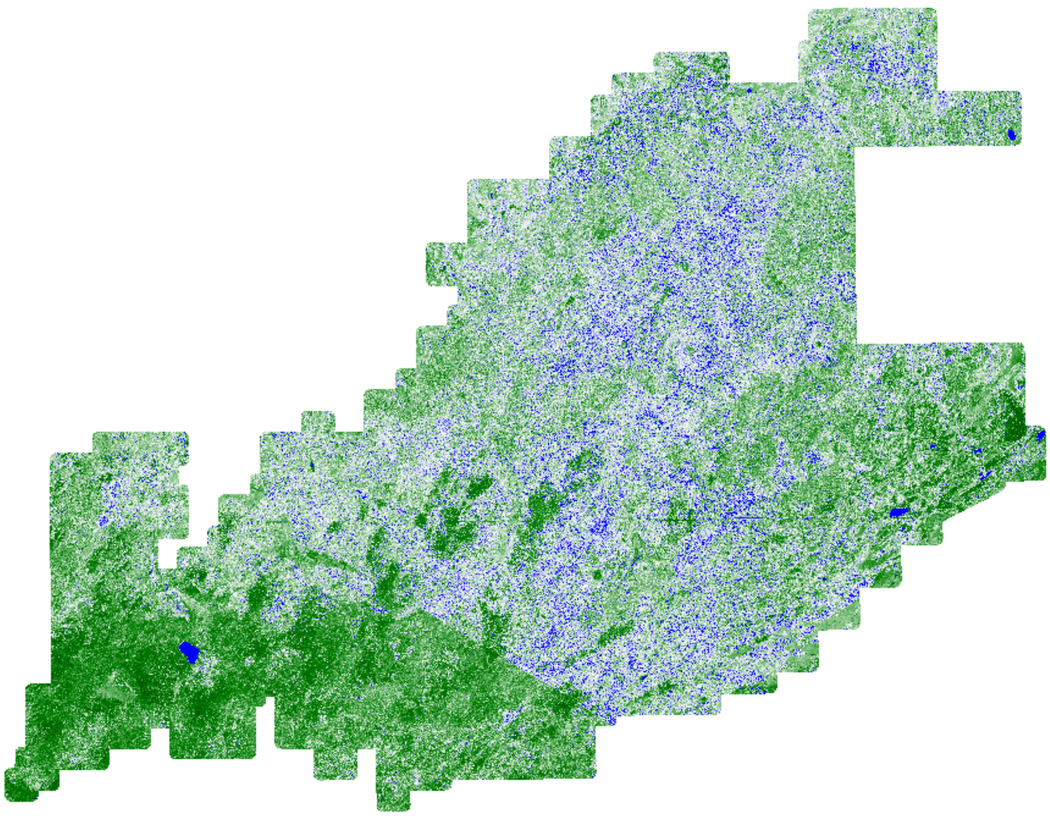
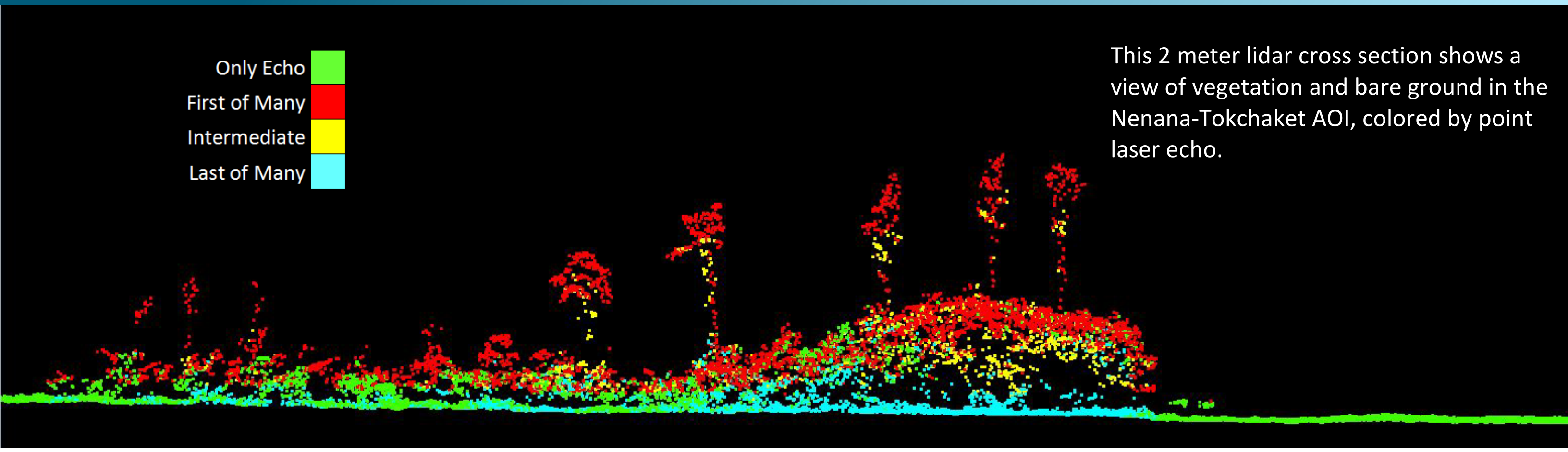


