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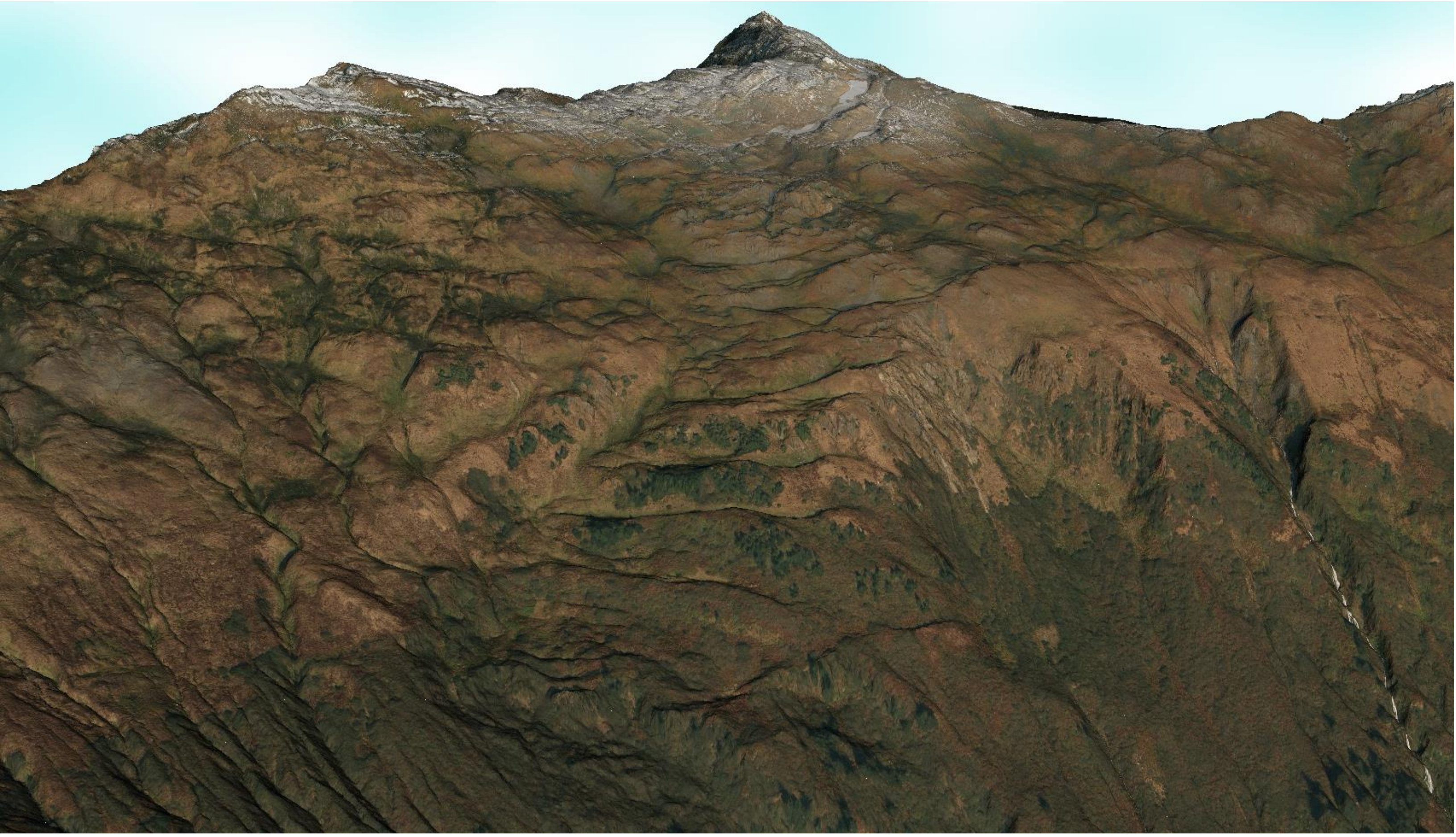

Juneau Landslide, Alaska 2021

Lidar Technical Data Report

Task Order: 140G0221F0157
Project ID: 0040535274

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Work Unit ID: 221068

Prepared For:

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Cover Photo: A view looking toward a slumping hillslope in the Juneau Landslide project area above Salmon Creek. The image was created from the lidar bare earth model colored by publicly available NAIP imagery.

Introduction

This photo taken by DOWL surveying staff shows a view of the Survey Equipment set up within the Juneau Landslide project area in Alaska.

In June 2021, NV5 Geospatial (NV5) was contracted by the United States Geological Survey (USGS) to collect high resolution QL0 lidar data in the summer of 2021 for the Juneau Landslide site in southeast, Alaska. The Juneau Landslide project area covers approximately 17 square miles near Juneau, Alaska, and includes the Bartlett Regional Hospital, as well as the Salmon Creek Reservoir and Dam. Data were collected to aid USGS, the Alaska Light and Power Company (AELP), and the City and Borough of Juneau in conducting landslide assessments and planning for buttressing of these critical resources within the project area, in addition to supporting the 3DEP mapping initiative.

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, and the project extent is shown in Figure 1.

Table 1: Acquisition dates, acreage, and data types collected on the Juneau Landslide site

Project Site	Project Size	Acquisition Dates	Data Type
Juneau Landslide, Alaska 2021	11,066 acres	06/28/2021, 08/21/2021 - 08/22/2021	QL0 Topographic Lidar

Deliverable Products

Table 2: Products delivered to USGS for the Juneau Landslide site

Juneau Landslide, Alaska 2021 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 • Hydroflattened Bare Earth Digital Elevation Model (DEM) • Maximum Surface Height Model (DSM) • Swath Separation Images • Intensity Images
Vectors	ESRI Geodatabase (*.gdb) • Defined Project Area • Lidar Tile Index • 3D Water's Edge Breaklines • 3D Bridge Breaklines • Ground Survey Data • Flightline Swath Shapes • Flightline Index

