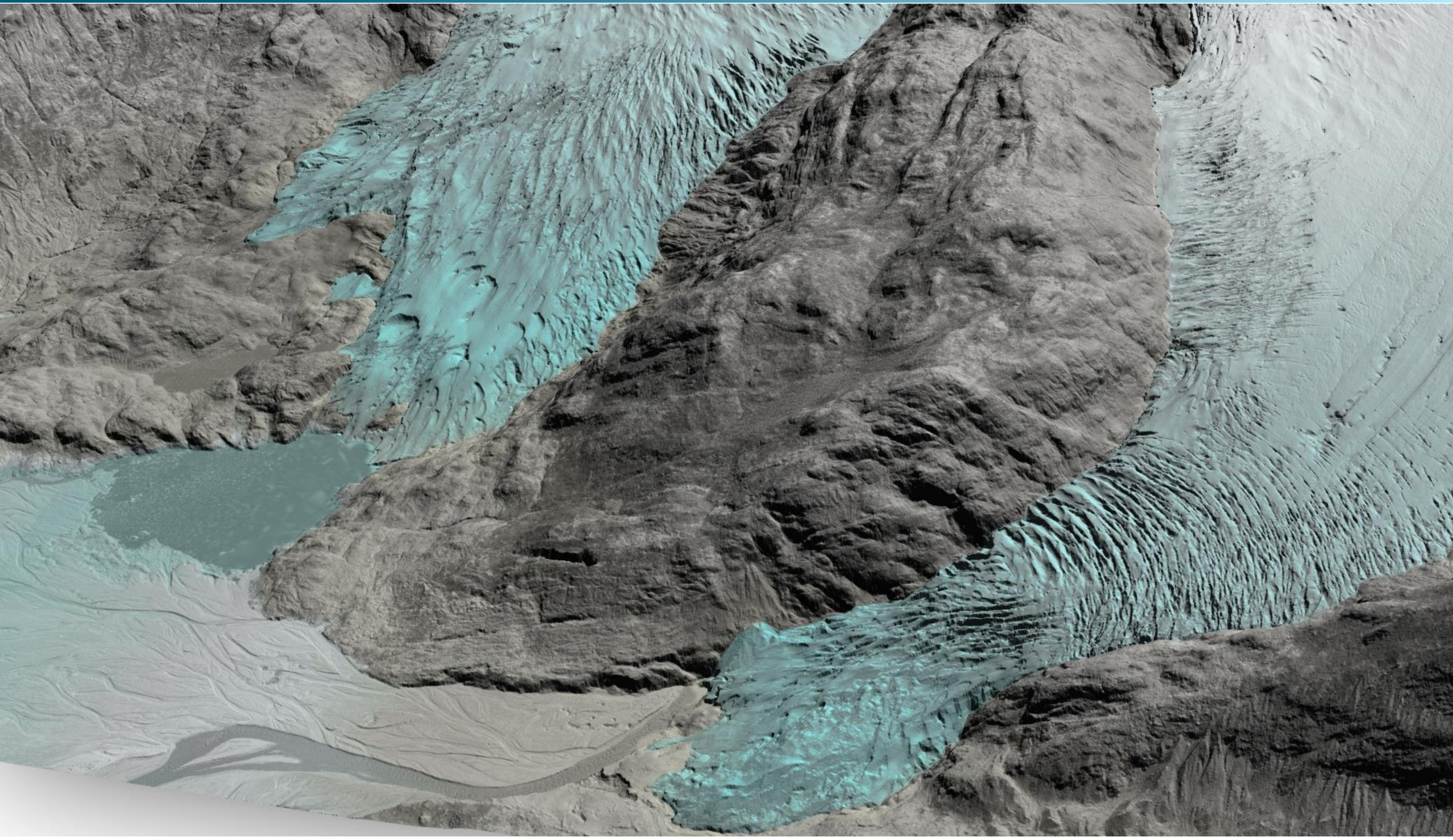
May 04, 2020



Glacier Bay, Alaska Delivery 1 Lidar Technical Data Report

Contract No. G16PC00016 Order No. 140G0219F0200

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Cover Photo: A view looking at the Riggs Glacier within the Glacier Bay Project Area. The image was created from the lidar bare earth model.

INTRODUCTION

This photo taken by acquisition staff shows a vegetated area view of the Glacier Bay, Alaska Delivery 1 site.

In July in 2019, Quantum Spatial (QSI) was contracted by United States Geological Survey (USGS) to collect QL1 and QL2 Light Detection and Ranging (lidar) data in the summer of 2019 for the Glacier Bay, Delivery 1 site in Alaska. This is the first delivery of two and covers all areas collected during the 2019 Alaska acquisition season. Quantum Spatial was able to acquire and process nearly 38% of the project site before being limited by seasonal weather and tides. Execution of the remaining project area is scheduled to occur in the summer of 2020. Data were collected to aid USGS in assessing the topographic and geophysical properties of the study area, including glacial advancement, retreat and mass.

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 USGS is shown in Table 2, the delivery 1 project extent is shown in Figure 1 and a comprehensive deliverable map is shown in Figure 2.

Table 1: Acquisition dates, acreage, and data types collected on the Glacier Bay, Alaska Delivery 1 site

Project Site	Delivered Acres	Acquisition Dates	Data Type
Glacier Bay, Alaska Delivery 1	130,339	07/31/2019 – 08/11/2019	QL1 lidar
	345,212	07/30/2019 – 09/15/2019	QL2 lidar

Deliverable Products

Table 2: Products delivered to USGS for the Glacier Bay, Alaska Delivery 1 site

Glacier Bay Delivery 1 Lidar Products Projection: UTM Zone 8 North Horizontal Datum: NAD83 (2011) Vertical Datum: NAVD88 (GEOID12B) Units: Meters	
Points	LAS v 1.4 • All Classified Returns
Rasters	0.5 Meter GeoTiffs • QL1 Hydroflattened Bare Earth Model (DEM) • QL1 Highest Hit Digital Surface Model (DSM) 1.0 Meter GeoTiffs • QL2 Hydroflattened Bare Earth Model (DEM) • QL2 Highest Hit Digital Surface Model (DSM) • Intensity Images
Vectors	Shapefiles (*.shp) • Project Boundary • Lidar Tile Index • Ground Survey Shapes ESRI File Geodatabase (*.gdb) • Flightline Index • Flightline Swath Coverage Extents • Water's Edge Breaklines