Figure 7: The normalized difference vegetation index (NDVI) for the Nenana-Totchaket lidar dataset



Lidar Density

The acquisition parameters were designed to acquire an average first-return density of 8 points/m^2 (0.74 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 Nenana-Totchaket project was 1.72 points/ft^2 (18.47 points/m^2) while the average ground classified density was 0.28 points/ft^2 (3.03 points/m^2) (Table 14). 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 8 through Figure 10.

Table 14: Average lidar point densities

Classification	Point Density
First-Return	1.72 points/ft^2 18.47 points/m^2
Ground Classified	0.28 points/ft^2 3.03 points/m^2

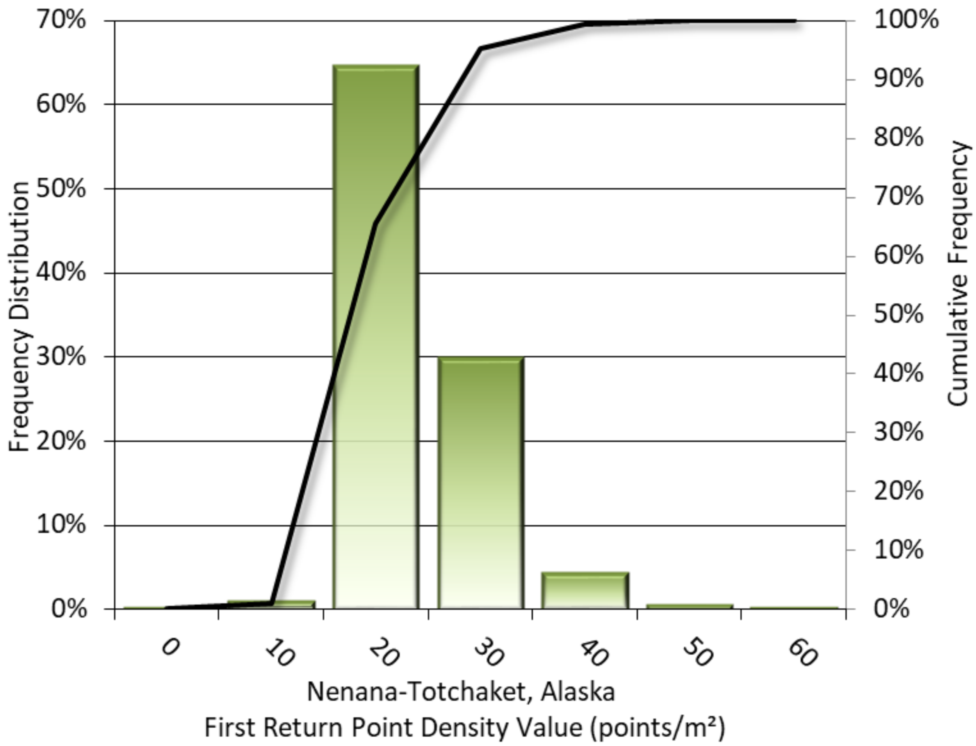


Figure 8: Frequency distribution of first return point density values per 100 x 100 m cell