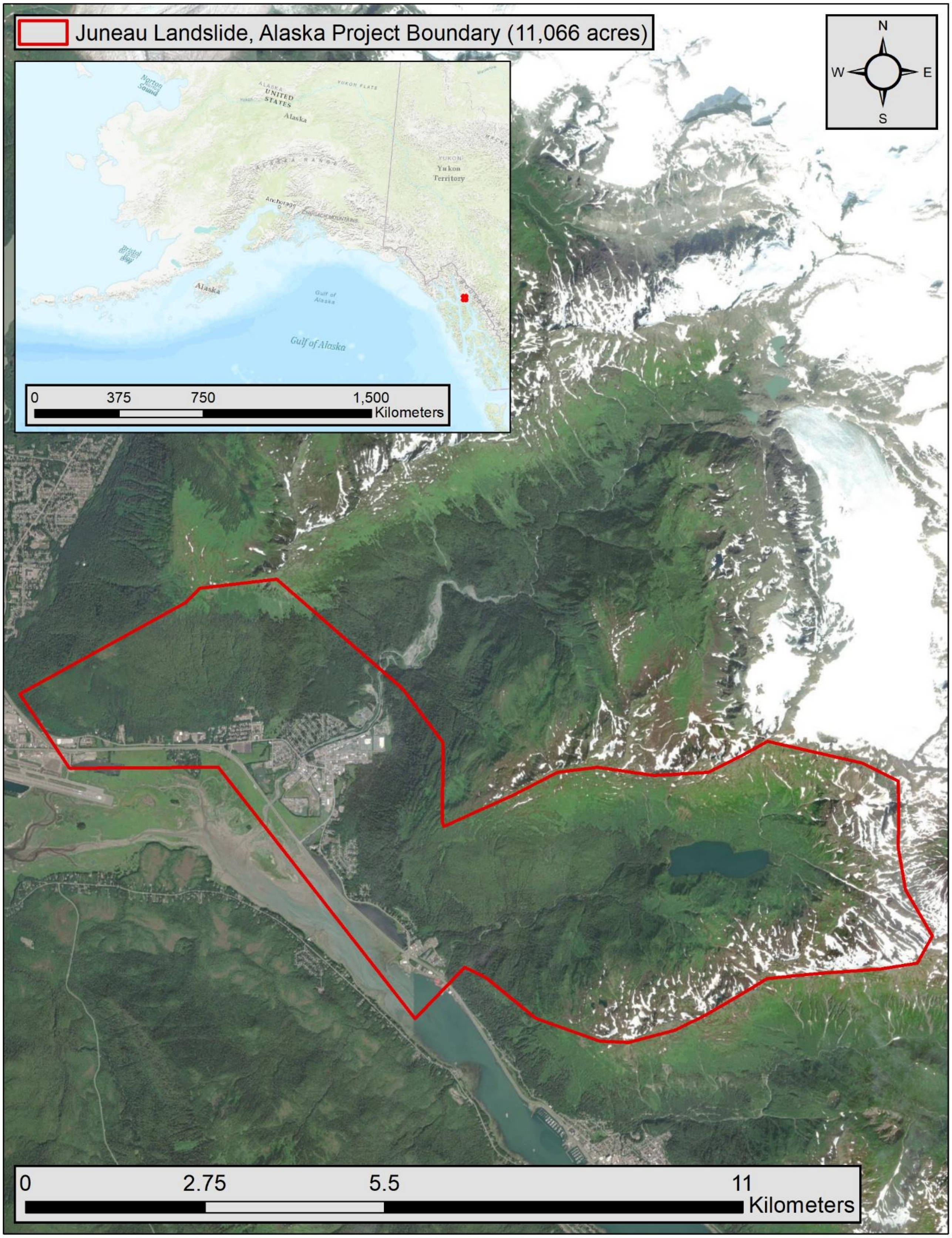
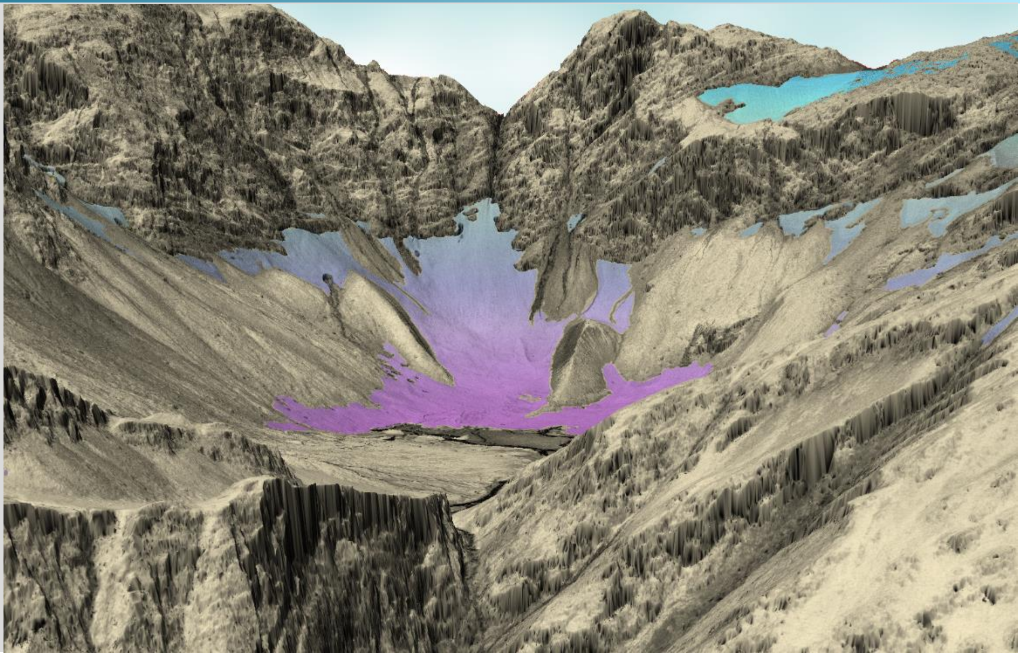


Figure 1: Location map of the Juneau Landslide site in Alaska

A view looking southwards towards the mountains above Salmon creek reservoir highlighting Snow classified LAS points. This image was created using the bare earth surface model and colored by elevation.



Planning

In preparation for data collection, NV5 Geospatial closely reviewed the project area and developed specialized flight and ground survey plans to ensure complete coverage of the Juneau Landslide study area at the target point density of ≥12.0 points/m^2 (ANPS ≤0.289 meters) to ensure that the data met USGS QL0 standards. 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 flights were continuously monitored due to their potential impact on the daily success of airborne and ground operations. Due to weather conditions in the state of Alaska, data acquisition for the Juneau Landslide project began in June and was ultimately completed in late August 2021. 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 VQ-1560ii system mounted in a Cessna Caravan. Table 3 summarizes the settings used to yield an average pulse density of ≥12 pulses/m^2 over the Juneau Landslide project area. The Riegl VQ-1560ii laser system can record unlimited range measurements (returns) per pulse, however a maximum of 15 returns can be stored due to LAS v1.4 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	06/28/2021, 08/21/2021, 08/22/2021
Aircraft Used	Cessna Caravan
Sensor	Riegl
Laser	VQ-1560ii
Maximum Returns	15
Resolution/Density	Average 12 pulses/m^2
Nominal Pulse Spacing	0.289 m
Survey Altitude (AGL)	1,200 m
Survey speed	145 knots
Field of View	58.5º
Mirror Scan Rate	Uniform Point Spacing
Target Pulse Rate	1096 kHz
Pulse Length	3.0 ns
Laser Pulse Footprint Diameter	30 cm
Central Wavelength	1064 nm
Pulse Mode	Multiple Times Around (MTA)
Beam Divergence	0.25 mrad
Swath Width	1,344 m
Swath Overlap	55%
Intensity	16-bit
Vertical Accuracy (QL0)	$RMSE_Z$ (Non-Vegetated) ≤ 5 cm
	NVA (95% Confidence Level) ≤ 9.8 cm
	VVA (95^{th} Percentile) ≤ 15 cm