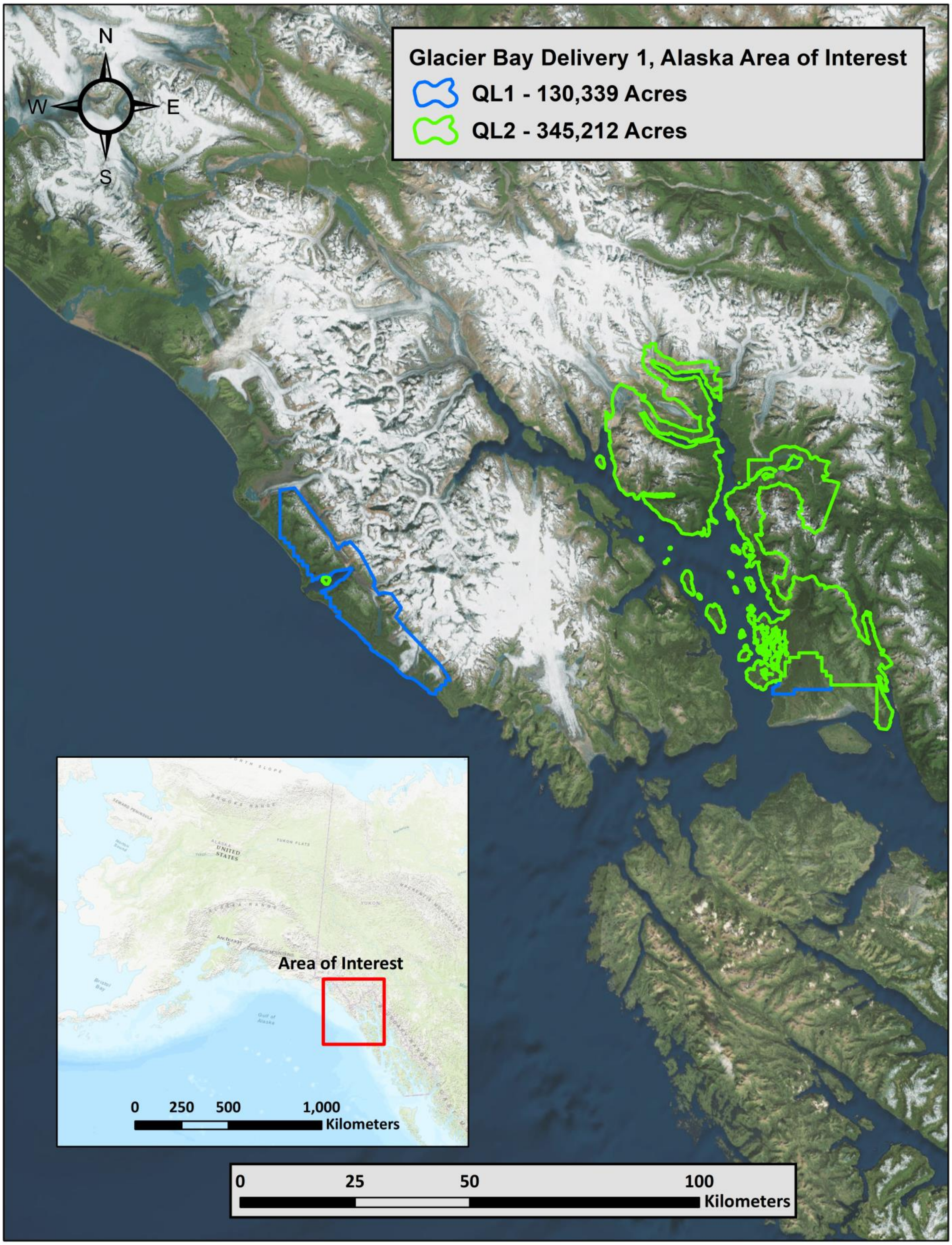


Figure 1: Location map of the Glacier Bay, Alaska Delivery 1 site in Alaska

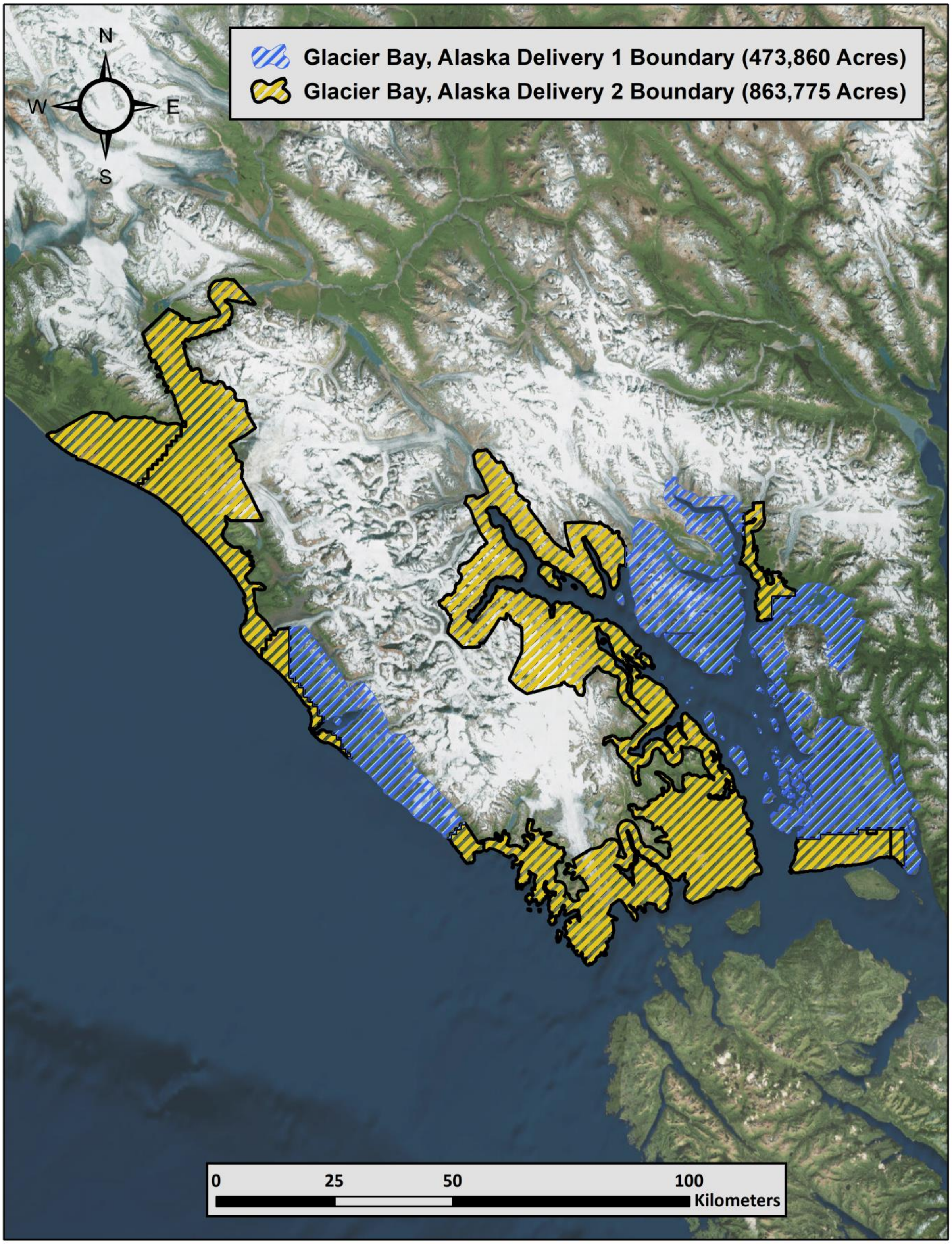


Figure 2: Glacier Bay, Alaska Delivery Map

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 Glacier Bay, Alaska Delivery 1 lidar study area at the target point density of ≥8.0 points/m^2 for all QL1 portions and ≥2.0 points/m^2 for all QL2 portions. 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 Lidar Survey

The lidar survey was accomplished using a Riegl Q1560 laser system mounted in a Cessna Caravan. Table 3 summarizes the settings used to yield an average pulse density of ≥8 pulses/m^2 for all QL1 portions and ≥2.0 points/m^2 for all QL2 portions over the Glacier Bay, Alaska Delivery 1 project area. 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		
Quality Level	QL1	QL2
Acquisition Dates	July 31, August 7 - 11, September 7, September 15, 2019	July 31, August 1 - 10, September 7, September 11, September 15, 2019
Aircraft Used	Cessna Caravan	Cessna Caravan
Sensor	Riegl	Riegl
Laser	Q1560	Q1560
Maximum Returns	Unlimited	Unlimited
Resolution/Density	Average 8 pulses/m^2	Average 2 pulses/m^2
Nominal Pulse Spacing	0.35	0.71 m
Survey Altitude (AGL)	1,300 m	2,620 m
Survey speed	140 knots	140 knots
Field of View	58.5 º	58.5 º
Mirror Scan Rate	142 lines Per Second	142 lines Per Second
Target Pulse Rate	800 kHz	800 kHz
Pulse Length	3 ns	3 ns
Laser Pulse Footprint Diameter	23 cm	47 cm
Central Wavelength	1064 nm	1064 nm
Pulse Mode	Multiple Times Around (MTA)	Multiple Times Around (MTA)
Beam Divergence	0.18 mrad	0.18 mrad
Swath Width	1,456 m	2,934 m
Swath Overlap	50 %	50 %
Intensity	16-bit	16-bit
Accuracy	$RMSE_Z$ (Non-Vegetated) ≤ 10 cm NVA (95% Confidence Level) ≤ 19.6 cm VVA (95^{th} Percentile) ≤ 30 cm	

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.

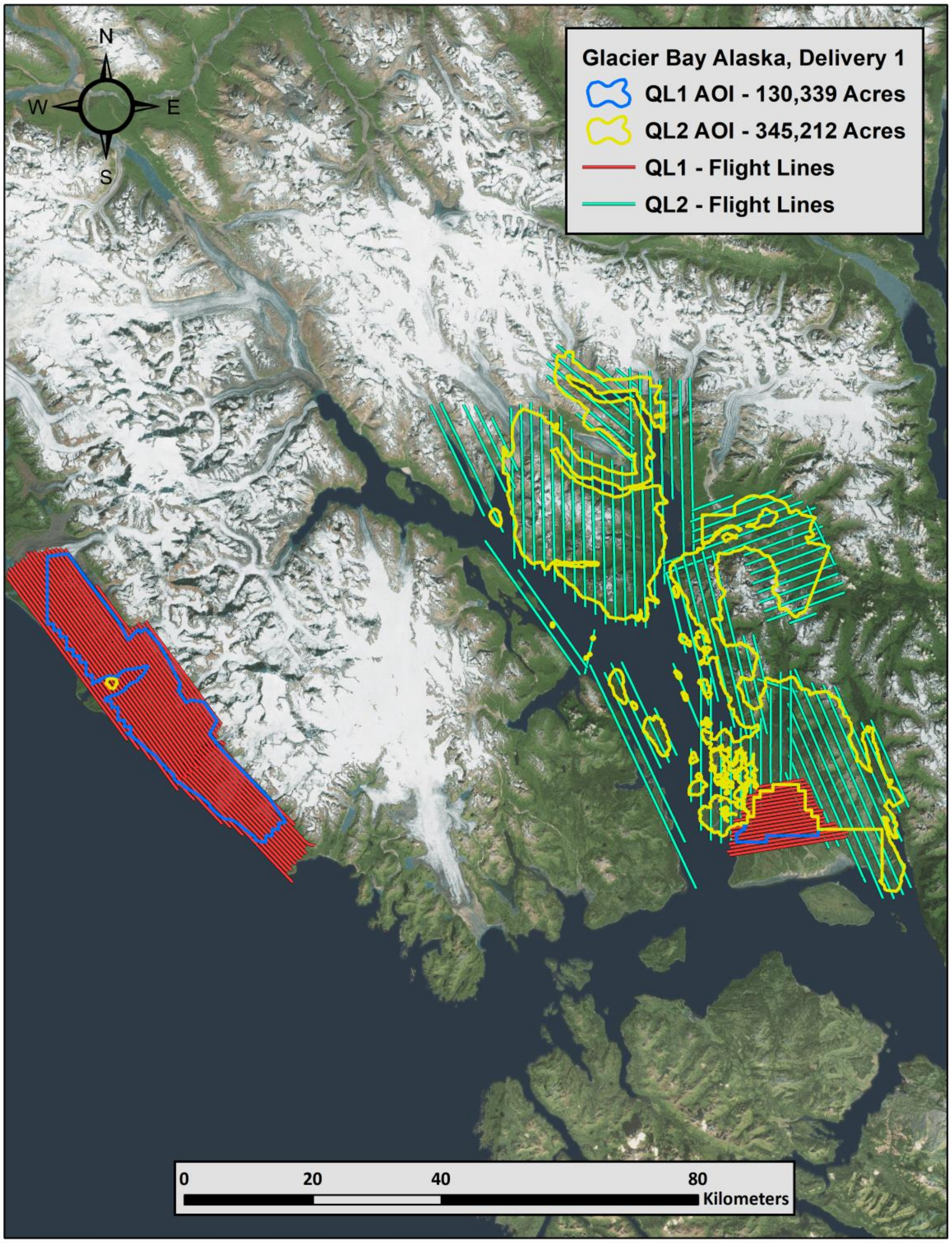


Figure 3: Flight line location map of the Glacier Bay, Alaska Delivery 1 site

Ground Survey

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

Base Stations

Monumentation utilized for the collection of ground survey points included 46 monuments set or discovered by DOWL during the ground survey. Monument locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage (Table 4, Figure 4).