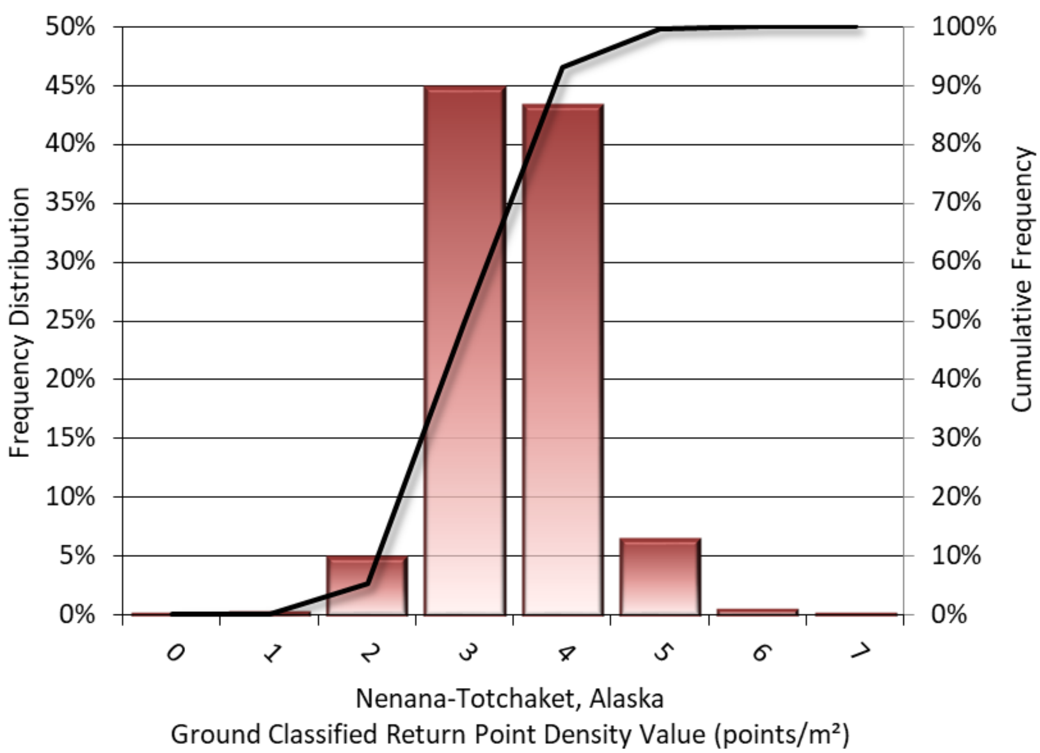


Figure 9: Frequency distribution of ground-classified return point density values per 100 x 100 m cell

