July 21, 2020

Eklutna River Lidar and Imagery project

Technical Data Report

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CONTENTS

Cover Photo: View of the Eklutna Lake taken during acquisition of spherical imagery and 4K video footage.

INTRODUCTION

This photo taken by DOWL survey staff shows a photo control point taken on the corner of a footbridge within the Eklutna River Lidar and Imagery project site.

In the spring of 2020, Quantum Spatial was contracted by McMillen Jacobs Associates to collect Light Detection and Ranging (lidar) data and digital video and imagery in May 2020 for the Eklutna River Lidar and Imagery project site in southern Alaska. Data were collected to aid the client in assessing the topographic and geophysical properties of the study area to support their efforts in restoring fish habitat on the Eklutna River.

This report accompanies the delivered lidar data, video, and imagery products, 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 McMillen Jacobs Associates is shown in Table 2, and the project extent is shown in Figure 1.

Table 1: Acquisition dates, acreage, and data types collected of the Eklutna River Lidar and Imagery project site

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
Eklutna River Lidar and Imagery project	6,487	8,129	5/15/2020	LiDAR
			5/27/2020	3- band (RGB) Digital Imagery
			5/30/2020	High Definition 4k Video
			5/30/2020	Immersive 360˚ Spherical Imagery

Table 2: Products delivered to McMillen Jacobs Associate for the Eklutna River Lidar and Imagery project site

Eklutna River Lidar & Imagery Products Projection: UTM Zone 6 North Horizontal Datum: NAD83 (2011) Vertical Datum: NAVD88 (GEOID12B) Units: Meters	
Points	LAS v 1.4 • All Classified Returns • Classified Ground Returns
Rasters	0.5 Meter GeoTIFFs • Bare Earth Digital Elevation Model (DEM) • Highest Hit Digital Surface Model (DSM)
Vectors	Shapefiles (*.shp) • Survey Boundary • Tiling Delineations • Flight Index
Digital Imagery/Videography	15 Centimeter GeoTIFFs • Imagery Mosaics (RGB) MPEG • High Definition 4k Video MapPro360 • Immersive 360˚ Spherical Imagery TIFF • Individual Historical Film Scans

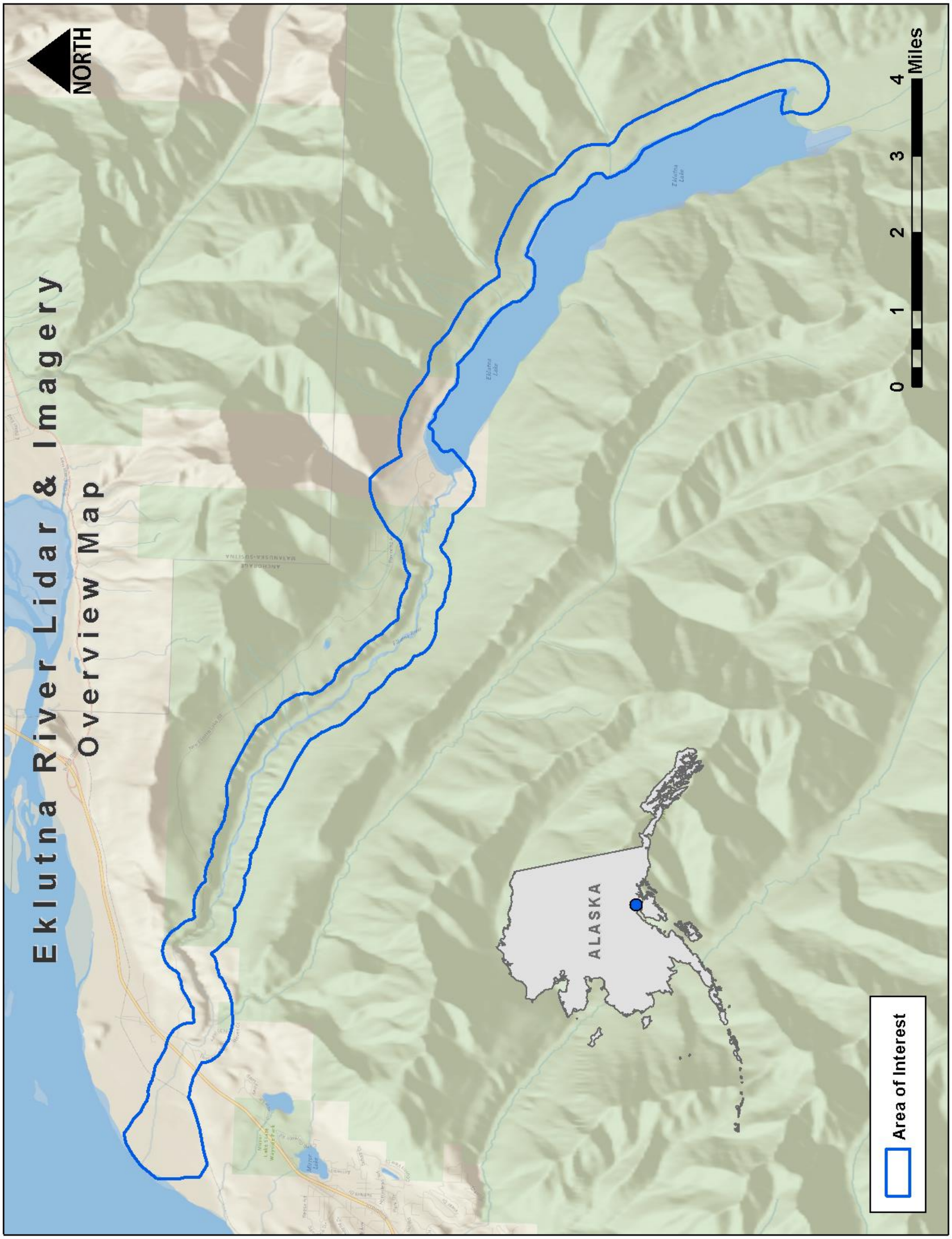


Figure 1: Location map of the Eklutna River Lidar and Imagery project site in southern Alaska