Table 4: Monument positions for the Glacier Bay, Alaska Delivery 1 acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Monument ID	Latitude	Longitude	Ellipsoid (meters)
1	58° 27' 10.99029"	-135° 51' 18.67030"	35.499
2	58° 26' 12.38889"	-135° 36' 25.93424"	193.171
401	58° 30' 11.88674"	-135° 29' 58.12001"	6.377
402	58° 30' 12.51651"	-135° 30' 00.97998"	6.516
403	58° 30' 29.98978"	-135° 30' 12.19195"	8.737
404	58° 30' 31.42403"	-135° 30' 12.28280"	8.930
405	58° 27' 07.07795"	-135° 50' 41.88253"	27.323
406	58° 27' 07.08000"	-135° 50' 35.64214"	26.314
407	58° 27' 07.27368"	-135° 46' 17.23174"	17.575
408	58° 54' 45.43448"	-136° 07' 32.81893"	6.800
409	58° 54' 48.25525"	-136° 07' 28.64093"	10.192
410	58° 54' 49.63371"	-136° 07' 25.82334"	8.568
411	58° 36' 11.70341"	-135° 51' 30.90230"	6.965
412	58° 36' 17.18298"	-135° 51' 14.62444"	7.625
413	58° 36' 12.22902"	-135° 51' 29.16439"	8.794
415	58° 31' 04.01258"	-136° 11' 07.31290"	7.350
416	58° 31' 04.75756"	-136° 11' 10.41574"	7.537
417	58° 31' 05.35796"	-136° 11' 09.48278"	8.866
420	58° 49' 56.77355"	-136° 23' 54.47468"	9.967
421	58° 49' 50.05231"	-136° 24' 03.18384"	9.113
422	58° 49' 58.46350"	-136° 23' 48.28837"	11.305

Monument ID	Latitude	Longitude	Ellipsoid (meters)
423	58° 49' 58.20619"	-136° 23' 49.21583"	10.630
424	58° 55' 02.68728"	-136° 31' 46.69309"	9.517
426	58° 39' 05.52405"	-136° 24' 07.82077"	7.339
427	58° 39' 06.39539"	-136° 24' 06.71957"	8.163
428	58° 39' 05.10362"	-136° 24' 09.76044"	8.956
429	58° 21' 57.65780"	-136° 51' 38.59757"	8.594
430	58° 21' 58.46200"	-136° 51' 40.52667"	8.918
431	58° 22' 03.10183"	-136° 51' 37.55823"	13.048
432	58° 22' 17.37202"	-136° 22' 39.00280"	6.268
433	58° 22' 19.93220"	-136° 22' 34.86674"	8.749
434	58° 22' 18.27281"	-136° 22' 35.20227"	6.921
435	58° 26' 12.06628"	-135° 45' 39.80177"	14.175
436	58° 26' 11.51022"	-135° 45' 40.11323"	14.119
437	58° 26' 12.29031"	-135° 45' 40.59424"	14.190
USCG A	58° 25' 04.47501"	-135° 41' 51.12220"	10.431
5 1959	58° 27' 14.64605"	-135° 53' 10.87991"	9.405
Park 1966	58° 27' 13.41752"	-135° 53' 13.16749"	10.017
Composite 4	58° 53' 00.59962"	-136° 34' 17.52455"	12.635
BM 5 1972	58° 54' 46.97766"	-136° 06' 45.04709"	11.015
2648 B	58° 23' 51.59281"	-136° 27' 53.37768"	9.345
Jamie 1970	58° 54' 55.06129"	-136° 31' 40.76396"	15.420
ALUM 1938 No. 2	58° 31' 05.26558"	-136° 11' 01.87865"	9.821
ALUM 1938	58° 31' 05.11032"	-136° 11' 02.94976"	10.310
None 1938 No. 1	58° 31' 04.55942"	-136° 12' 53.37833"	9.997
NPS PIPE	58° 27' 21.75354"	-135° 52' 28.94115"	11.497

Ground Survey Points (GSPs)

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

Land Cover Class

Collected ground survey points provided to QSI were used during lidar calibration, post-processing, and accuracy assessment. Ground control points were collected on hard surfaces as feasible, and ground check point data were collected over a variety of land surface types to be used in non-vegetated and vegetated vertical accuracy assessment. Relative errors for any GSP position must be less than 1.5 cm horizontal and 2.0 cm vertical in order to be accepted. GSPs were collected within as many flightlines as possible; however, the distribution of GSPs depended on ground access constraints and will not be equitably distributed throughout the study area due to the remote nature of the project sites (Figure 4). Vertical accuracy statistics were calculated for all land cover types to assess confidence in the lidar derived ground models across land cover classes (Table 5, see Lidar Accuracy Assessments, page 21).

Table 5: Land Cover Types and Descriptions

Land cover type	Land cover code	Example	Description	Accuracy Assessment Type
Tall Grass	TG		Herbaceous grasslands in advanced stages of growth	VVA
Forest	FR		Forested areas	VVA
Shrub	SH		Areas of low-lying shrub vegetation	VVA
Bare Earth	BE		Areas of bare earth surface	NVA
Urban	UA		Areas dominated by urban development, including parks	NVA

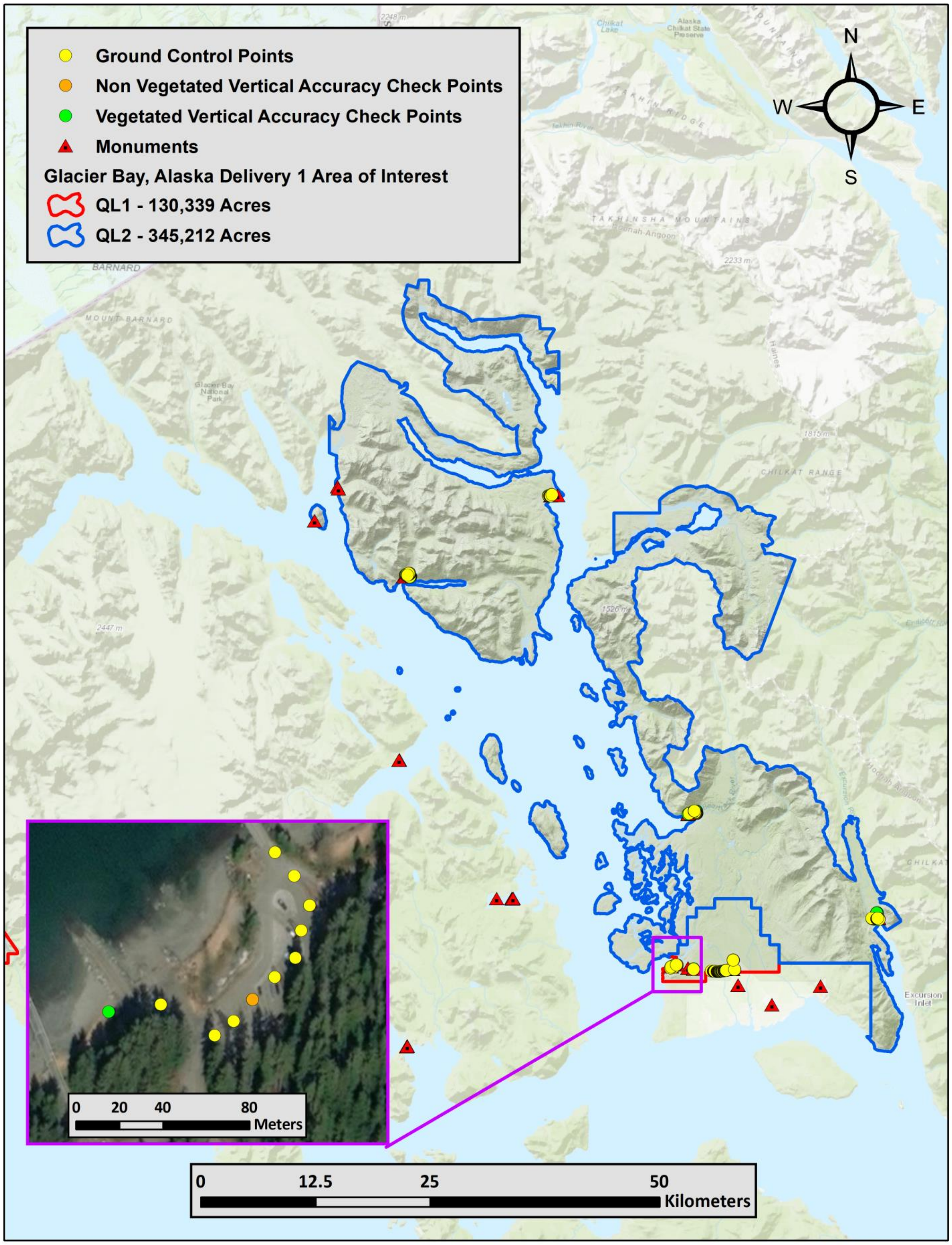
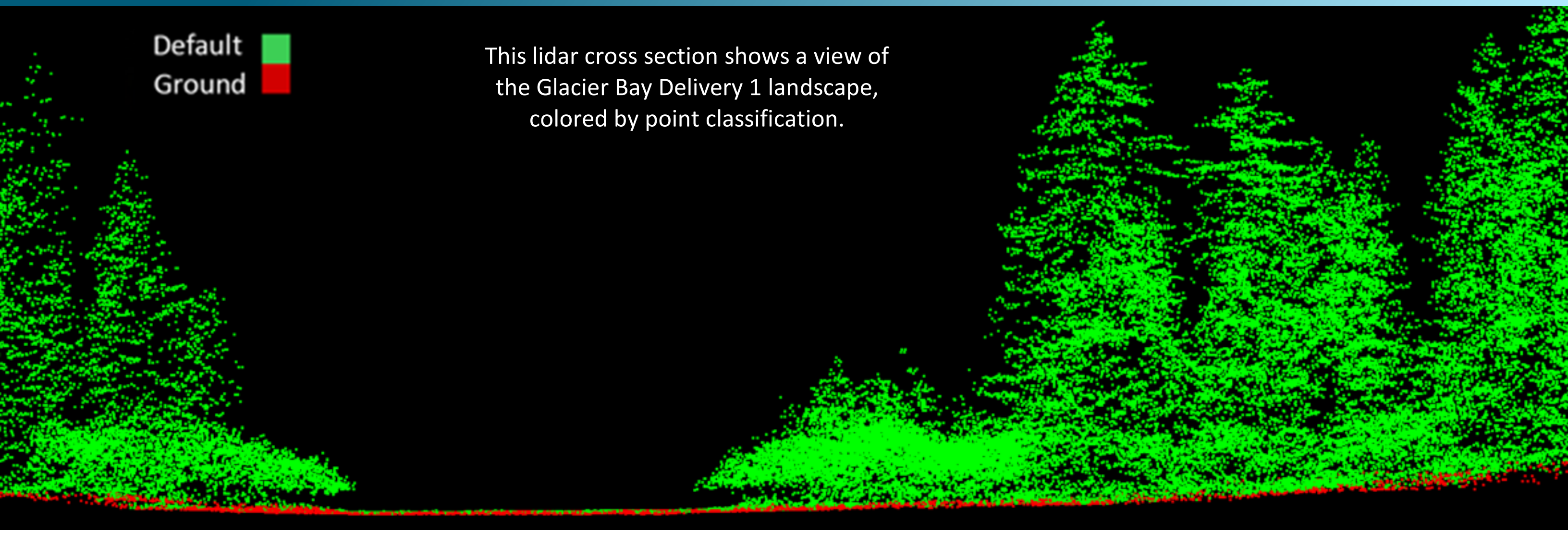