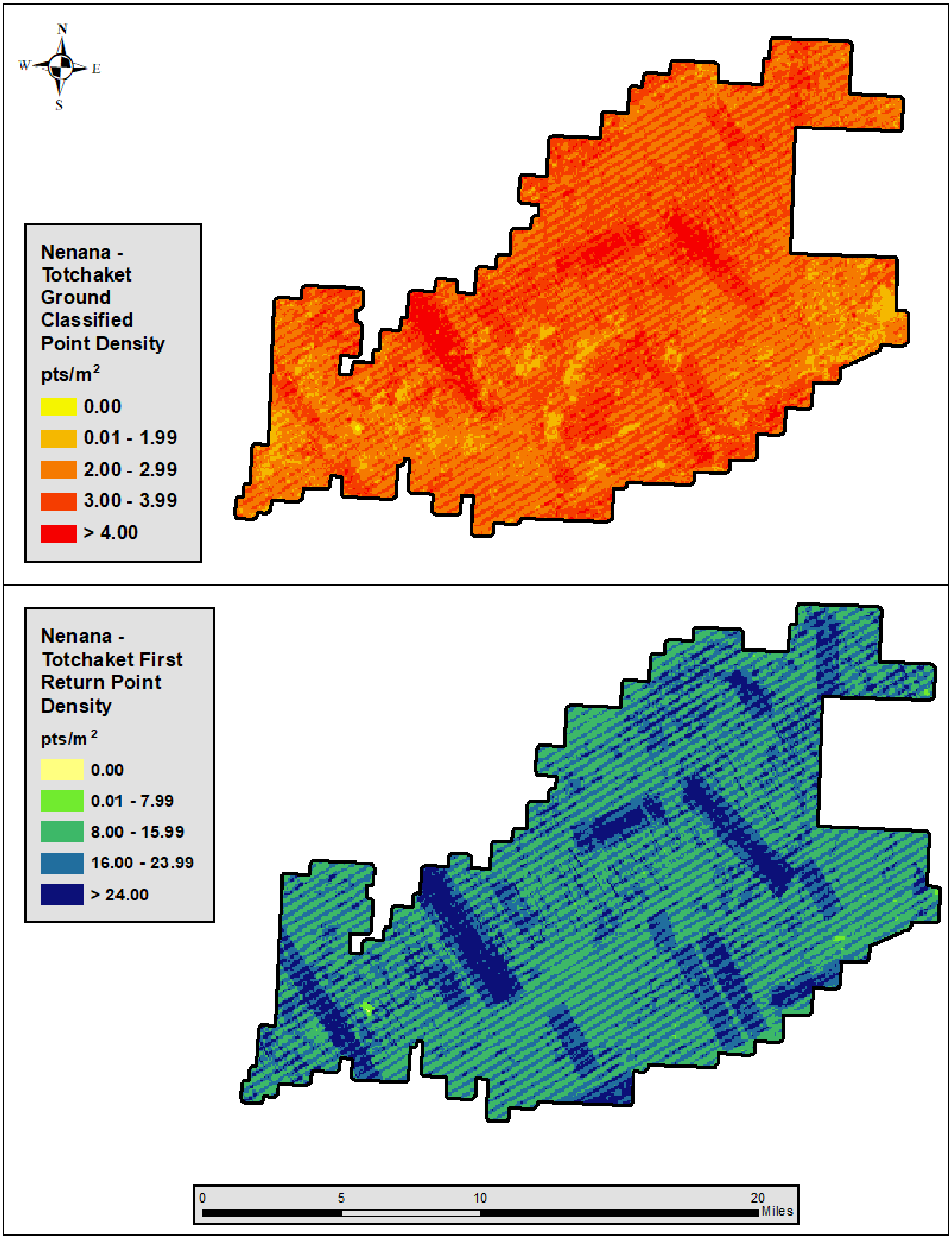


Figure 10: First return and ground-classified point density map for the Nenana-Totchaket site (100 m x 100 m cells)

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[3]. 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 15.

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 Nenana-Totchaket survey, 22 ground check points were withheld from the calibration and post processing of the lidar point cloud, with resulting non-vegetated vertical accuracy of 0.123 feet (0.038 meters) as compared to unclassified LAS, and 0.101 feet (0.031 meters) as compared to the bare earth DEM, with 95% confidence (Figure 11; Figure 12).

Quantum Spatial also assessed absolute accuracy using 8 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 15 and Figure 13.

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[3] 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 15: Absolute accuracy results

Absolute Vertical Accuracy			
	NVA, as compared to unclassified LAS	NVA, as compared to bare earth DEM	Ground Control Points
Sample	22 points	22 points	8 points
95% Confidence (1.96*RMSE)	0.123 ft 0.038 m	0.101 ft 0.031 m	0.130 ft 0.040 m
Average	0.032 ft 0.010 m	-0.016 ft -0.005 m	-0.011 ft -0.003 m
Median	0.046 ft 0.014 m	-0.015 ft -0.005 m	-0.031 ft -0.009 m
RMSE	0.063 ft 0.019 m	0.051 ft 0.016 m	0.066 ft 0.020 m
Standard Deviation (1σ)	0.055 ft 0.017 m	0.050 ft 0.015 m	0.070 ft 0.021 m