ACQUISITION

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 Eklutna River Lidar and Imagery project study area at the target point density of ≥20.0 points/m^2. Acquisition parameters including orientation relative to terrain, flight altitude, pulse rate, scan angle, and ground speed were adapted to optimize flight paths and flight times while meeting all contract specifications.

Factors such as satellite constellation availability and weather windows must be considered during the planning stage. Any weather hazards or conditions affecting the flight were continuously monitored due to their potential impact on the daily success of airborne and ground operations. In addition, logistical considerations including private property access 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 ≥20 pulses/m^2 over the Eklutna River Lidar and Imagery 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	May 15, 2020
Aircraft Used	Cessna Caravan 208B
Sensor	Leica ALS80
Maximum Returns	Unlimited
Resolution/Density	Average 20 pulses/m^2
Nominal Pulse Spacing	0.3 m
Survey Altitude (AGL)	1270 m
Survey speed	105
Field of View	28º
Mirror Scan Rate	59.7 Hz
Target Pulse Rate	449.8 kHz
Laser Pulse Footprint Diameter	32 cm
Pulse Mode	Multiple Pulses in Air (MPiA)
Swath Width	633.29 m
Swath Overlap	60%


Leica ALS80 lidar sensor

All areas were surveyed with an opposing flight line side-lap of ≥60% (≥100% overlap) 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.

Digital Imagery

Aerial imagery was collected using an UltraCam Eagle M3 megapixel digital camera (Table 4) mounted in a Cessna Caravan. The UltraCam Eagle M3 is a large format digital aerial camera manufactured by Vexcel (formerly 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 M3	
Focal Length	80 mm
Data Format	RGB
Pixel Size	5.2 μm
Image Size	20,010 x 13,080 pixels
Frame Rate	1.8 seconds
FOV	60° x 30°

For the Eklutna River Lidar and Imagery project site, images were collected in four spectral bands (red, green, blue, and NIR) with 60% along track overlap and 30% side lap between frames. The acquisition flight parameters were designed to yield a native pixel resolution of 15 cm. Orthophoto specifications specific to the Eklutna River Lidar and Imagery project area in Table 5.

Table 5: Project-specific orthophoto specifications

Digital Orthophotography Specifications	
Equipment	UltraCam EagleM3
Spectral Bands	Red, Green, Blue
Resolution	15 cm pixel size
Along Track Overlap	≥60%
Flight Altitude (MSL)	3,000 meters
GPS Baselines	≤25 nm
GPS PDOP	≤3.0
GPS Satellite Constellation	≥6
Horizontal Accuracy	2 ft
Image	8-bit GeoTiff

360 Degree Spherical Imagery and 4k Video

360-degree perspective high resolution spherical imagery and video were collected on May 30, 2020.

The Garmin camera system was mounted on a Bell 206L-3 helicopter and collected from an approximate height of 300 feet above ground moving east to west as well as 100 feet above ground level where permissible for safety flying west to east.

The video was captured at 4k resolution using a camera array which captures overlapping look angles that are then blended together using proprietary software. The resulting product is a video in mp4 format; the user may pan within the video play to view continuous multiple perspectives as the video plays. The spherical video was also delivered within the MapPro360 online viewer. The MapPro360 viewer features video playback as well as an inset active map location (https://biglook360.com/eklutna/).

Table 6: Project-specific spherical imagery & 4K Video specifications

360 Degree Spherical Video and Imagery Specifications	
Camera System Mount	Insta 360 camera & VRIB360 camera
Helicopter	Bell 206L-3
Video Resolution	5760*2880 @ 30 fps
Format	Mp4 LOG
Video Coding	H264
Video Bitrate	120 Mbps

Figure 2: Screen capture showing 4K video footage of the Eklutna River viewed using the MapPro360 software.

Ground Survey


Control station established at Eklutna Lake

Ground control surveys, including monumentation, aerial targets and ground control points (GCPs) were conducted by A. William Stoll (AK PLS# 12041) with 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 and digital imagery products. Please see Figure 3 for distribution of ground control points, as well as locations of selected Continuously Operating Reference Stations (CORS); see Table 7 for CORS positions. CORS provided redundant control within the mission areas for LiDAR flights, and were also used for collection of ground survey points collected. Please see "Certifications" section for the Survey and Mapping Report provided by DOWL.