Figure 4: Ground survey location map



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 Glacier Bay, 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
1 - O	Edge Clip / Overlap	Laser returns at the outer edges of flightlines that are geometrically unreliable
2	Ground	Laser returns that are determined to be ground using automated and manual cleaning algorithms
7 - W	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 - W	High Noise	Above-ground laser returns that are often associated with birds, scattering from reflective surfaces, or atmospheric noise

Classification Number	Classification Name	Classification Description
20	Ignored Ground	Ground points proximate to water's edge breaklines; ignored for correct model creation
22	Temporal Exclusion	Laser returns that are determined to be due to temporal differences in flight lines and are excluded

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.	POSPac v8.3
Calculate laser point position by associating SBET position to each laser point return time, scan angle, intensity, etc. Create raw laser point cloud data for the entire survey in *.las (ASPRS v. 1.4) format. Convert data to orthometric elevations by applying a geoid correction.	POSPac v8.3 RiProcess v 1.8.5
Import raw laser points into manageable blocks to perform manual relative accuracy calibration and filter erroneous points. Classify ground points for individual flight lines.	TerraScan v.19
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
Generate bare earth hydro flattened models. Generate highest hit models as a surface expression of all classified points. Generate 16-bit intensity images at a 1.0 m resolution for all areas. Export models in a cloud optimized GeoTIFF format at a 0.5 meter pixel resolution for all QL1 areas and at a 1.0 meter pixel resolution for all QL2 areas.	LAS Product Creator 3.0 (QSI proprietary)

Feature Extraction

Hydroflattening and Water's Edge Breaklines

Hydroflattening was performed for all rivers, lakes, and tidal waters within the Glacier Bay, 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 tidal waters bordering the project area, 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.

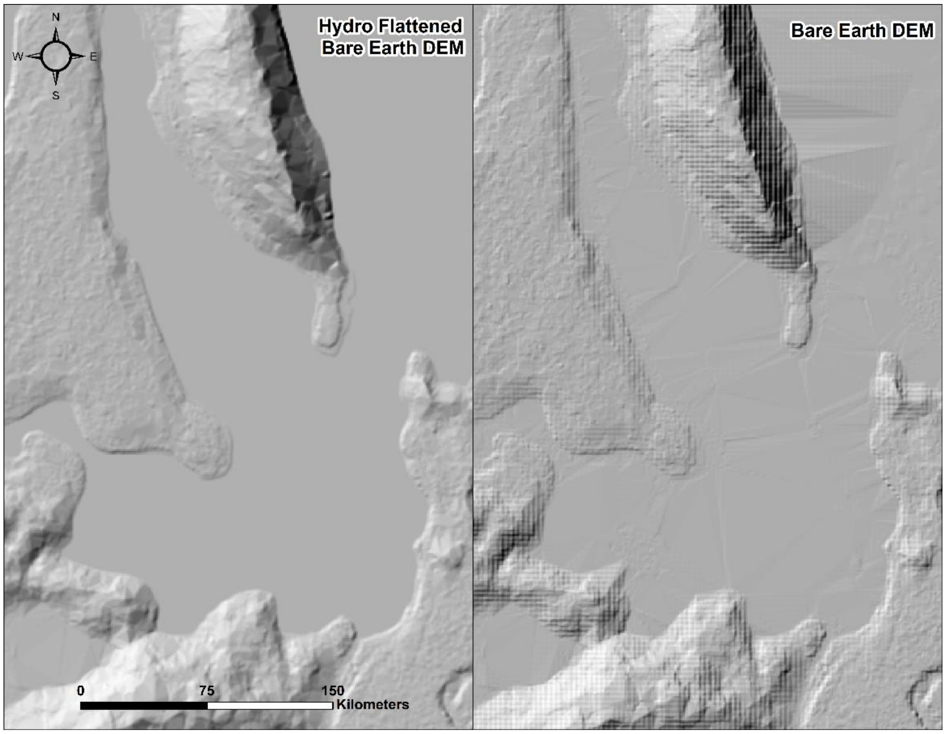
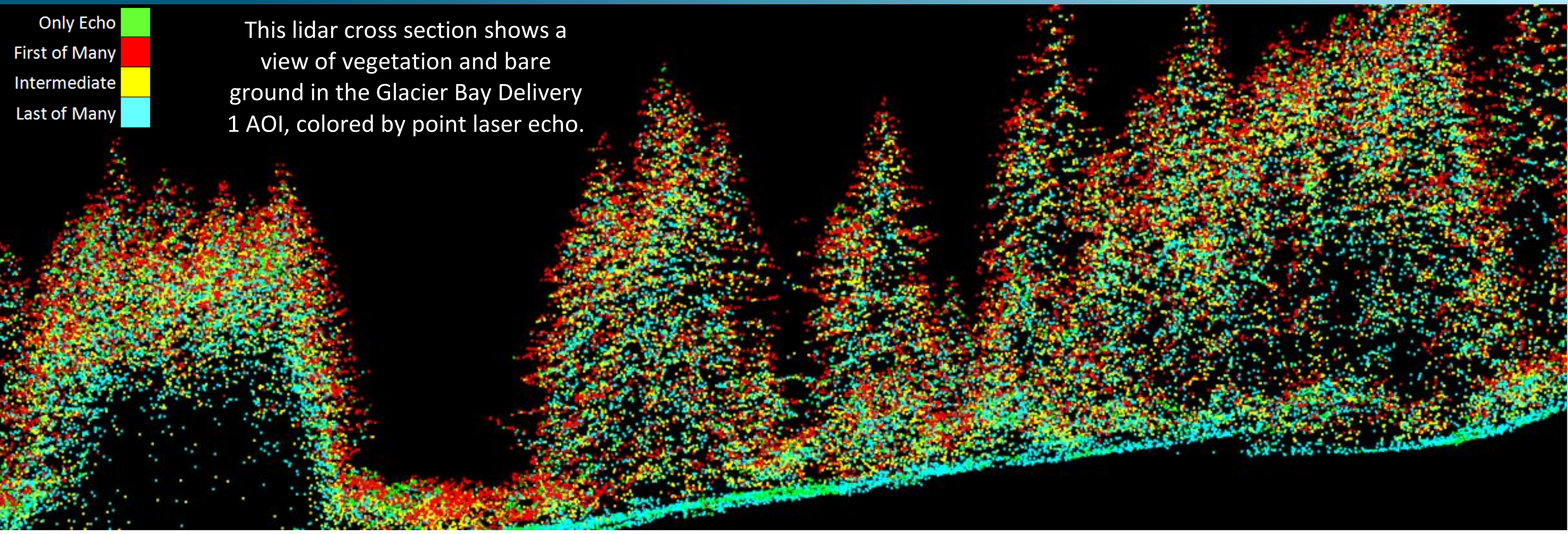


Figure 5: Example of hydroflattening in the Glacier Bay, Alaska Delivery 1 Lidar dataset



Lidar Density

The acquisition parameters were designed to acquire an average first-return density of 8 points/m^2 (0.74 points/ft^2) for QL1 areas, and ≥2 points/ m^2 (0.19 points/ft^2) for the QL2 areas. First return density describes the density of pulses emitted from the laser that return at least one echo to the system. Multiple returns from a single pulse were not considered in first return density analysis. Some types of surfaces (e.g., breaks in terrain, water and steep slopes) may have returned fewer pulses than originally emitted by the laser. First returns typically reflect off the highest feature on the landscape within the footprint of the pulse. In forested or urban areas the highest feature could be a tree, building or power line, while in areas of unobstructed ground, the first return will be the only echo and represents the bare earth surface.

The average first-return density of lidar data for the Glacier Bay, Alaska Delivery 1 QL1 project areas was 10.69 points/m^2, while the average first-return density of lidar data for the QL2 project areas was 4.00 points/m^2 (Table 8). Ground classified density of lidar data for the Glacier Bay, Alaska Delivery 1 QL1 project areas was 1.91 points/m^2, while the ground classified density for the QL2 project areas was 1.14 points/m^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 11.