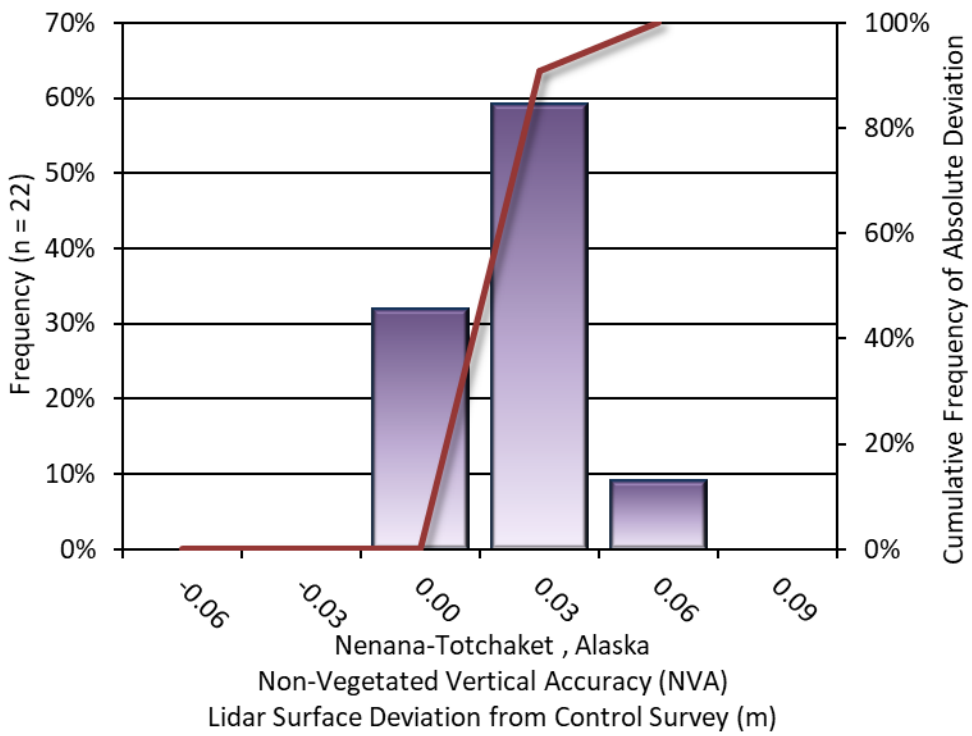

Figure 11: Frequency histogram for lidar unclassified LAS deviation from ground check point values (NVA)

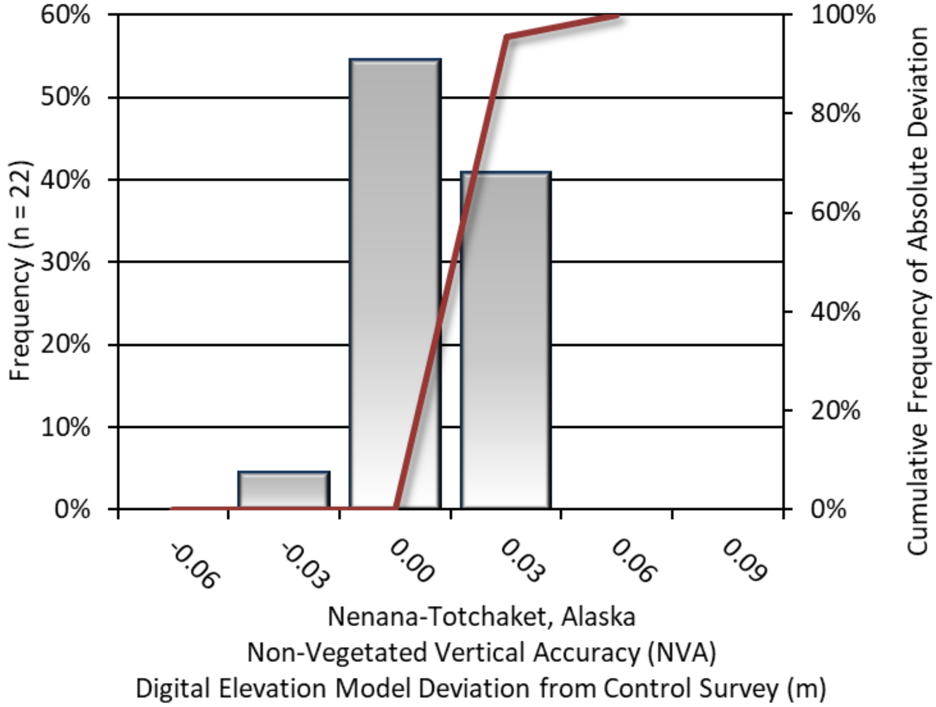

Figure 12: Frequency histogram for lidar bare earth DEM surface deviation from ground check point values (NVA)