Table 7: CORS positions for the Eklutna River Lidar and Imagery project acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

CORS ID	Latitude	Longitude	Ellipsoid (meters)
AC48	60° 38' 45.10436"	-147° 20' 34.77058"	379.15
AC51	61° 29' 53.10299"	-151° 50' 07.16141"	956.91
AC79	59° 59' 52.32591"	-147° 24' 10.87112"	287.80

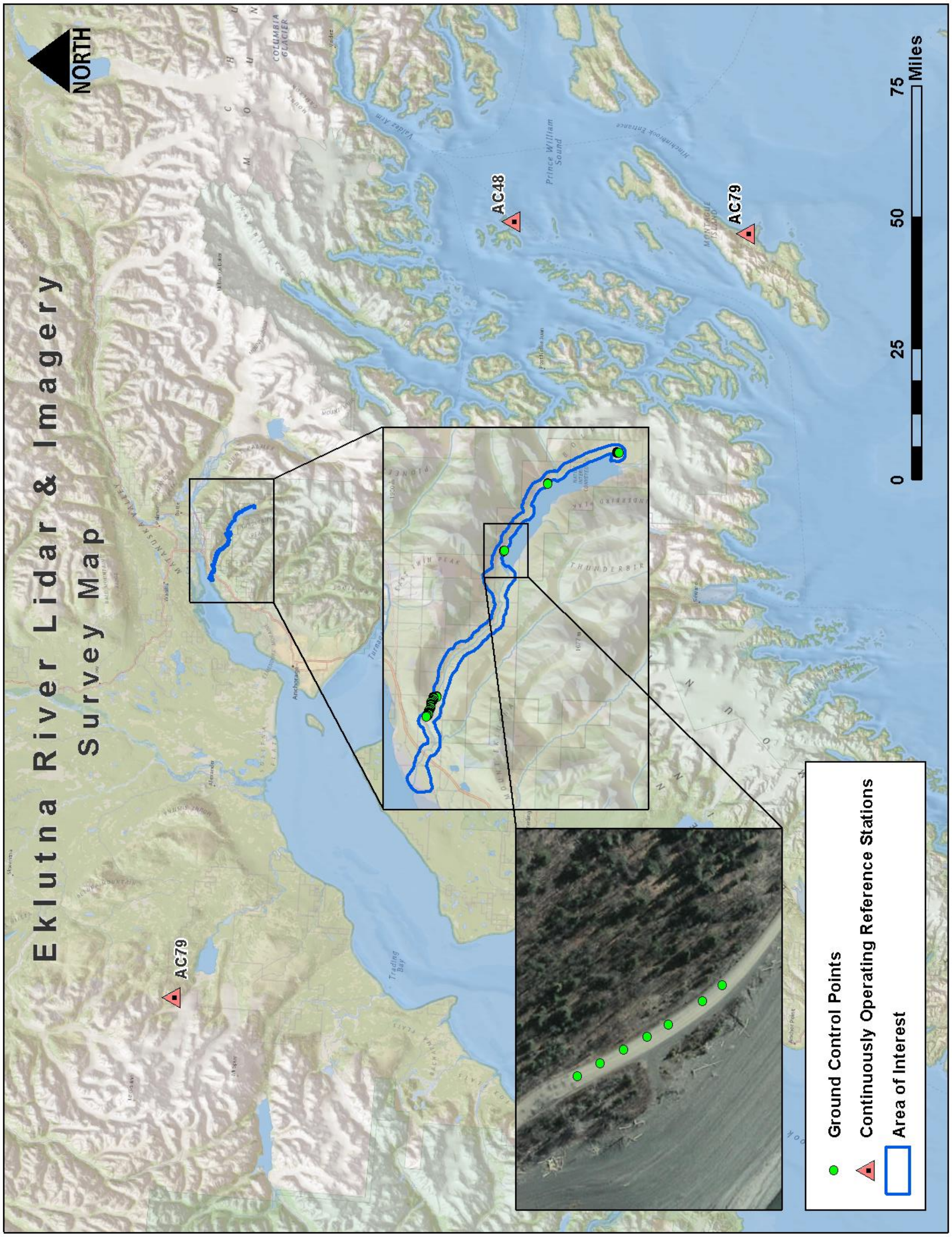
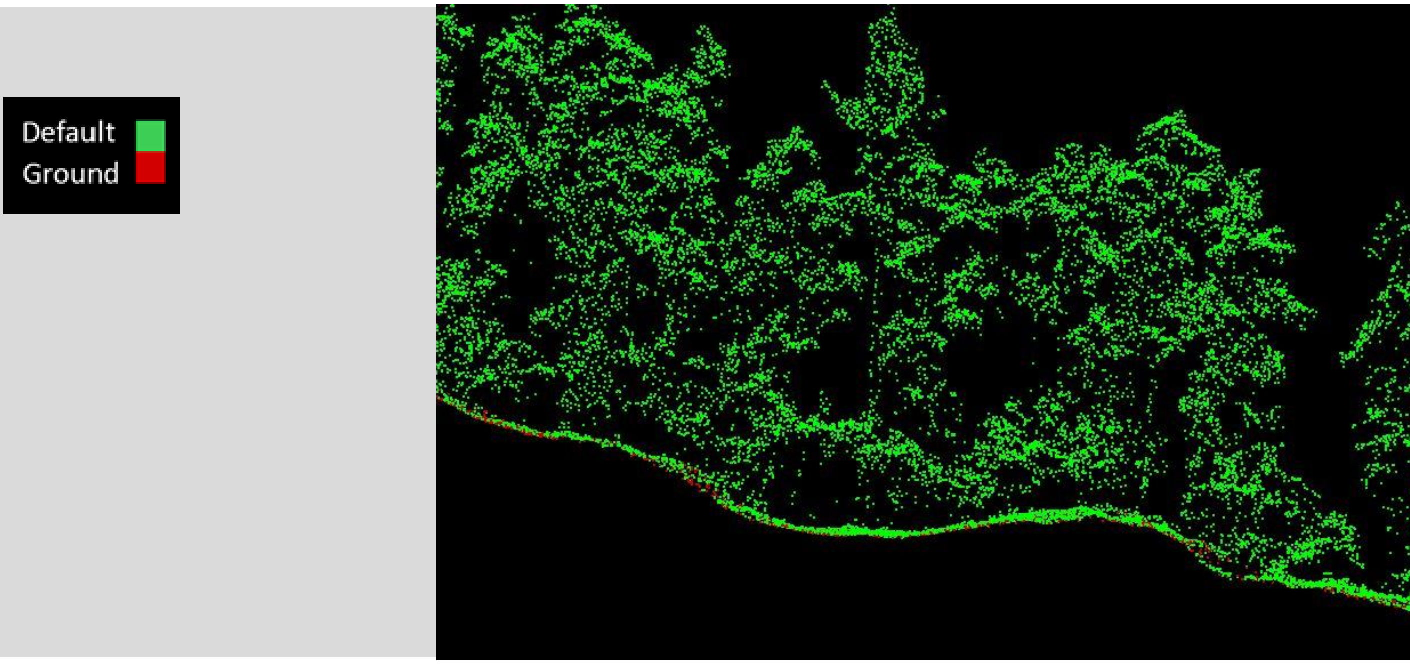