Table 8: Average combined lidar point densities

Classification	QL1 Point Density	QL2 Point Density
First-Return	10.69 points/m^2	4.00 points/m^2
Ground Classified	1.91 points/m^2	1.14 points/m^2

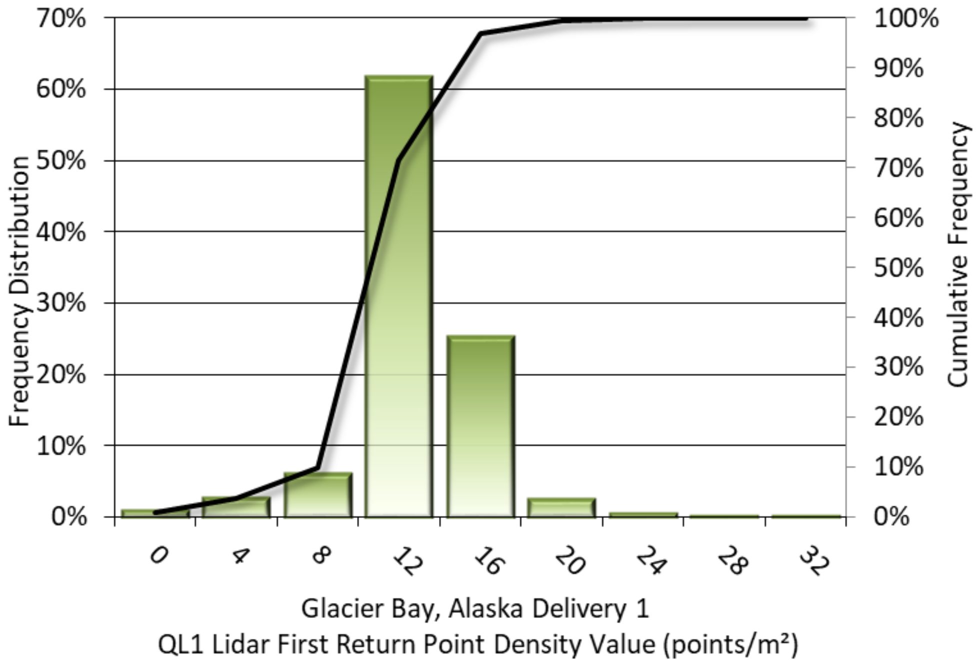


Figure 6: Frequency distribution of QL1 first return point density values per 100 x 100 m cell

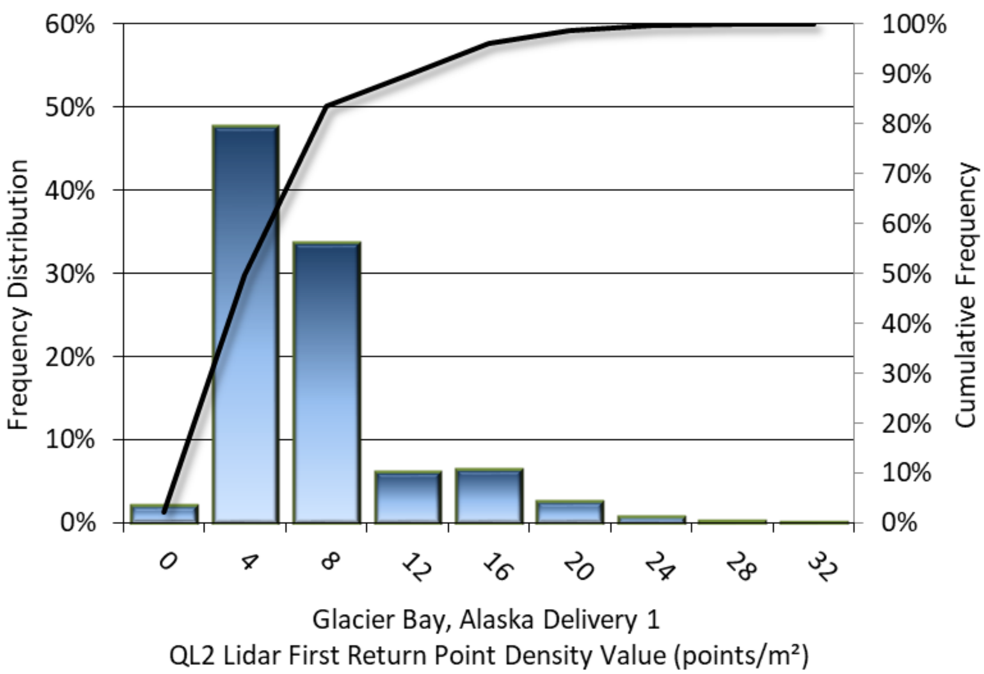


Figure 7: Frequency distribution of QL2 first return point density values per 100 x 100 m cell

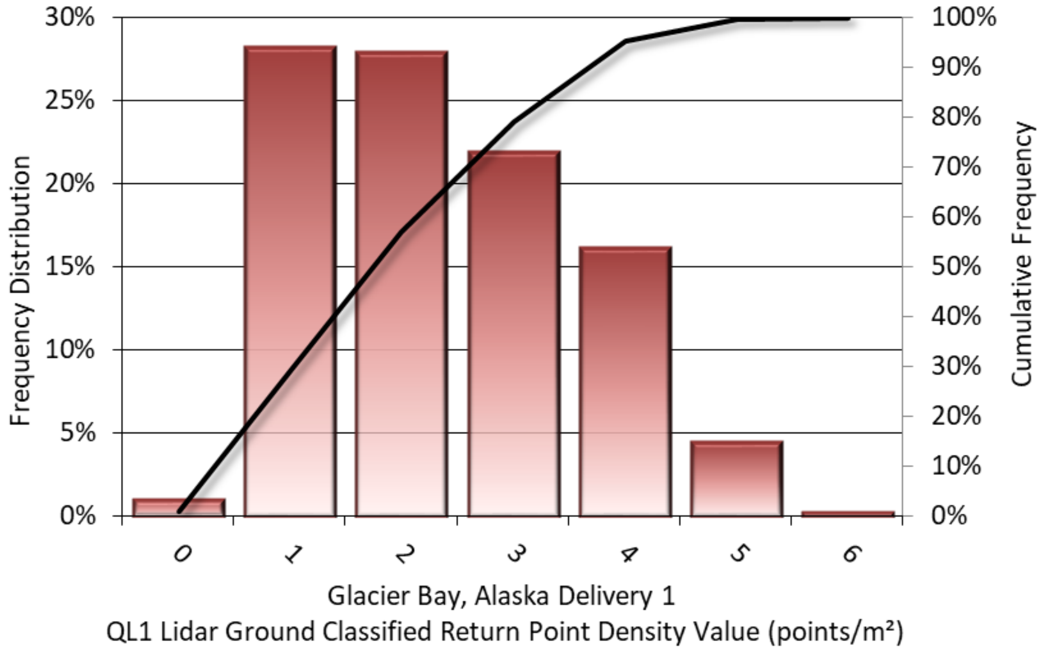


Figure 8: Frequency distribution of QL1 ground-classified return point density values per 100 x 100 m cell

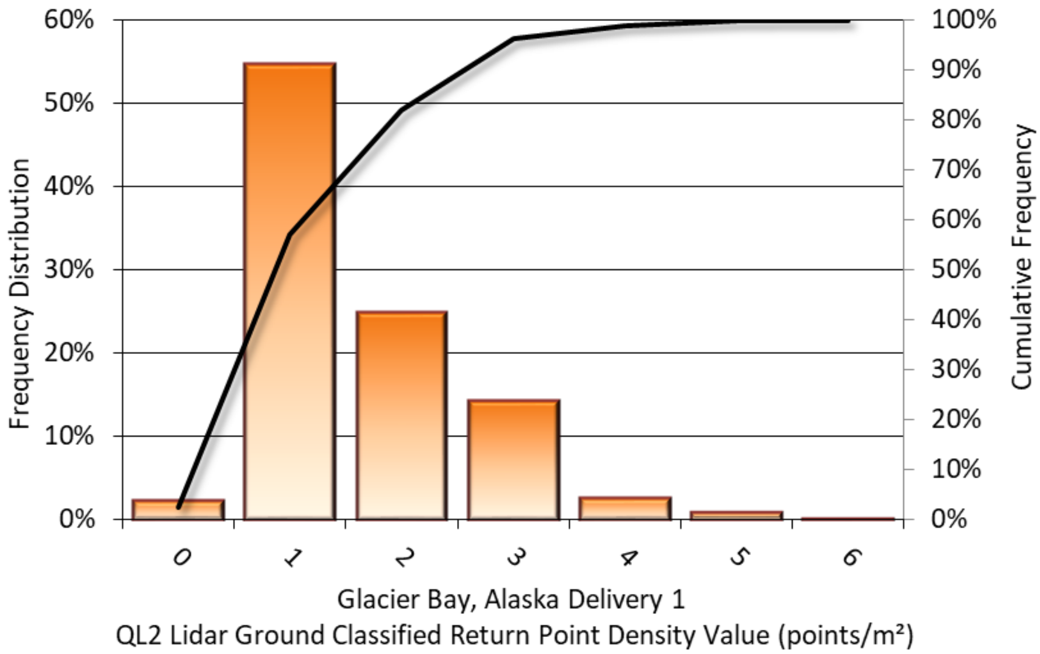


Figure 9: Frequency distribution of QL1 ground-classified return point density values per 100 x 100 m cell

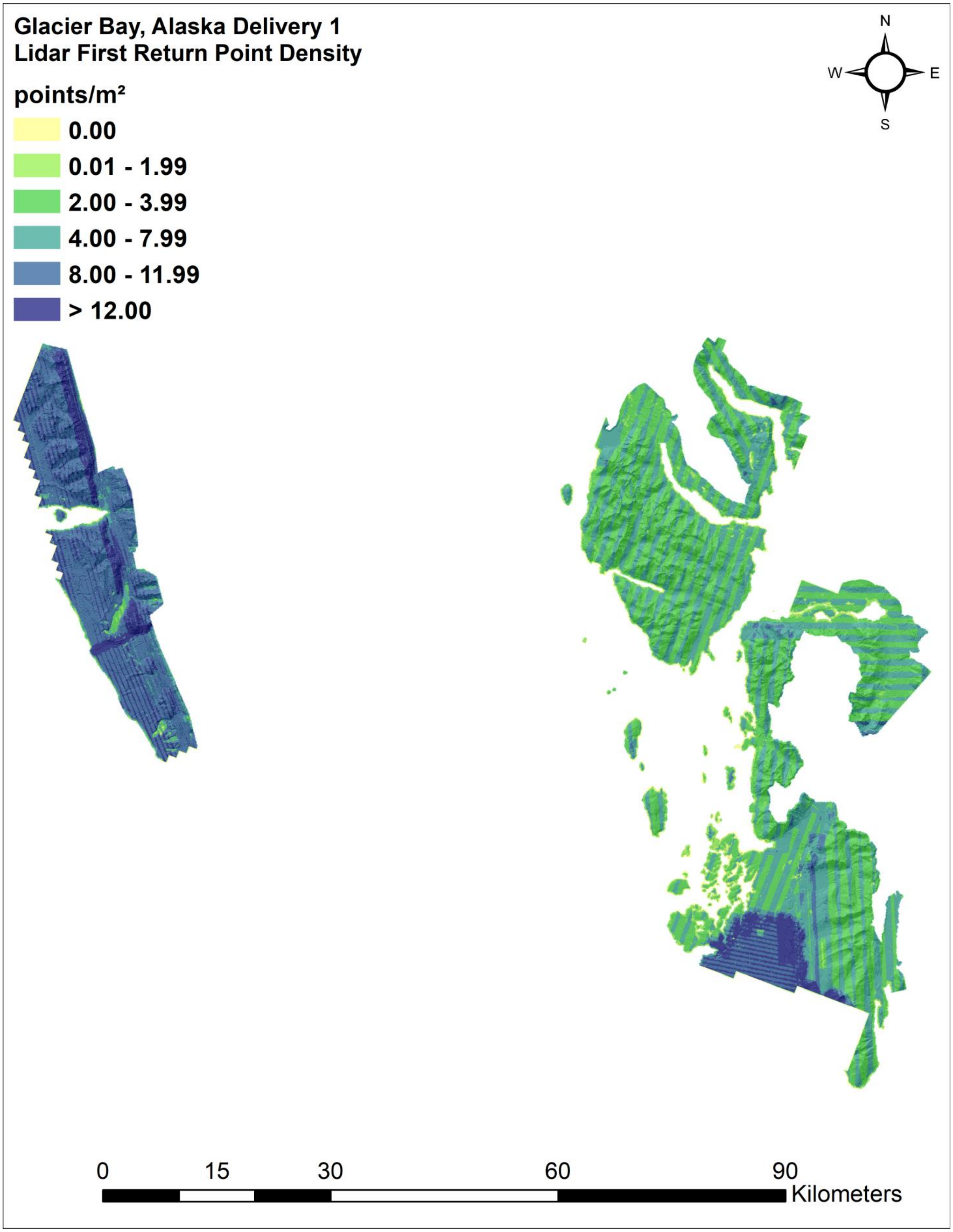


Figure 10: First return point density map for the Glacier Bay, Alaska Delivery 1 site (100 m x 100 m cells)