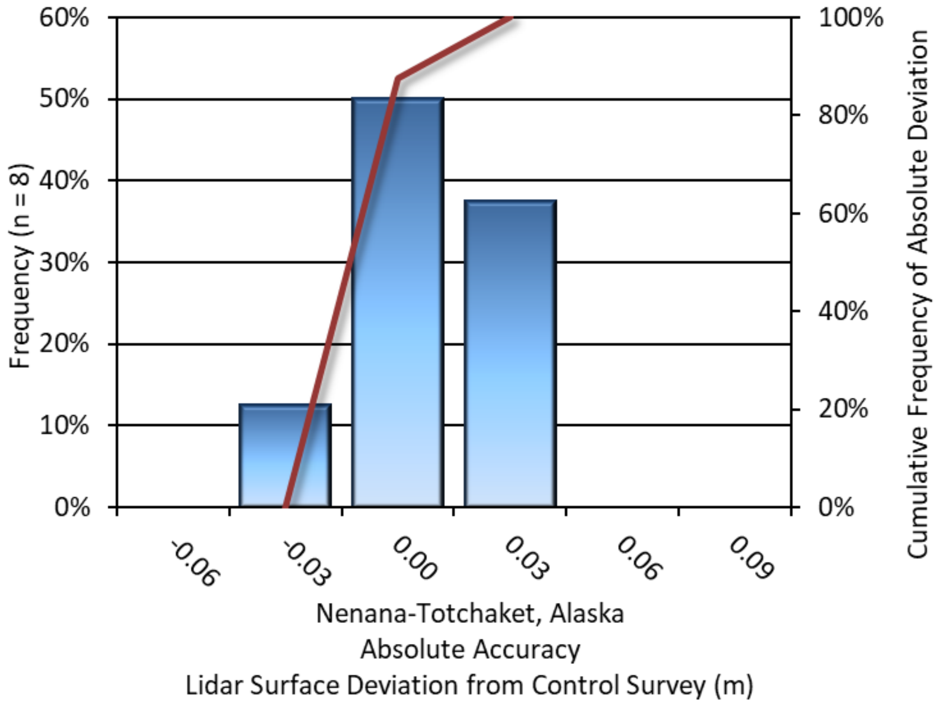

Figure 13: Frequency histogram for lidar surface deviation from ground control point values

Lidar Vegetated Vertical Accuracies

Quantum Spatial 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 Nenana-Totchaket survey, 13 vegetated check points were collected, with resulting vegetated vertical accuracy of 0.854 feet (0.260 meters) as compared to the bare earth DEM, evaluated at the 95th percentile (Table 16; Figure 14).

Table 16: Vegetated vertical accuracy results

Vegetated Vertical Accuracy	
Sample	13 points
95th Percentile	0.854 ft 0.260 m
Average	0.448 ft 0.136 m
Median	0.440 ft 0.134 m
RMSE	0.507 ft 0.155 m
Standard Deviation (1σ)	0.248 ft 0.076 m

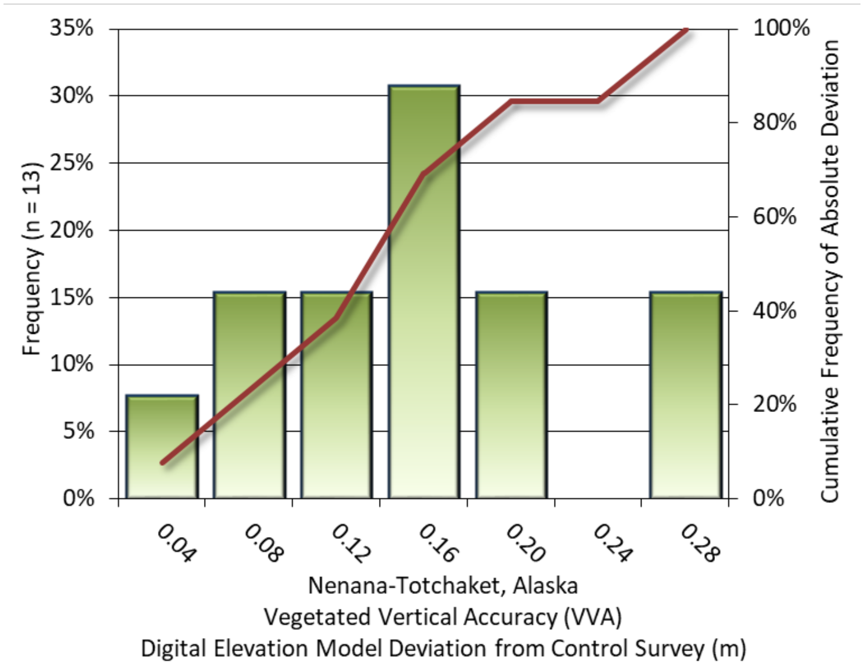

Figure 14: Frequency histogram for lidar surface deviation from vegetated check point values (VVA)

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 Nenana-Totchaket lidar project was 0.047 feet (0.014 meters) (Table 17, Figure 15).