Figure 3: Ground survey location map

PROCESSING



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

Table 8: ASPRS LAS classification standards applied to the Eklutna River Lidar and Imagery project 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

Table 9: 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
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 Leica CloudPro
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
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
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 TerraModeler
Generate bare earth models as triangulated surfaces. Generate highest hit models as a surface expression of all classified points. Export all surface models as GeoTIFFs (.tif) format at a 15-centimeter pixel resolution.	TerraScan TerraModeler ArcMap

Digital Imagery

As with the lidar, the collected digital imagery went through multiple processing steps to create final imagery products. Initially, image radiometric values were calibrated to specific gain and exposure settings. Photo position and orientation were then calculated by linking the time of image capture to the smoothed best estimate of trajectory (SBET) file created during lidar post-processing. Within Leica Photogrammetry Suite (LPS), an automated aerial triangulation was performed to tie images together and adjust the photo block to align with ground control.

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. The processing workflow for orthophotos is summarized in Table 6.

Table 6: Orthophoto processing workflow

Orthophoto Processing Step	Software Used
Resolve GPS kinematic corrections for the aircraft position data using kinematic aircraft GPS (collected at 2 HS) and static ground GPS (1 Hz) data collected over geodetic controls.	POSPac MMS v. 7.2
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. 7.2
Create an exterior orientation file (EO) for each photo image with omega, phi, and kappa.	POSPac MMS v. 7.2
Convert Level 00 raw imagery data into geometrically corrected Level 02 image files.	UltraMap 2.3.2
Apply radiometric adjustments to Level 02 image files to create Level 03 Pan-sharpened TIFFs.	UltraMap 2.3.2
Apply EO to photos, measure ground control points and perform aerial triangulation.	Inpho Match-AT 8.0.6
Import DEM, orthorectify and clip triangulated photos to the specified area of interest.	Inpho OrthoMaster 8.0.6
Mosaic orthorectified imagery, blending seams between individual photos and correcting for radiometric differences between photos.	Inpho OrthoVista 8.0.6

Historical Film Scans

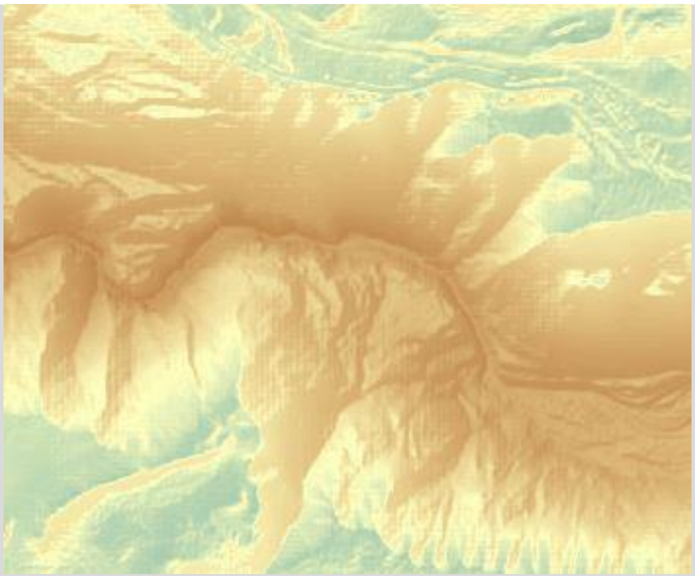
Through Quantum Spatial's legacy companies in Alaska, a large archive of vertical and oblique aerial imagery is available. The following table lists archived aerial imagery relevant to the Eklutna River study area which were delivered as part of this project. See Table 11 for delivered historical film scans.

Table 11: Historical film scans delivered as part of the Eklutna River Lidar and Imagery Project

Content	Date	Year	Scale	Number of Frames
Eklutna Lake Oblique view	9/10	1939	N/A	2
Eklutna River, Eklutna Lake, Eklutna Glacier	8/2, 8/7	1950	1" = 3,333'	4
Eklutna River, Eklutna Lake, Eklutna Glacier	7/12, 7/29	1957	1" = 3,500'	5
Eklutna Lake	6/11	1962	1" = 1,000'	8
Eklutna River and part of Eklutna Lake	8/31	1962	1" = 1,667'	5
Eklutna River, Eklutna Lake, Eklutna Glacier	7/9	1963	1" = 1,800'	11
Site specific airstrip	7/9	1963	1" = 250'	3
Eklutna Lake	6/11	1965	1" = 1,000'	7
Eklutna River, Eklutna Lake	9/16	1969	1" = 2,000'	12
Site specific recreational sites	10/21	1963	1" = 250"	6

Figure 4: Oblique view of Eklutna Lake from historical film archives (9/10/1939).