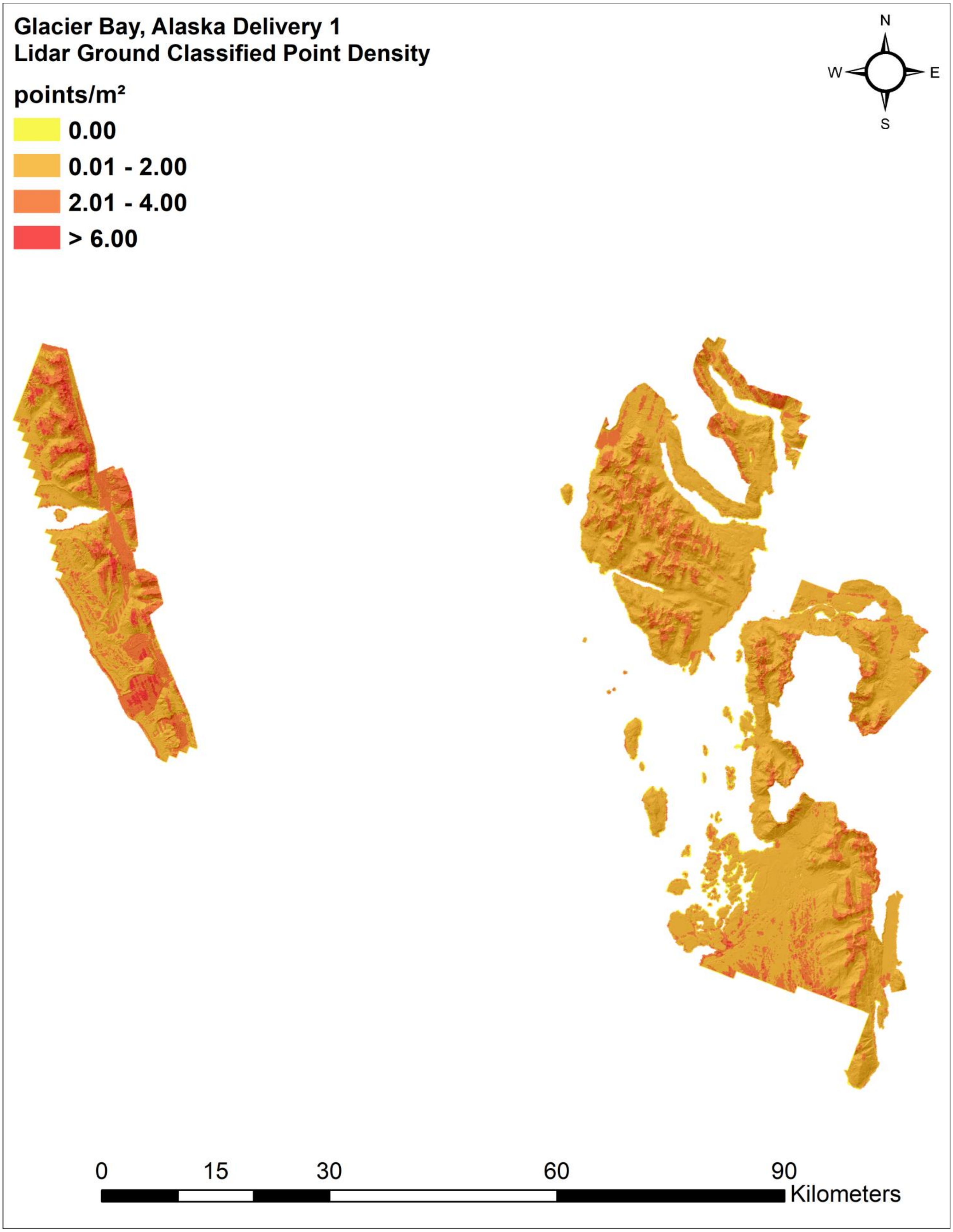


Figure 11: Ground point density map for the Glacier Bay, Alaska Delivery 1 site (100 m x 100 m cells)

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[1]. NVA compares known ground check point data that were withheld from the calibration and post-processing of the lidar point cloud to the triangulated surface generated by the unclassified lidar point cloud as well as the derived gridded bare earth DEM. NVA is a measure of the accuracy of lidar point data in open areas where the lidar system has a high probability of measuring the ground surface and is evaluated at the 95% confidence interval (1.96 * RMSE), as shown in Table 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 Glacier Bay, Alaska Delivery 1 survey, 33 ground check points were withheld from the calibration and post processing of the lidar point cloud, with resulting non-vegetated vertical accuracy of 0.073 meters as compared to unclassified LAS, and 0.069 meters as compared to the bare earth DEM, with 95% confidence (Figure 12, Figure 13).

QSI also assessed absolute accuracy using 194 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 14.

[1] 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	33 points	33 points	194 points
95% Confidence (1.96*RMSE)	0.073 m	0.069 m	0.083 m
Average	0.017 m	-0.005 m	-0.002 m
Median	0.016 m	-0.008 m	0.000 m
RMSE	0.037 m	0.035 m	0.042 m
Standard Deviation (1σ)	0.034 m	0.035 m	0.043 m

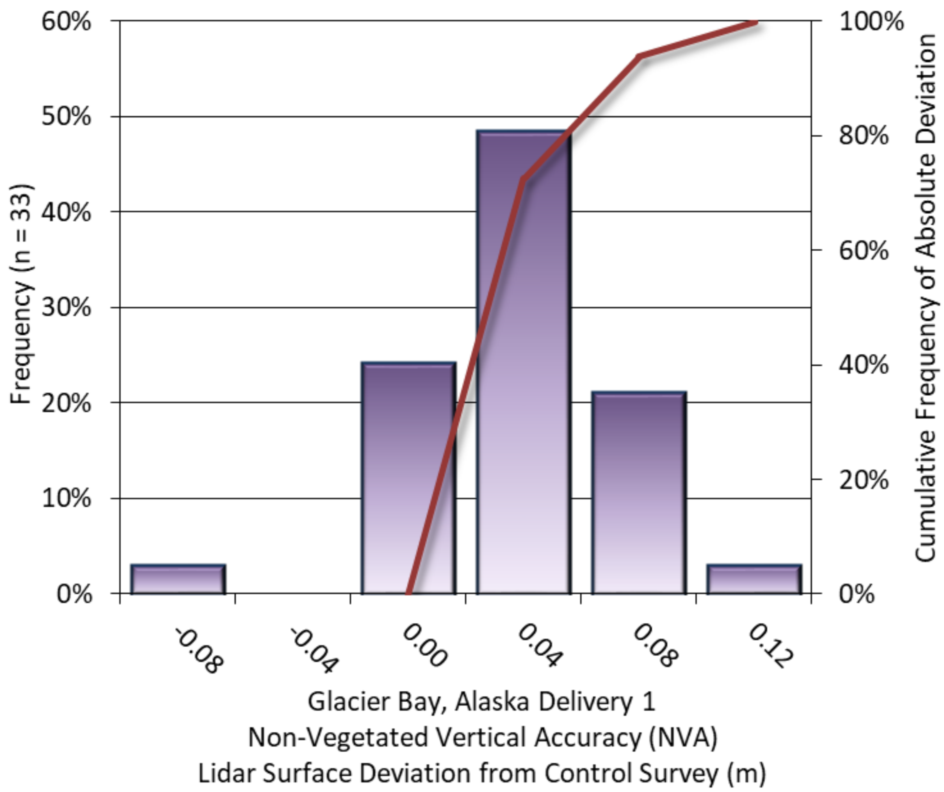


Figure 12: Frequency histogram for lidar unclassified LAS deviation from ground check point values (NVA)