Riegl VQ-1560ii lidar sensor

All areas were surveyed with an opposing flight line side-lap of ≥50% (≥100% overlap) in order to reduce laser shadowing and increase surface laser painting. To accurately solve for laser point position (geographic coordinates x, y and z), the positional coordinates of the airborne sensor and the attitude of the aircraft were recorded continuously throughout the lidar data collection mission. Position of the aircraft was measured twice per second (2 Hz) by an onboard differential GPS unit, and aircraft attitude was measured 200 times per second (200 Hz) as pitch, roll and yaw (heading) from an onboard inertial measurement unit (IMU). To allow for post-processing correction and calibration, aircraft and sensor position and attitude data are indexed by GPS time.

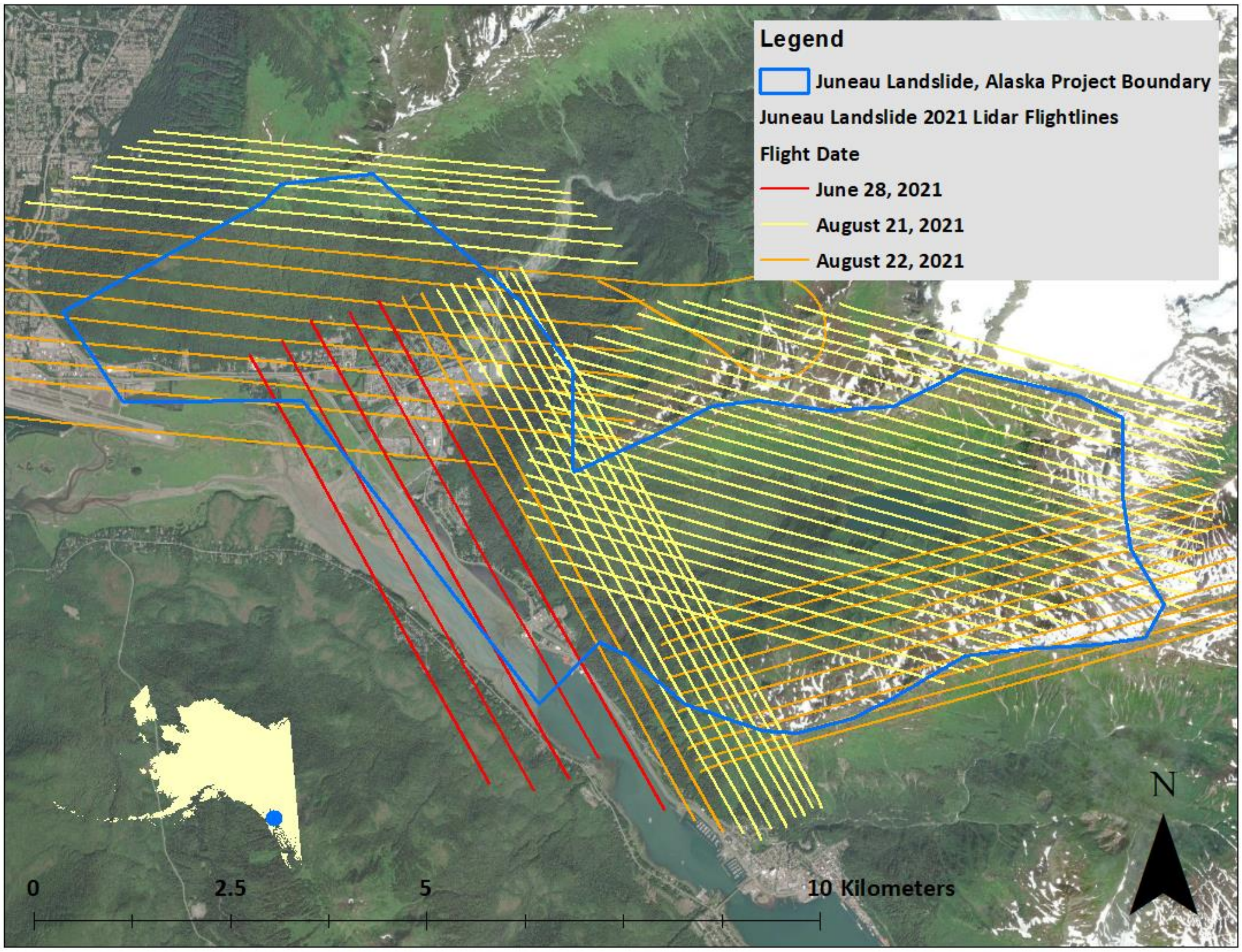


Figure 2: Juneau Landslide, Alaska Lidar Flightline Map

Data users should be mindful of overlap areas between the June and August collection dates. The temporal offset point classification (Class 22) was used to denote changes of the water and ground surfaces in this area due to melting snow piles, intermittent construction projects, and large vegetation changes. Nevertheless, lingering small scale offsets may be observed in this area due to differing grass or other minor vegetation height changes. These small-scale changes are acceptable variations in the data over a three-month collection period.