This image shows a top down view of a portion of the Eklutna River within the project area. The image was created from the LiDAR bare earth model colored by elevation.



Lidar Density

The acquisition parameters were designed to acquire an average first-return density of 20 points/m^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 Eklutna River Lidar and Imagery project was 45.99 points/m^2 while the average ground classified density was 4.99 points/m^2 (Table 2). The statistical and spatial distributions of first return densities and classified ground return densities per 300 m x 300 m cell are portrayed in Figure 5 through Figure 7.

Table 12: Average lidar point densities

Classification	Point Density
First-Return	45.99 points/m^2
Ground Classified	4.99 points/m^2

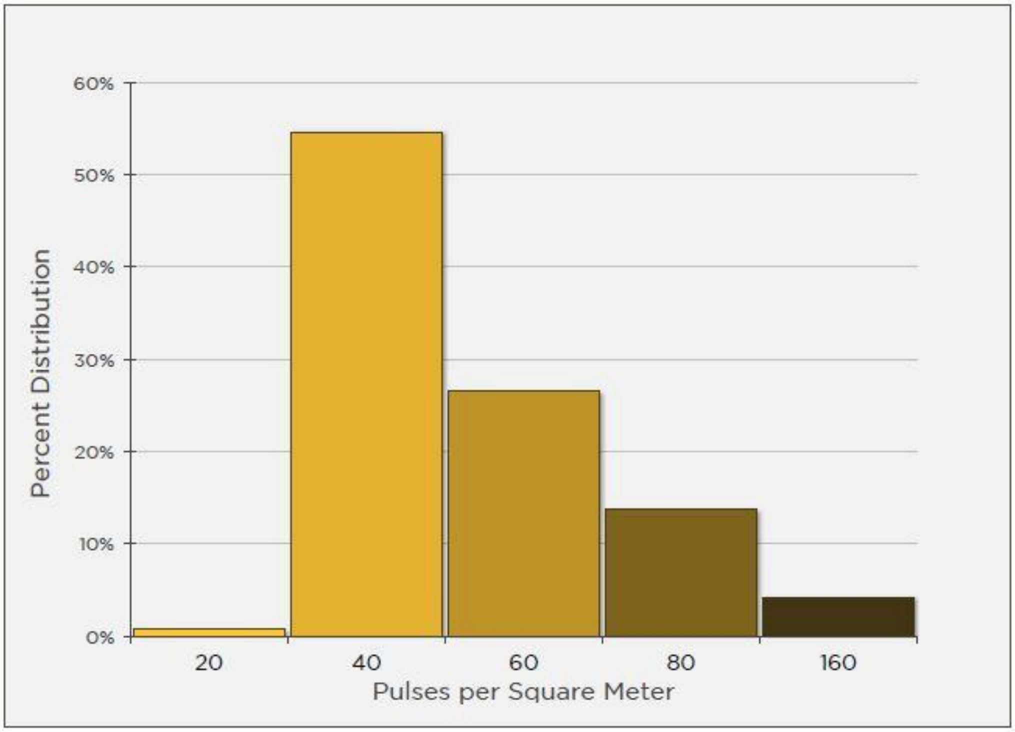


Figure 5: Frequency distribution of first return point density values per 300 x 300 m cell