Table 17: Relative accuracy results

Relative Accuracy	
Sample	66 surfaces
Average	0.047 ft 0.014 m
Median	0.047 ft 0.014 m
RMSE	0.047 ft 0.014 m
Standard Deviation (1σ)	0.003 ft 0.001 m
1.96σ	0.005 ft 0.002 m

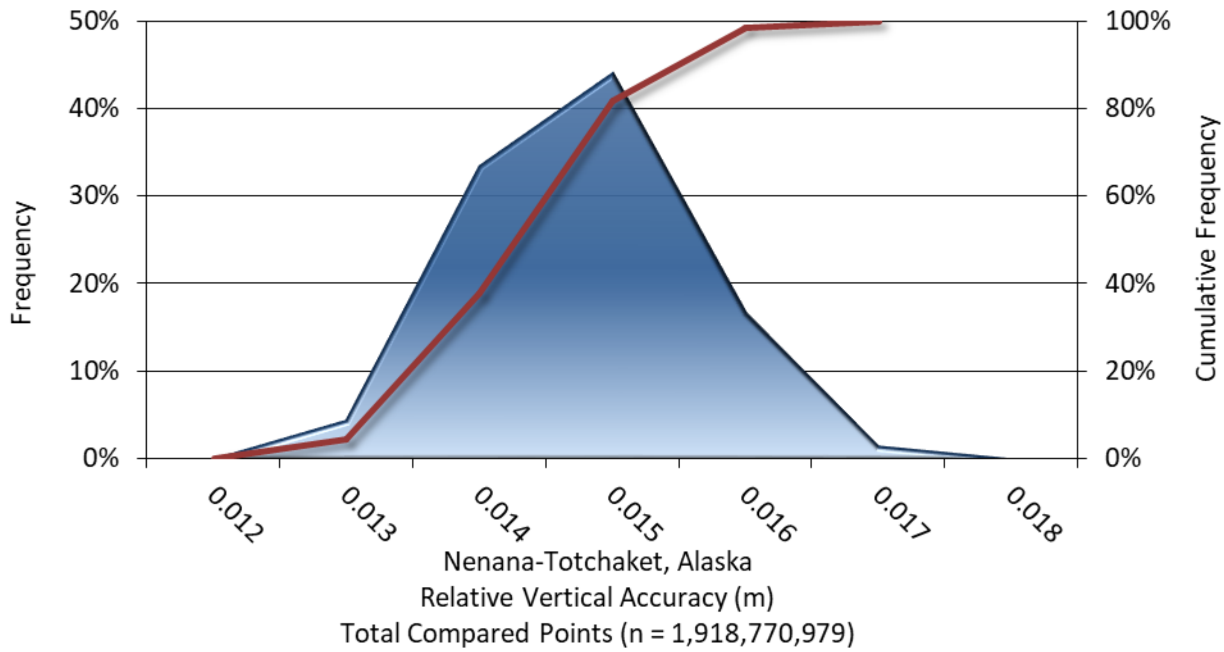

Figure 15: Frequency plot for relative vertical accuracy between flight lines

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 1,900 meters, an IMU error of 0.005 decimal degrees, and a GNSS positional error of 0.036 meters, this project was compiled to meet 1.70 feet (0.52 m) horizontal accuracy at the 95% confidence level (Table 18).

Table 18: Horizontal Accuracy

Horizontal Accuracy	
$RMSE_r$	0.98 ft 0.29 m
ACC_r	1.70 ft 0.52 m

Digital Imagery Accuracy Assessment

Imagery accuracy was assessed using control points as check points collected by Quantum Spatial. Three photo identifiable points were utilized as check points. The photo identifiable survey points in the orthoimagery were measured and the displacement recorded for statistical analysis.

Table 19 presents the complete photo accuracy statistics, Figure 16 contains a scatterplot displaying the XY deviation, in feet, of aerial triangulation check points as compared to the orthoimagery in the collection area.