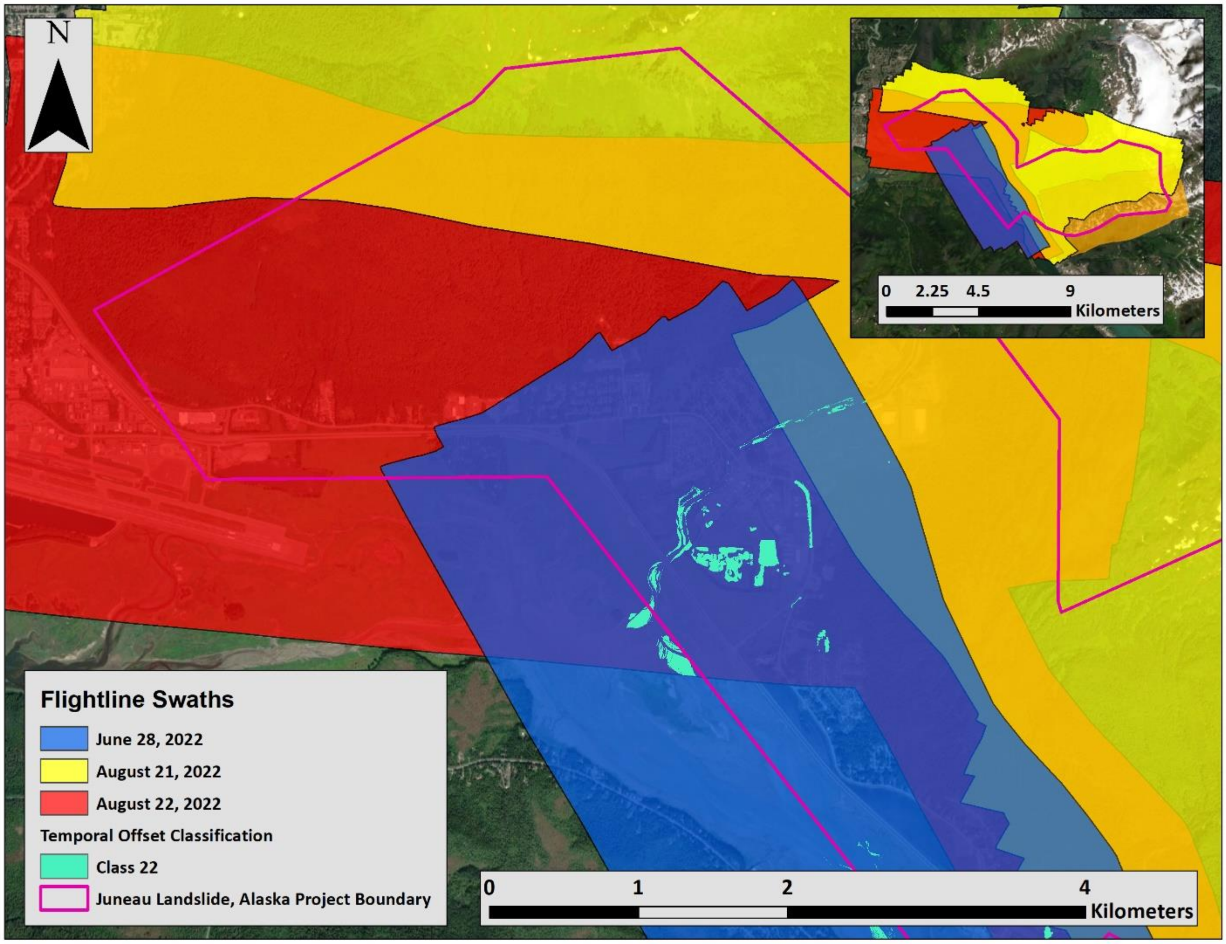


Figure 3: Redelivery area displaying temporal offsets areas

Ground Survey

Ground control surveys, including monumentation and ground survey points (GSPs) were conducted by DOWL[1] 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. Please see the included Juneau USGS Lidar Mapping Report provided by DOWL for more information regarding the ground survey.

Base Stations

Base stations were utilized for the collection of ground survey points by DOWL. Base station locations included 2 aluminum capped monuments set by DOWL during acquisition. Monument locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage (Table 4, Figure 4).

Table 4: Base station positions for the Juneau Landslide acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Monument ID	Latitude	Longitude	Ellipsoid (meters)
JLM-201	58° 21’ 27.89658”	-134° 33’ 40.15225”	9.065
JLM-202	58° 19’ 56.66659”	-134° 29’ 48.98247”	9.336

Ground Survey Points (GSPs)

Ground survey points were collected by DOWL and provided to NV5 Geospatial to be used in lidar calibration and post-processing, and for accuracy assessment. DOWL provided ground control point data for lidar calibration and non-vegetated (NVA) and vegetated (VVA) check point data for accuracy assessment.

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 19).

[1] https://www.dowl.com/

Table 5: Land Cover Types and Descriptions

Land Cover Type	Land Cover Code	Example	Description	Accuracy Assessment Type
Shrub	SH		Low growth shrub or alder-dominated terrain	VVA
Forest	FOR		Forested areas	VVA
Bare Earth	BE		Areas of bare earth surface	NVA
Urban	UA		Areas dominated by urban development, including parks	NVA