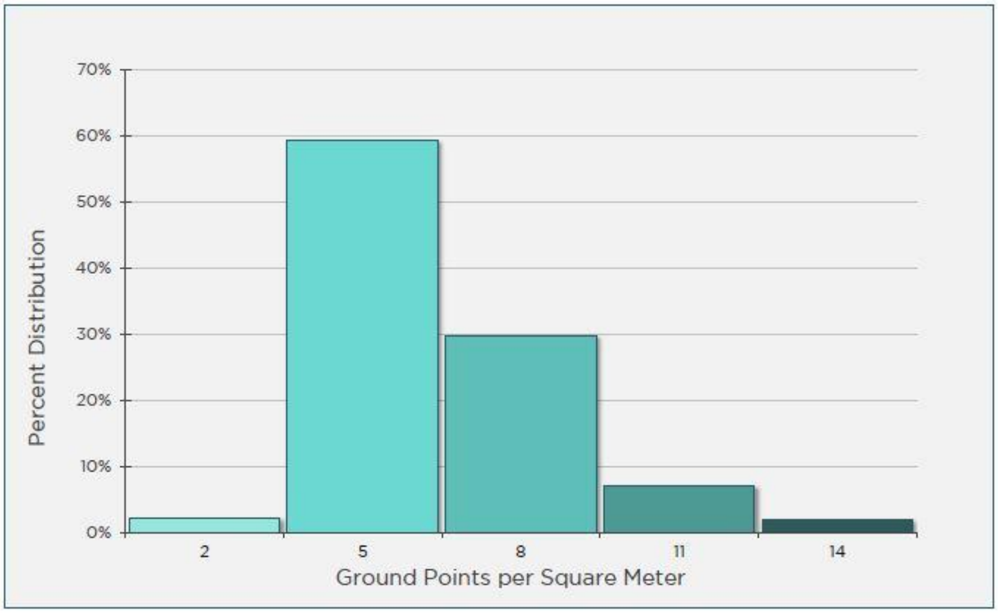
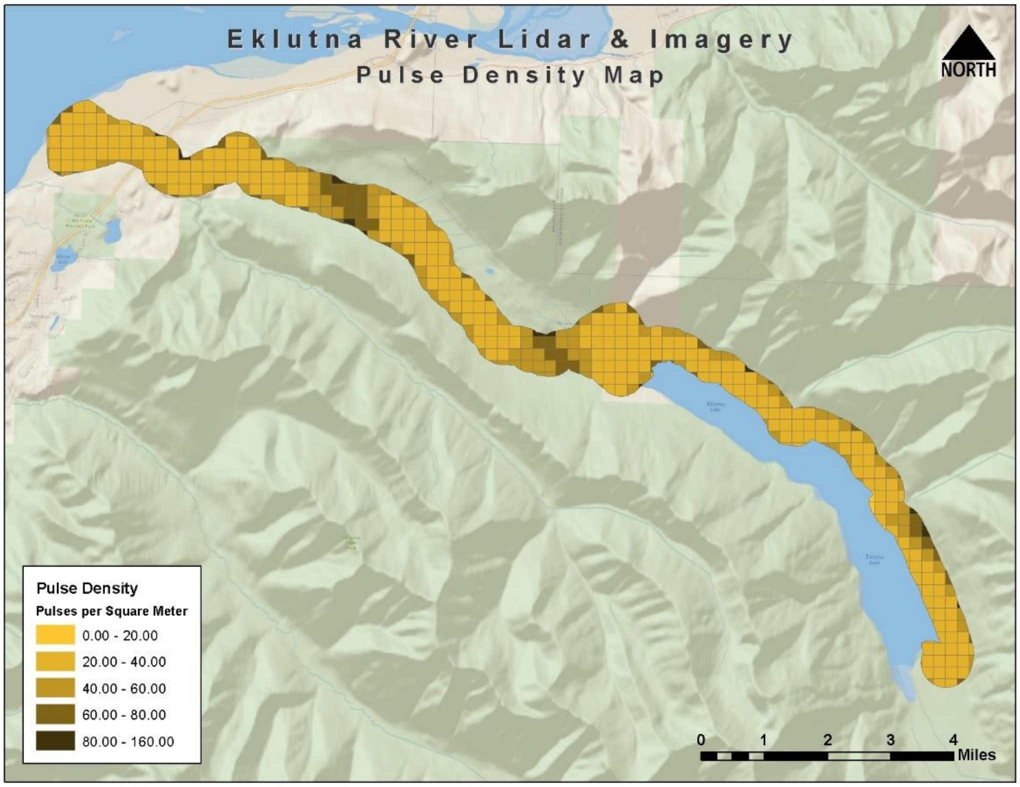


Figure 6: Frequency distribution of ground-classified return point density values per 300 x 300 m cell



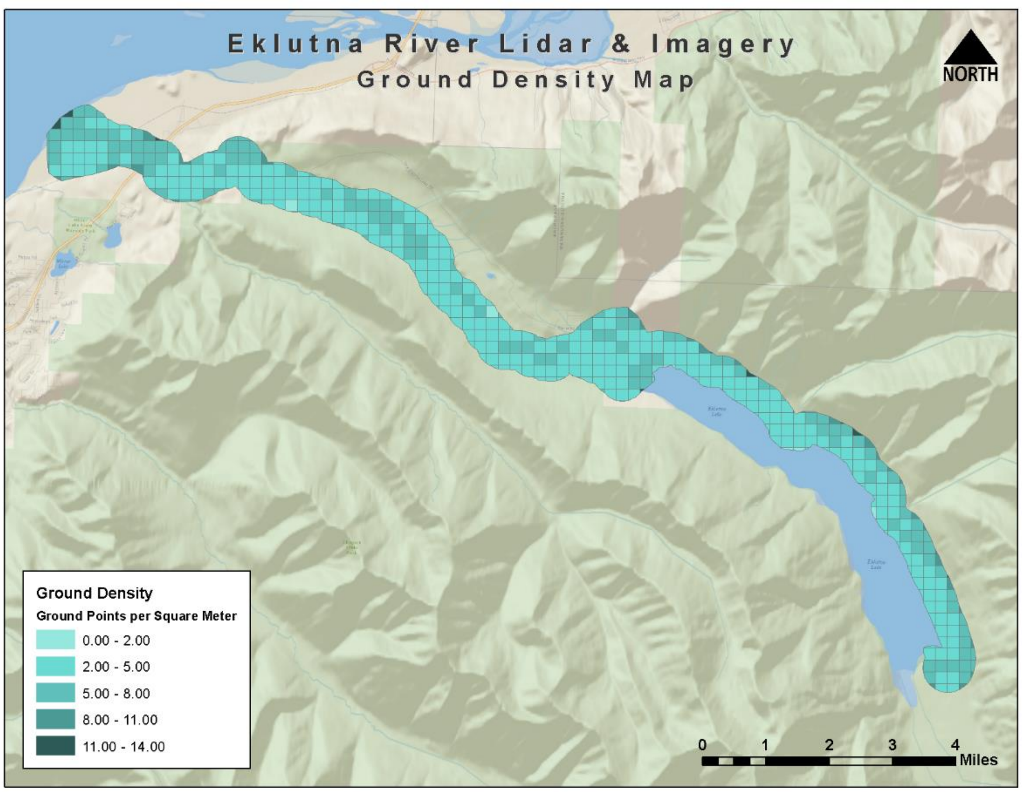


Figure 72: Ground-classified and first return point density map for the Eklutna River Lidar and Imagery site (300m x 300m cells)

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 to the triangulated surface generated by the unclassified lidar point cloud. 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 73. The mean and standard deviation (sigma σ) of divergence of the ground surface model from ground survey 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 Eklutna River Lidar and Imagery project survey, a sufficient number of reserved ground survey points were not available for testing; therefore 52 ground control points were used to asses and report NVA as "compiled to meet" (Table 13, Figure 8). 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 13 and Figure 8.