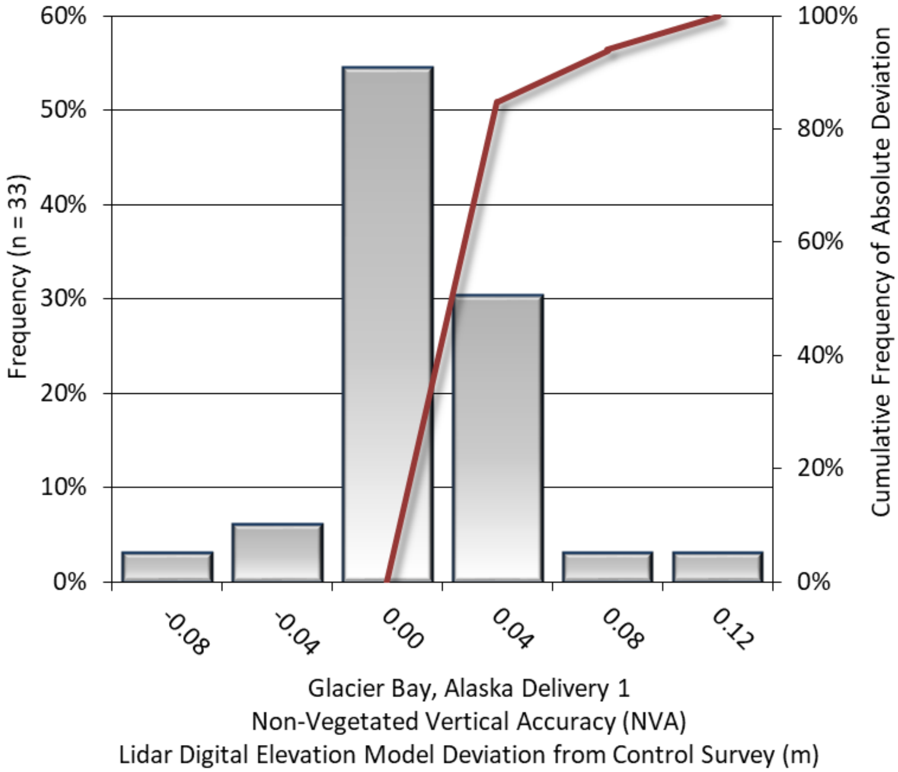


Figure 13: Frequency histogram for lidar bare earth DEM surface deviation from ground check point values (NVA)

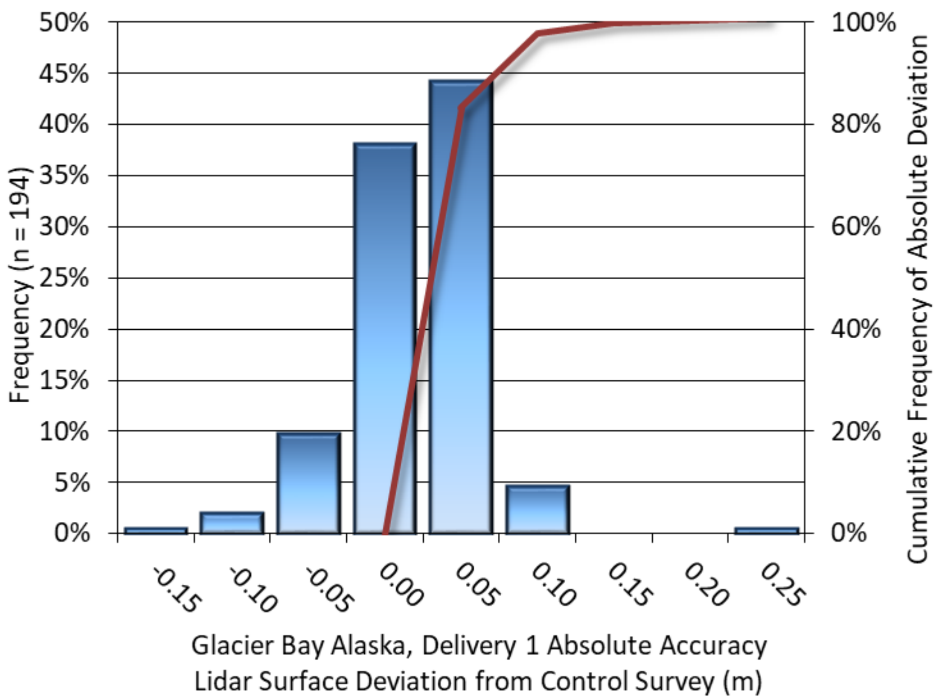


Figure 14: Frequency histogram for lidar surface deviation from ground control point values

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 Glacier Bay, Alaska Delivery 1 survey, 82 vegetated check points were evaluated, with resulting VVA of 0.329 meters as compared to the bare earth DEM, evaluated at the 95th percentile (Table 10, Figure 15).

QSI recognizes that we did not meet the required maximum VVA of 0.30 meters evaluated at the 95th percentile. Because the NVA requirement is met without difficulty, we believe the substandard VVA indicates poor penetration of dense grasslands within the project area. Figure 16 exemplifies one such area where the elevation of the VVA check point significantly differed from the lidar-derived ground surface. Current generation lidar systems are unlikely to achieve greater penetration without significantly reducing flight efficiency.

Table 10: Vegetated vertical accuracy results

Vegetated Vertical Accuracy	
Sample	82 points
95th Percentile	0.329 m
Average	0.101 m
Median	0.070 m
RMSE	0.151 m
Standard Deviation (1σ)	0.114 m

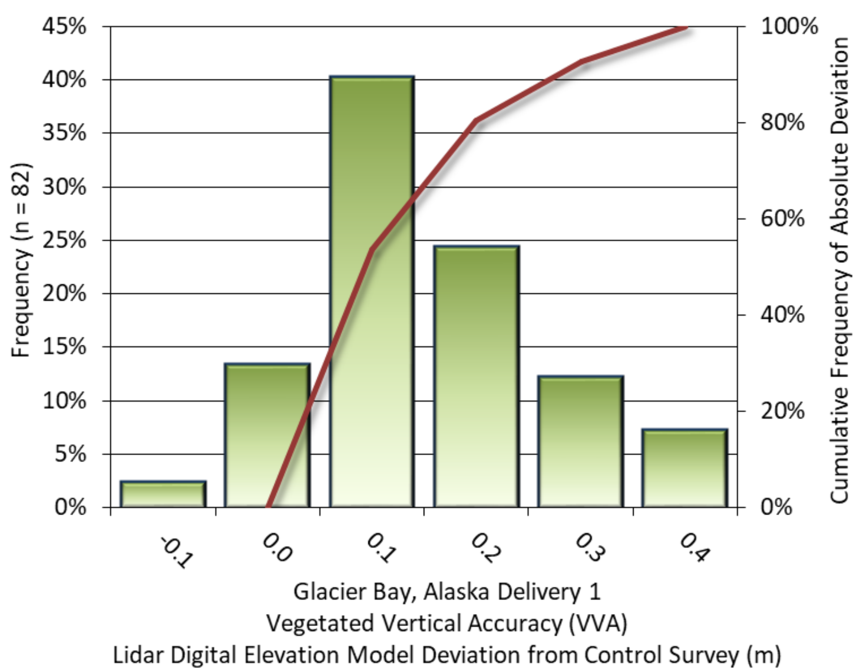


Figure 15: Frequency histogram for lidar surface deviation from vegetated check point values (VVA)

Figure 16: Area where vegetated vertical accuracy check points were taken in thick tall grass.

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 Glacier Bay, Alaska Delivery 1 Lidar project was 0.063 meters (Table 11, Figure 17).

Table 11: Relative accuracy results

Relative Accuracy	
Sample	158 surfaces
Average	0.063 m
Median	0.061 m
RMSE	0.066 m
Standard Deviation (1σ)	0.021 m
1.96σ	0.042 m

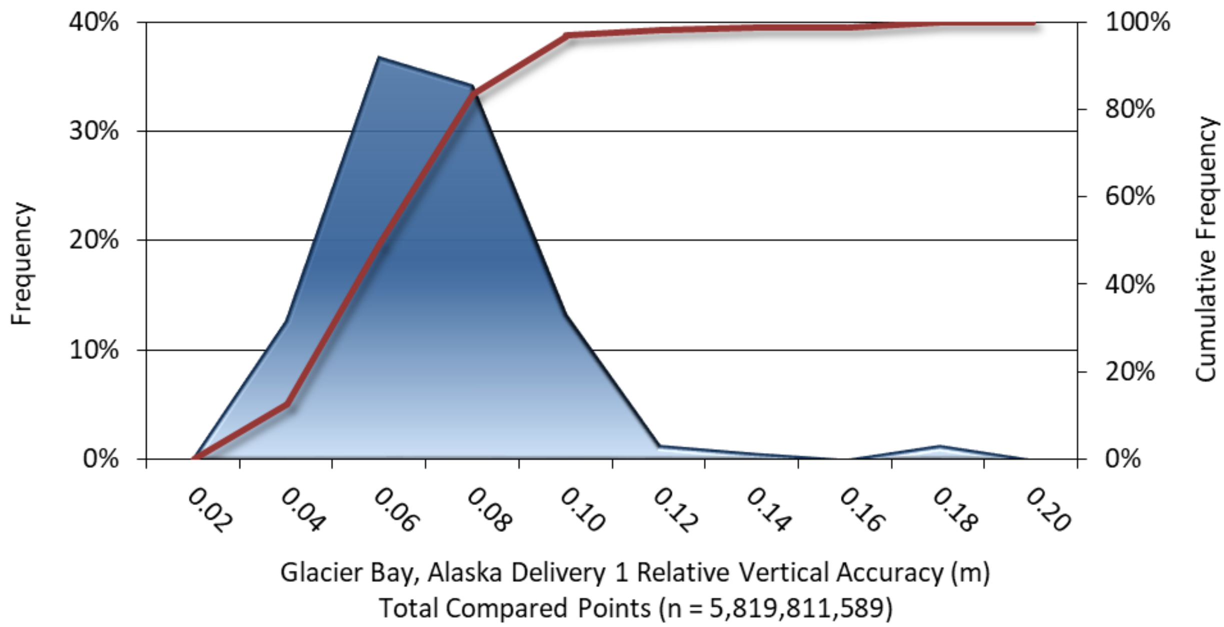


Figure 17: Frequency plot for relative vertical accuracy between flight lines

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 2620 meters, an IMU error of 0.002 decimal degrees, and a GNSS positional error of 0.015 meters, this project was compiled to meet 0.28 m horizontal accuracy at the 95% confidence level.

Table 12: Horizontal Accuracy

Horizontal Accuracy	
$RMSE_r$	0.16 m
ACC_r	0.28 m

CERTIFICATIONS

Quantum Spatial, Inc. provided lidar services for the Glacier Bay, 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 (May 4, 2020)

May 4, 2020

Tucker Selko
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 conducted for this report was conducted between June 28 and September 15, 2019.

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” as closely as feasible for the given project area.

Evon P. Silvia

May 4, 2020

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

- QUALITY CONTROL CERTIFICATION -

DOWL

I hereby certify that an independent ground survey was performed by DOWL under my supervision to obtain data for and to check the reliability of the Lidar Based surface model created by Quantum Spatial Incorporated (QSI).

This Quality Control data was collected between July 22nd and July 28th, 2019 and analyzed April 30th, 2020.