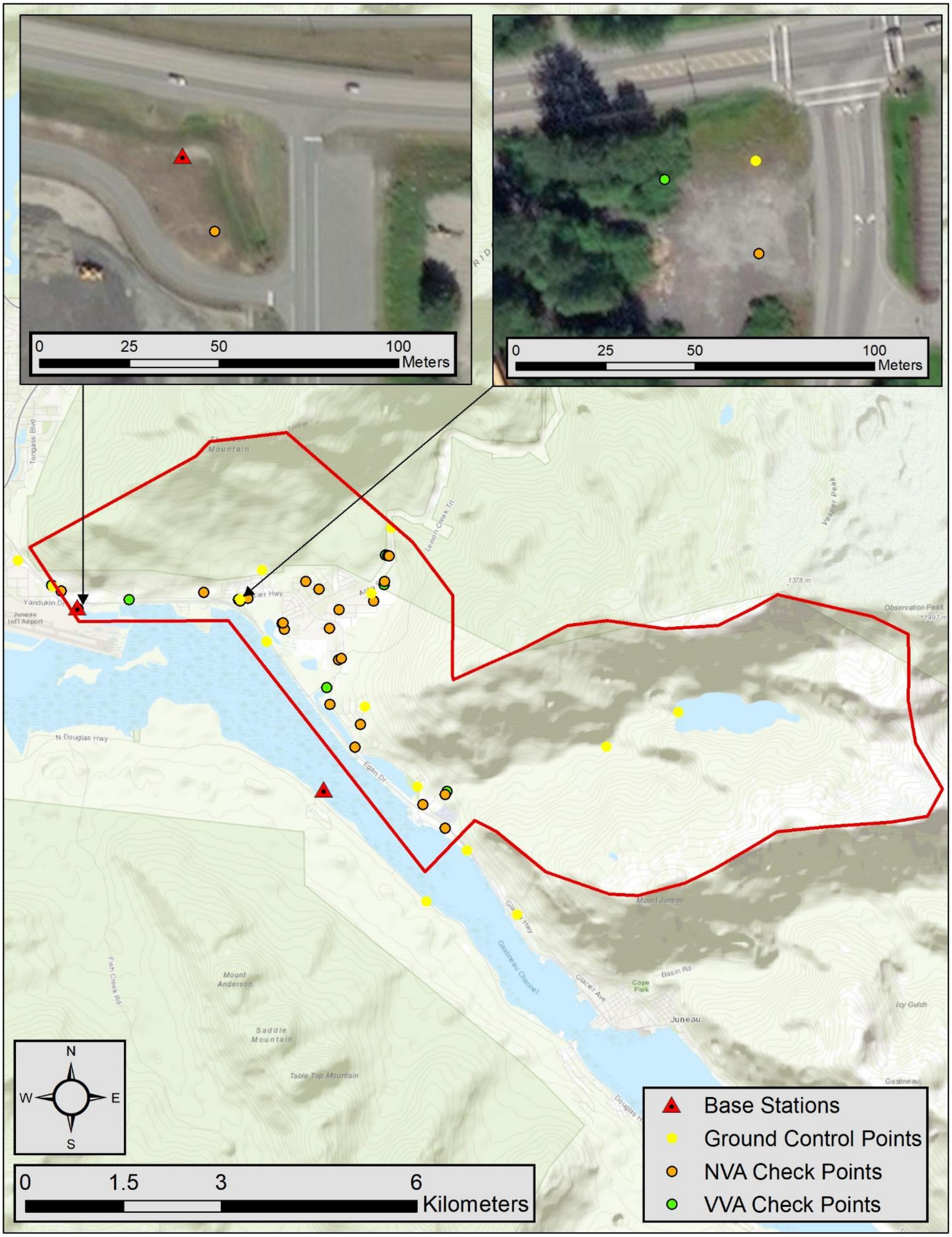
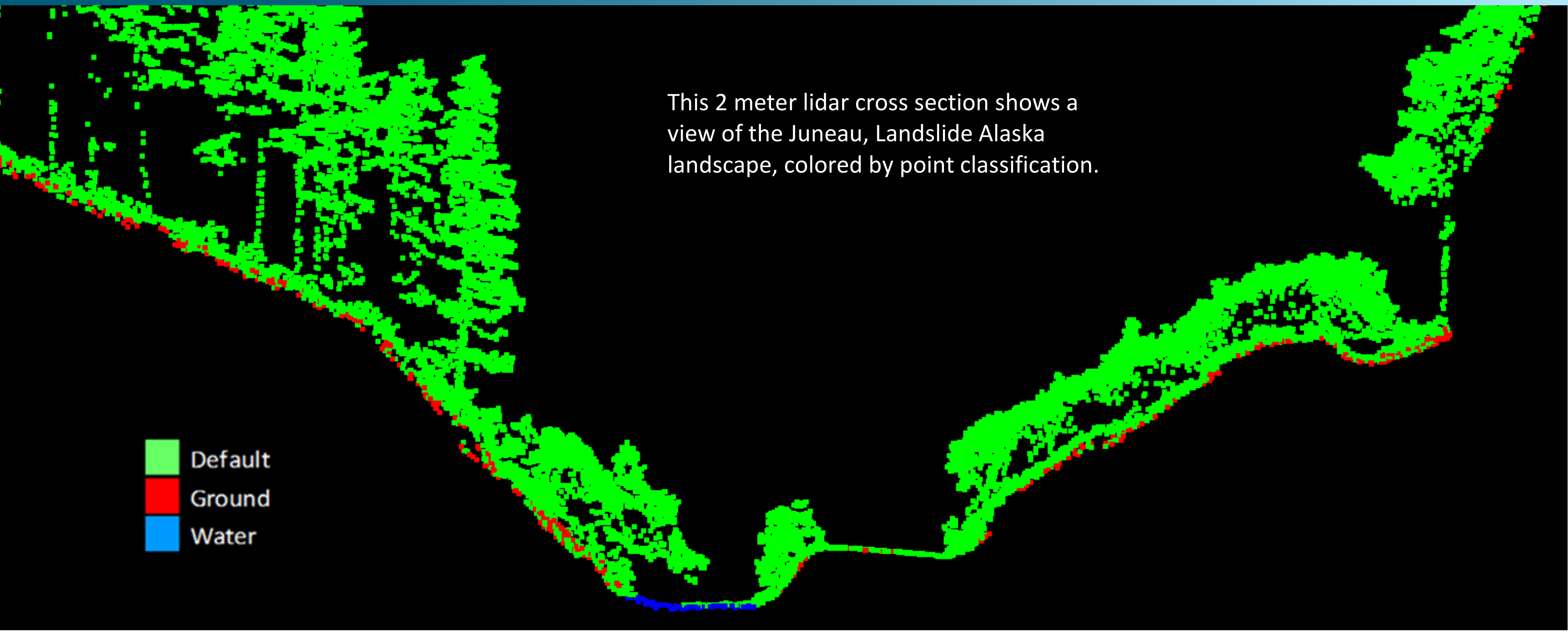


Figure 4: Ground survey location map



Lidar Data

Upon completion of data acquisition, NV5 Geospatial 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.

During initial review, USGS called out several areas of intraswath separation noticeable in the swath separation imagery. A thorough reinspection of the project density and swath separation rasters and produced one instance in which the aircraft and resulting points were meaningfully impacted by turbulence (Figure 5). The flightline where this turbulence event occurred was identified and a noise removal procedure was run in the affected area. The anomalous points from the affected flightline were classified to noise (Class 7). Additionally, the ground classification was recomputed in this area to be consistent with its surroundings. The remaining areas called out by the USGS review were unaffected by this approach as they were due to vegetation, snow, or other temporally related offsets and not turbulence during the aerial acquisition of the data. Figure 5 displays the areas where turbulence-disturbed data was addressed and the areas where intraswath separation remains due to vegetation, snow drifts, construction, and other unavoidable temporally related offsets. Examples of the intraswath separation imagery before and after the turbulence-based noise removal occurred are included.