Table 73: Absolute accuracy results

Absolute Vertical Accuracy	
Ground Control Points	
Sample	52 points
95% Confidence (1.96*RMSE)	0.052 m
Average	0.019 m
Median	-0.002 m
RMSE	0.027 m
Standard Deviation (1σ)	0.019 m

[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.

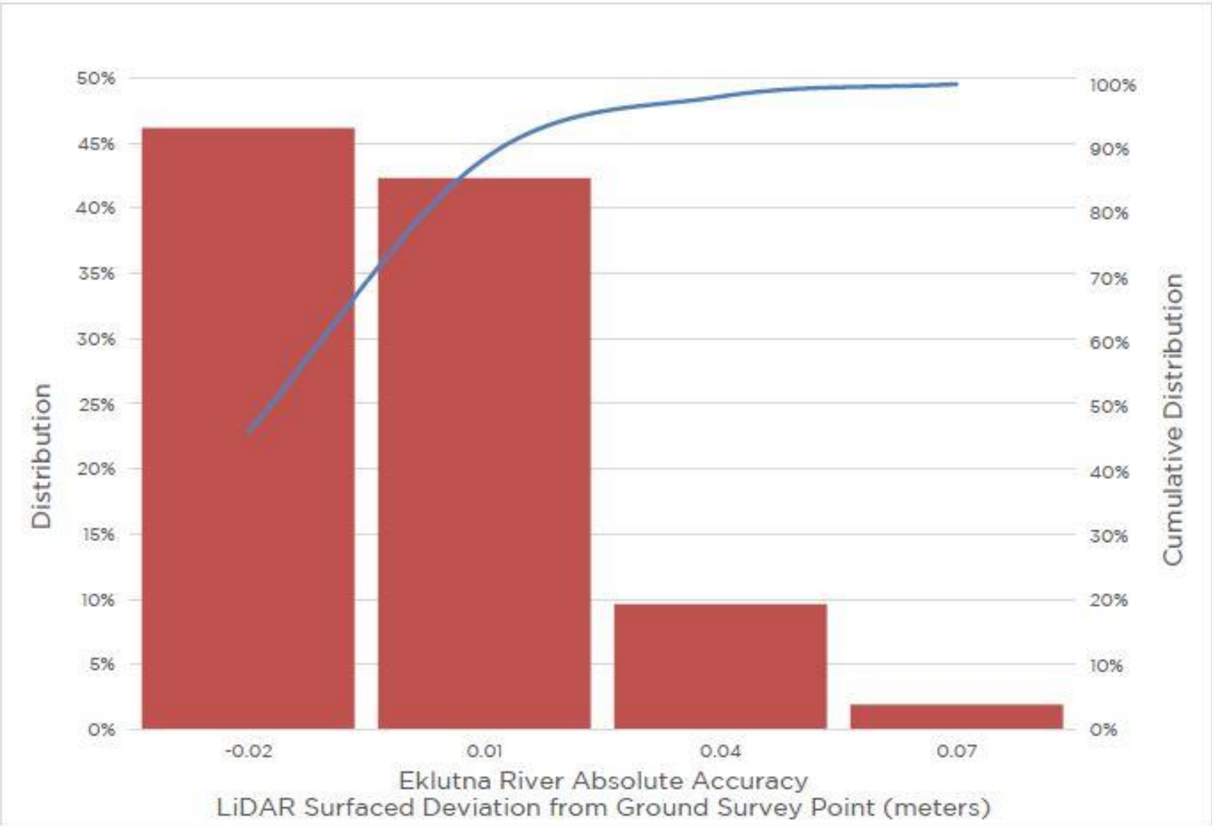


Figure 8: Frequency histogram for lidar bare earth DEM surface deviation from ground check point values (NVA)

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 Eklutna River Lidar and Imagery project Lidar project was 0.036 meters, or 0.118 feet (Table 14, Figure 9).

Table 14: Relative accuracy results

Relative Accuracy	
Sample	44 surfaces
Average	0.118 ft 0.036 m
Median	0.119 ft 0.036 m
Standard Deviation (1σ)	0.122 ft 0.037 m