Table 19: Orthophotography accuracy statistics for Nenana-Totchaket

Nenana- Totchaket Orthoimagery Accuracy	
No. Observations	3
MIN ΔX	-0.260 ft -0.079 m
MIN ΔY	0.000 ft -0.079 m
MAX ΔX	0.521 ft 0.079 m
MAX ΔY	0.521 ft 0.159 m
MEAN ΔX	0.000 ft -0.026 m
MEAN ΔY	0.174 ft 0.026 m
$RMSE_X$	0.368 ft 0.079 m
$RMSE_Y$	0.301 ft 0.102 m
$RMSE_H$	0.475 ft 0.130 m
NSSDA	0.823 ft 0.224 m
SX	0.451 ft 0.092 m
SY	0.301 ft 0.121 m
SH	0.376 ft 0.106 m
CE90	0.807 ft 0.228 m
CE95	0.920 ft 0.261 m
SRMSE H	0.217 ft 0.061 m
CI	0.425 ft 0.120 m

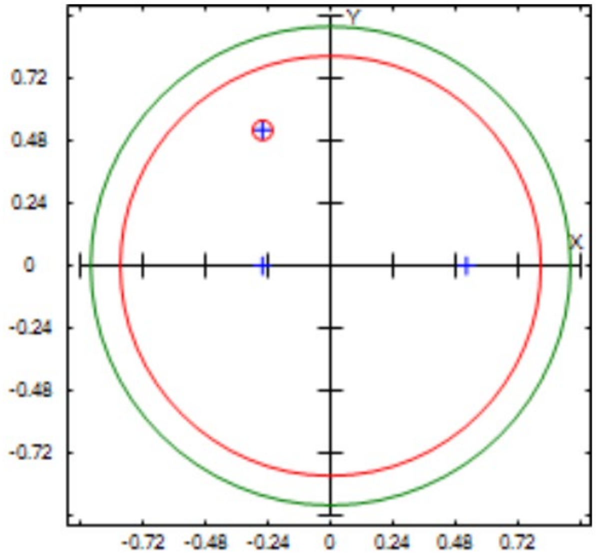

Figure 16: Scatterplot displaying the XY deviation, in feet, of aerial triangulation check points as compared to the orthoimagery in the collection area.

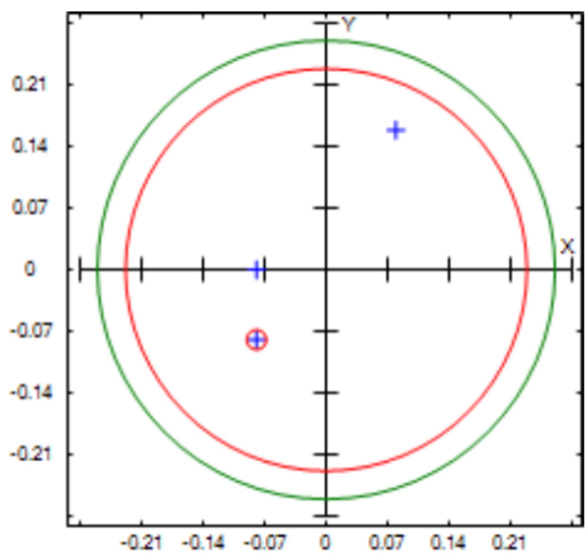

Figure 17: Scatterplot displaying the XY deviation, in meters, of aerial triangulation check points as compared to the orthoimagery in the collection area.

Quantum Spatial, Inc. provided lidar & imagery services for the Nenana-Totchaket project as described in this report.

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

Caitlin Vernlund
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. Field work for this report was conducted on July 11-31, 2020 for the lidar and ground surveys and on August 13-14, 2020 for the imagery.

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, PLS
Quantum Spatial, Inc.
Corvallis, OR 97330

Signed: Dec 2, 2020
COA: 125659

Glossary

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

<u>1.96 * RMSE Absolute Deviation</u>: 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.

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

> **<u>Absolute Accuracy</u>:** 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.
>
> **<u>Relative Accuracy</u>:** 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).
>
> **<u>Root Mean Square Error (RMSE)</u>:** 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.

<u>Data Density</u>: A common measure of Lidar resolution, measured as points per square meter.

<u>Digital Elevation Model (DEM)</u>: 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.

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

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

<u>Overlap</u>: The area shared between flight lines, typically measured in percent. 100% overlap is essential to ensure complete coverage and reduce laser shadows.

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

<u>Pulse Returns</u>: 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.

<u>Real-Time Kinematic (RTK) Survey</u>: 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.

<u>Post-Processed Kinematic (PPK) Survey</u>: 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.

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

<u>Native Lidar Density</u>: 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.