To independently check the lidar surface created by QSI, we compared 309 points to the completed lidar surface. For the Quality Control (QC) check, QSI returned the surface elevation for each of the points provided. The computed elevation from the lidar surface was compared to the field collected elevation for representative performance of the lidar surface and processing. Of the 309 points, 33 are vegetated, and the remaining 176 are non-vegetated. Of those points, they were effectively spread throughout the project in clusters based on access. Most points were collected from boat with minimal hiking. Of the Non-vegetated points, 90% were within +/-0.2', with the remaining outliers contained within +/-0.32'. Of the Vegetated points, 90% were within +/-0.5', with the remaining outliers contained within +/-1.28'. 95% of the points are within 1' of the lidar surface. Many more QC points were collected; however not all the area was mapped this season. Of the collected points 40% of the points were collected on Bare Earth surfaces, 20% were forested, 14% were shrubs and low brush, 23% were grass and dense lower vegetation and 3% were urban. Very representative of the observed acquisition area.

A. William Stoll, PLS
Alaska Professional Land Surveyor No. 12041

April 30th 2020
Date

GLOSSARY

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

1.96 * RMSE Absolute Deviation: Value for which the data are within two standard deviations (approximately 95th percentile) of a normally distributed data set, based on the FGDC standards for Non-vegetated Vertical Accuracy (NVA) reporting.

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

> **Absolute Accuracy:** The vertical accuracy of lidar data is described as the mean and standard deviation (sigma σ) of divergence of lidar point coordinates from ground survey point coordinates. To provide a sense of the model predictive power of the dataset, the root mean square error (RMSE) for vertical accuracy is also provided. These statistics assume the error distributions for x, y and z are normally distributed, and thus we also consider the skew and kurtosis of distributions when evaluating error statistics.
>
> **Relative Accuracy:** Relative accuracy refers to the internal consistency of the data set; i.e., the ability to place a laser point in the same location over multiple flight lines, GPS conditions and aircraft attitudes. Affected by system attitude offsets, scale and GPS/IMU drift, internal consistency is measured as the divergence between points from different flight lines within an overlapping area. Divergence is most apparent when flight lines are opposing. When the lidar system is well calibrated, the line-to-line divergence is low (<10 cm).
>
> **Root Mean Square Error (RMSE):** A statistic used to approximate the difference between real-world points and the lidar points. It is calculated by squaring all the values, then taking the average of the squares and taking the square root of the average.

Data Density: A common measure of lidar resolution, measured as points per square meter.

Digital Elevation Model (DEM): File or database made from surveyed points, containing elevation points over a contiguous area. Digital terrain models (DTM) and digital surface models (DSM) are types of DEMs. DTMs consist solely of the bare earth surface (ground points), while DSMs include information about all surfaces, including vegetation and man-made structures.

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

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

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

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

Pulse Returns: For every laser pulse emitted, the number of wave forms (i.e., echoes) reflected back to the sensor. Portions of the wave form that return first are the highest element in multi-tiered surfaces such as vegetation. Portions of the wave form that return last are the lowest element in multi-tiered surfaces.

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

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

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

Native Lidar Density: The number of pulses emitted by the lidar system, commonly expressed as pulses per square meter.

Relative Accuracy Calibration Methodology:

Manual System Calibration: Calibration procedures for each mission require solving geometric relationships that relate measured swath-to-swath deviations to misalignments of system attitude parameters. Corrected scale, pitch, roll and heading offsets were calculated and applied to resolve misalignments. The raw divergence between lines was computed after the manual calibration was completed and reported for each survey area.

Automated Attitude Calibration: All data were tested and calibrated using TerraMatch automated sampling routines. Ground points were classified for each individual flight line and used for line-to-line testing. System misalignment offsets (pitch, roll and heading) and scale were solved for each individual mission and applied to respective mission datasets. The data from each mission were then blended when imported together to form the entire area of interest.

Automated Z Calibration: Ground points per line were used to calculate the vertical divergence between lines caused by vertical GPS drift. Automated Z calibration was the final step employed for relative accuracy calibration.

Lidar accuracy error sources and solutions:

Type of Error	Source	Post Processing Solution
GPS (Static/Kinematic)	Long Base Lines	None
	Poor Satellite Constellation	None
	Poor Antenna Visibility	Reduce Visibility Mask
Relative Accuracy	Poor System Calibration	Recalibrate IMU and sensor offsets/settings
	Inaccurate System	None
Laser Noise	Poor Laser Timing	None
	Poor Laser Reception	None
	Poor Laser Power	None
	Irregular Laser Shape	None

Operational measures taken to improve relative accuracy:

Low Flight Altitude: Terrain following was employed to maintain a constant above ground level (AGL). Laser horizontal errors are a function of flight altitude above ground (about 1/3000th AGL flight altitude).

Focus Laser Power at narrow beam footprint: A laser return must be received by the system above a power threshold to accurately record a measurement. The strength of the laser return (i.e., intensity) is a function of laser emission power, laser footprint, flight altitude and the reflectivity of the target. While surface reflectivity cannot be controlled, laser power can be increased and low flight altitudes can be maintained.

Reduced Scan Angle: Edge-of-scan data can become inaccurate. The scan angle was reduced to a maximum of ±29^{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.

APPENDIX B – DOWL GROUND SURVEY REPORT

GLACIER BAY LIDAR MAPPING SUPPORT

SE ALASKA GLAVIER BAY/GUSTAVUS, ALASKA
SURVEYING AND MAPPING REPORT

Prepared for:

Quantum Spatial Incorporated
2014 Merrill Field Drive
Anchorage, Alaska 99501

Prepared by:

DOWL
4041 B Street
Anchorage, Alaska 99503
(907) 562-2000

DOWL Project Number: 1127.63055.01

Field Project dates: July 22nd through July 28th, 2019

REPORT DATA AUGUST 12, 2019

GLACIER BAY LIDAR MAPPING SUPPORT JULY 2019

TABLE OF CONTENTS

LIST OF ACRONYMS

CORS .... Continuously Operating Reference Station
FBK.... Survey Digital Field Book File
GCP....Ground Control Point
GNSS ....Global Navigation Satellite System
LGO ....Leica Geo Office
NGS....National Geodetic Survey
NOAA ....National Oceanic and Atmospheric Administration
NPS .... National Park Service
NTP....Notice to Proceed
OPUS ....Online Positioning User Service
QC .... Quality Control
QSI ....Quantum Spatial Incorporated
RFP ....Request for Proposal
TBC....Trimble Business Center
USC&GS.... U.S. Coast & Geodetic Survey

HORIZONTAL & VERTICAL CONTROL SUMMARY

1.0 INTRODUCTION

This project consists of locating and establishing Ground Control Points (GCP), and Quality Control (QC) points throughout Glacier Bay, Alaska to support the Aerial Mapping being performed by Quantum Spatial Incorporated (QSI). DOWL was hired by QSI as the independent subconsultant to perform these services. Incidental to these services was also the recovery and establishing of survey control to perform the above described services. Numerous National Geodetic Survey (NGS) monuments, and National Oceanic and Atmospheric Administration (NOAA) benchmarks were recovered and included in our control network. QSI provided DOWL with a list and general area of the requested QC and GCP data sets, and efforts were made to collect data in those areas. In certain instances, with recommendation from the National Park Service (NPS), certain areas were moved to better fit environmental conditions and for safety reasons.

2.0 HORIZONTAL CONTROL SUMMARY

A field survey was performed by DOWL from July 22, 2019 through July 28, 2019, under the supervision of A. William Stoll, PLS #12041. Before mobilizing to the field, Willie performed a robust search of the NGS record to determine existing monuments near to the desired locations. A list was compiled of monuments that would be the static primary control points for this project. Also, a thorough review of the Continuously Operating Reference Stations (CORS) was reviewed to determine which would be beneficial to have in the record.

After careful reconnaissance and recovery of local control, it was decided that the optimal location for a DOWL project control station was at the park service building. A control station was established to effectively work as a CORS station while on site. The averaged data from three days of Global Navigation Satellite System (GNSS) was sent to the NGS Online Positioning User Service (OPUS). The results of the OPUS solutions were then averaged, and that position was held for all data processing. A GNSS network was processed using Leica Geo Office (LGO) minimally constrained to that OPSU solution. Independent OPUS solutions were also processed for 16 of the control stations within the network and those values were compared to the local LGO network. The mean of those 16 points was 0.006 meters, with a max value of 0.07 meters, minimum value of 0.05 meters and a 95% confidence interval of 0.02 meters.

3.0 HORIZONTAL CONTROL STATEMENT

COORDINATE SYSTEM:
Coordinates are NAD83(2011)(2010.0000) Alaska State Plane Zone 1 Meters. Coordinates are based on the average of three OPUS derived solutions at Control Point 1 . The averaged OPUS solution was held in a minimally constrained network adjustment.

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4.0 VERTICAL CONTROL SUMMARY

Elevations are NAVD88 as determined by Geoid 12B expressed in Meters. Elevations are based on the average of three OPUS derived solutions at Control Point 1. The averaged OPUS solution was held in a minimally constrained network adjustment.

5.0 QUALITY ASSURANCE

Quality Assurance (QA) methods and procedures outlined in the statement of services were reviewed with our staff and adhered to. Some examples of QA methods include the following:

- All equipment utilized during this project was checked for accuracy, and adjusted when necessary, prior to commencing any work.
- Redundant distance measurements were made in feet and meters.
- Tripods with optical plummet tribrachs or laser plummet tribrachs were used to set up over the points while measuring all control.
- For each conventional total station set up (FBK), and daily GPS RTK rover, check shots were taken on control points at the beginning, end, and periodically during each session or day.

6.0 SURVEYOR'S CERTIFICATION

I, A. William Stoll, Alaska Land Surveyor #12041, do hereby certify that the information contained herein is the result of work performed by me or by others working under my direct supervision.

A. William Stoll, PLS
Alaska Professional Land Surveyor No. 12041

April 28, 2020
Date

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Glacier_Bay_D1_NIR_lidar_Report_FINAL

Final Audit Report 2020-05-04

Created:	2020-05-04
By:	Steven Schuetz (sschuetz@quantumspatial.com)
Status:	Signed
Transaction ID:	CBJCHBCAABAAvyQ92tnYHWAXlHx7toWSy2SvCk3iCeNN

"Glacier_Bay_D1_NIR_lidar_Report_FINAL" History

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