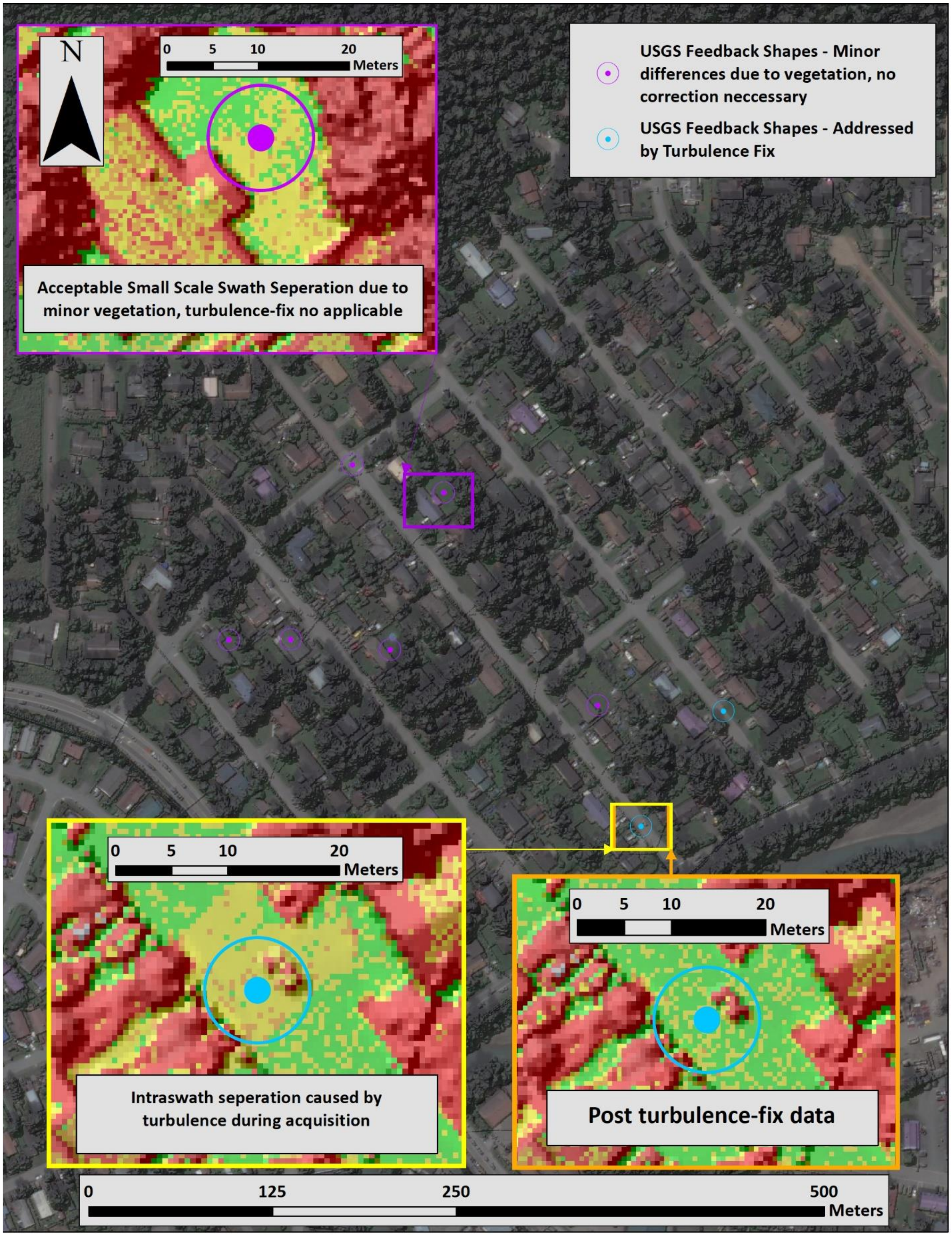


Figure 5: USGS feedback shapes and pre and post recalibrated swath separation imagery

Table 6: ASPRS LAS classification standards applied to the Juneau Landslide dataset

Classification Number	Classification Name	Point Count	Classification Description
1	Default/Unclassified	7,940,776,912	Laser returns that are not included in the ground class, composed of vegetation and anthropogenic features
1-W	Unclassified Withheld / Edge Clip	315,775,078	Laser returns at the outer edges of flightlines that are geometrically unreliable
2	Ground	241,567,981	Laser returns that are determined to be ground using automated and manual cleaning algorithms
7-W	Low Noise	3,594,981	Laser returns that are often associated with artificial points below the ground surface
9	Water	6,324,391	Laser returns that are determined to be water using automated and manual cleaning algorithms
17	Bridge	503,367	Bridge decks
18-W	High Noise	13,592,092	Laser returns that are often associated with birds, scattering from reflective surfaces.
20	Ignored Ground	178,416	Ground points proximate to water’s edge breaklines; ignored for correct model creation
21	Snow	15,276,326	Laser returns that are determined to be snow using manual identification.
22	Temporal Exclusion	5,566,648	Laser returns that are determined to be areas of temporal change using manual identification.

Table 7: Lidar processing workflow

Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS, Applanix PPRTX data 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 MMS v.8.5
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.	RiProcess v1.8.5
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.	BayesMap StripAlign v2.19
Import calibrated points into manageable blocks for editing.	TerraScan v.19.005
Classify resulting data to ground and other client designated ASPRS classifications. Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.19.005 TerraModeler v.19.002
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 Cloud Optimized GeoTiffs at a 0.5-meter pixel resolution.	Las Product Creator 3.0 (NV5 proprietary software) ArcMap v. 10.3.1
Export intensity images and swath separation images as Cloud Optimized GeoTIFFs at a 0.5-meter pixel resolution.	Las Product Creator 3.0 (NV5 proprietary software)

Hydroflattening and Water's Edge Breaklines

Lemon Creek and other closed water bodies with a surface area greater than 2 acres were flattened to a consistent water level. 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.

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 obtained from the filtered lidar returns to create the final 3D 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. Water surfaces were obtained from a TIN of the 3D water edge breaklines resulting in the final hydroflattened model (Figure 6).