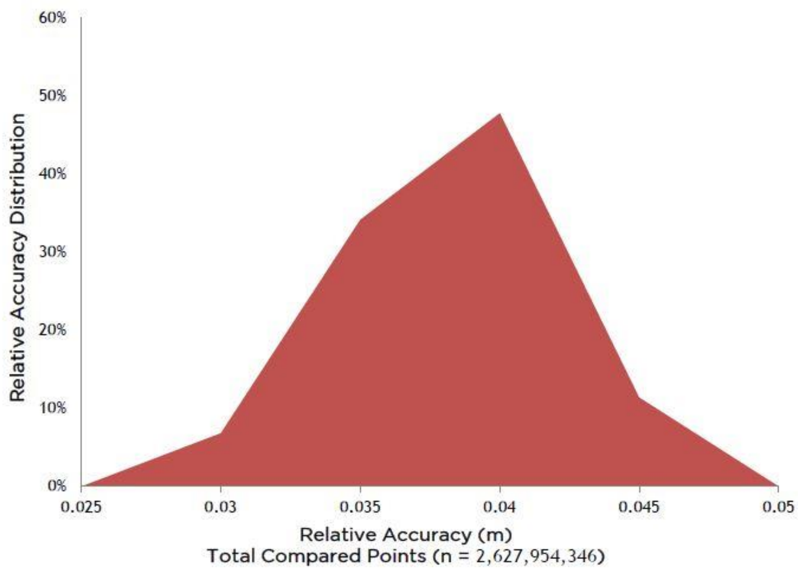


Figure 3: Frequency plot for relative vertical accuracy between flight lines

Digital Imagery Accuracy Assessment

Image accuracy was measured by air target location. Air target GPS points were measured against the placement of the air target in the imagery.

The horizontal accuracy specification for this project was 2.00 feet, or 0.610 meters $RMSE_h$; Quantum Spatial achieved an $RMSE_h$ of 0.19 feet, or 0.058 meters.

Error! Reference source not found. 20 presents the complete photo accuracy statistics; Figure 21 contains a scatterplot showing congruence between orthophotos in aerial target locations and corresponding GPS point measurements.

Figure 10: Orthophotography accuracy statistics for Eklutna River Lidar and Imagery project Accuracy results are in meters.

Error Statistics

Min ΔX:	-0.064	CE 95:	0.089
Min ΔY:	-0.011	Skew ΔX:	-0.595
Max ΔX:	0.021	Skew ΔY:	-0.199
Max ΔY:	0.074	Horiz. Bias:	0.033
Mean ΔX:	-0.009	SRMSE H:	0.014
Mean ΔY:	0.032	CI:	0.027
RmseX:	0.031		
RmseY:	0.049		
RmseH:	0.058		
NSSDA:	0.101		
No. Obs.:	7		
SX:	0.032		
SY:	0.041		
SH:	0.036		
CE 90:	0.078		

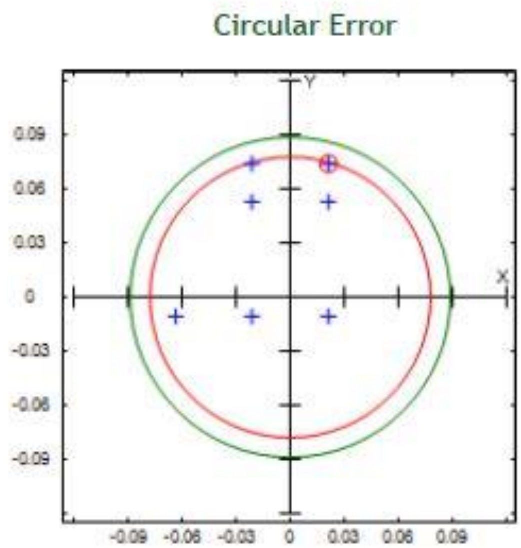


Figure 4: Image displaying the co-registration between the lidar intensity image and the orthophoto at a location within the Eklutna River Lidar and Imagery project site; values are in meters.

CERTIFICATIONS

EKLUTNA LAKE LIDAR AND IMAGERY MAPPING SUPPORT

EKLUTNA, ALASKA
SURVEYING AND MAPPING REPORT

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DOWL Project Number: 1127.63211.01

Field Project dates: May 16th through May 17th, 2020

REPORT DATA MAY 20TH, 2020

EKLUTNA LAKE LIDAR AND IMAGERY MAPPING SUPPORT

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 Photo ID panels and locating Ground Control Points (GCP) around Eklutna Lake and the Eklutna river 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. QSI provided DOWL with a list and general area of the requested Photo ID and GCP data sets, and efforts were made to collect data in those areas. Limited changes were made to their plan.

2.0 HORIZONTAL CONTROL SUMMARY

A field survey was performed by DOWL from May 16th through May 17th, 2020, by 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. Also, a thorough review of the Continuously Operating Reference Stations (CORS) was reviewed to determine which would be beneficial to have in the record. It was determined that local control was the best option for this project

A control station was established at Eklutna Lake, another mid-way along the Eklutna River, and a third at the Photo ID point near the Old Glenn intersection with the Eklutna River. Global Navigation Satellite System (GNSS) data was collected on both end points and sent to the NGS Online Positioning User Service (OPUS). The result of the OPUS solution at the control station at the Lake was held for all data processing. The second OPUS solution was used as verification of the initial control station. A GNSS network was processed using Leica Geo Office (LGO) minimally constrained to that OPSU solution.

3.0 HORIZONTAL CONTROL STATEMENT

COORDINATE SYSTEM:
Coordinates are NAD83(2011)(2010.0000) Alaska State Plane Zone 4 US Feet. Coordinates are based on an OPUS solution at Control Point 401. The OPUS solution was held in a minimally constrained network adjustment.

4.0 VERTICAL CONTROL SUMMARY

Elevations are NAVD88 as determined by Geoid 12B expressed in US Feet. Elevations are based on an OPUS solution at Control Point 401. The OPUS solution was held in a minimally constrained network adjustment.

EKLUTNA LAKE LIDAR AND IMAGERY MAPPING SUPPORT

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.

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

May 19, 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.

Appendix A - Accuracy Controls

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 ±14^{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.