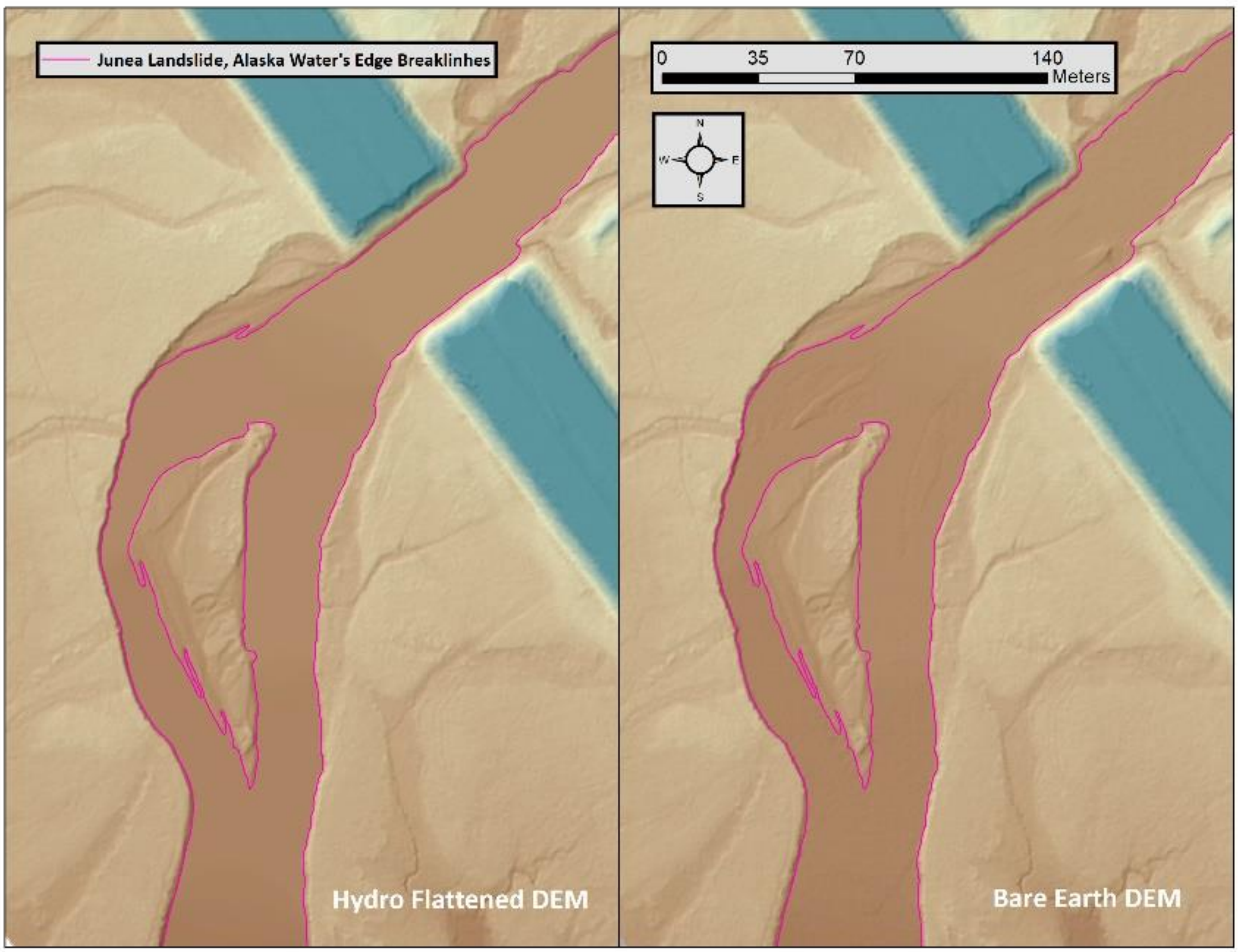
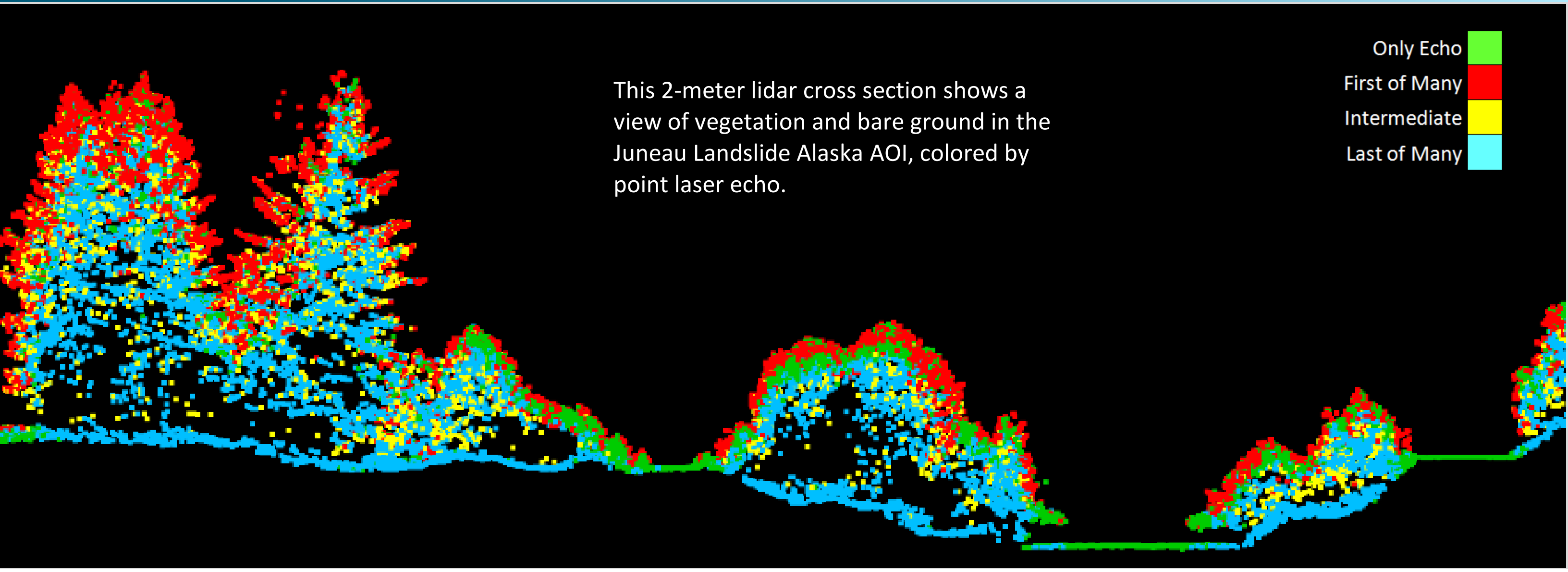


Figure 6: Example of hydroflattening in the Juneau Landslide Lidar dataset



Lidar Density

The acquisition parameters were designed to acquire an average first-return density of 12 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 Juneau Landslide project was 114.70 points/m^2 while the average ground classified density was 5.88 points/m^2 (

Table 8). The large discrepancy between target and achieved point density values for this project was due to extreme topography surrounding the landslide area in a narrow drainage. The steep slopes required closely spaced flightlines and significant overlap to ensure full ground coverage at all ranges. 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 7 through Figure 10.

Table 8: Average lidar point densities

Classification	Point Density
First-Return	114.70 points/m^2
Ground Classified	5.88 points/m^2

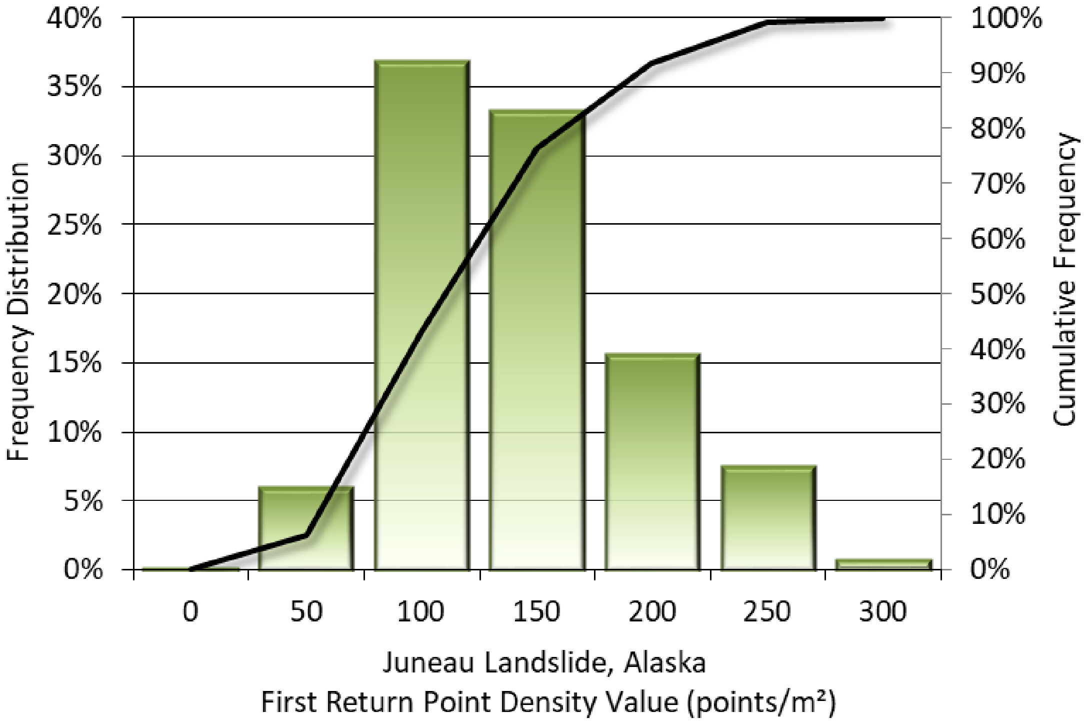


Figure 7: Frequency distribution of first return point density values per 100 x 100 m cell

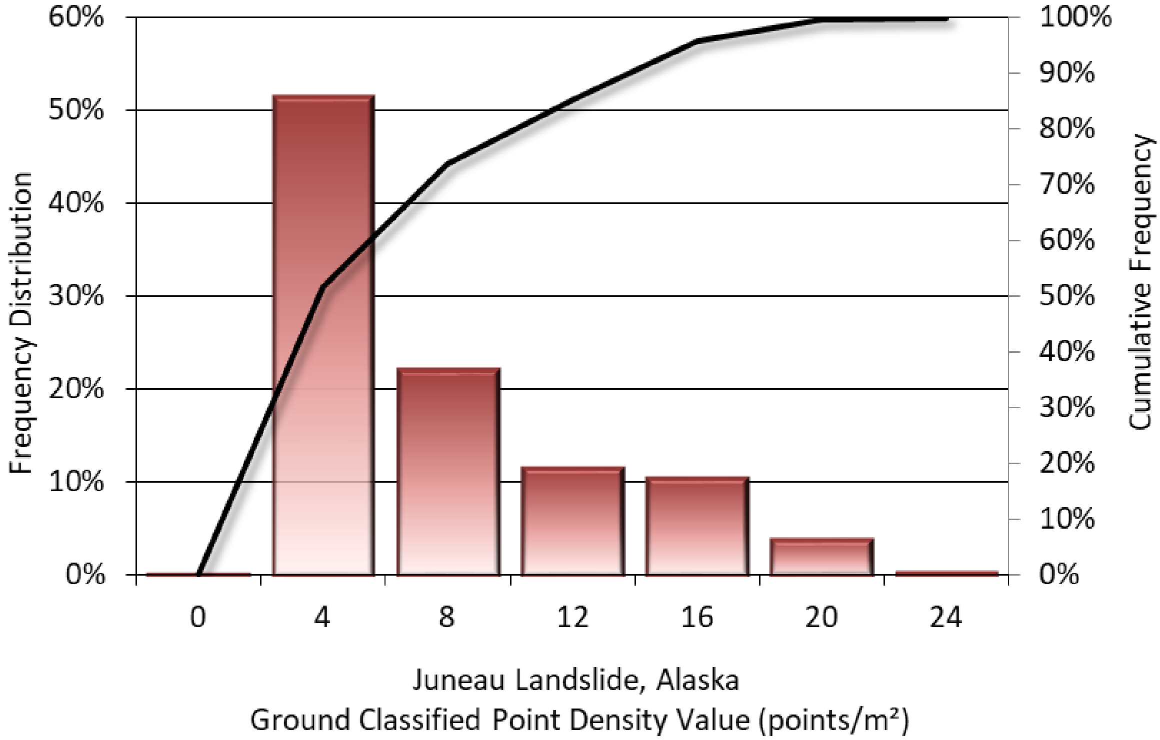


Figure 8: Frequency distribution of ground-classified return point density values per 100 x 100 m cell

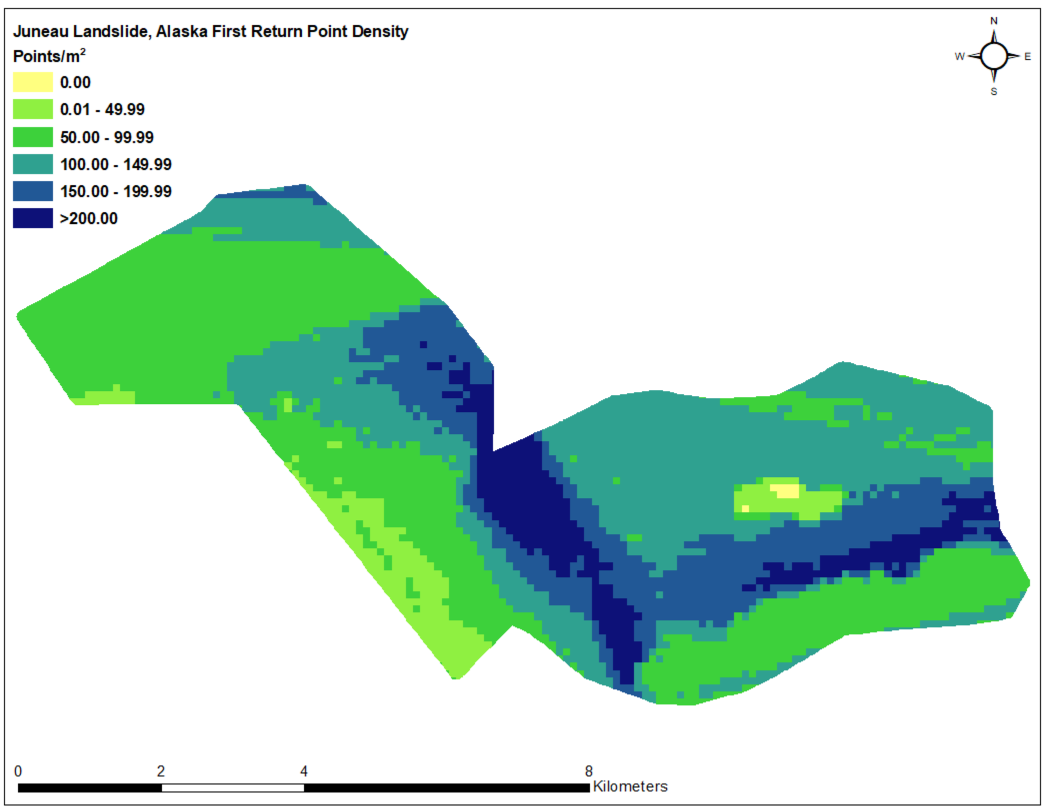


Figure 9: First return point density map for the Juneau Landslide site (100 m x 100 m cells)

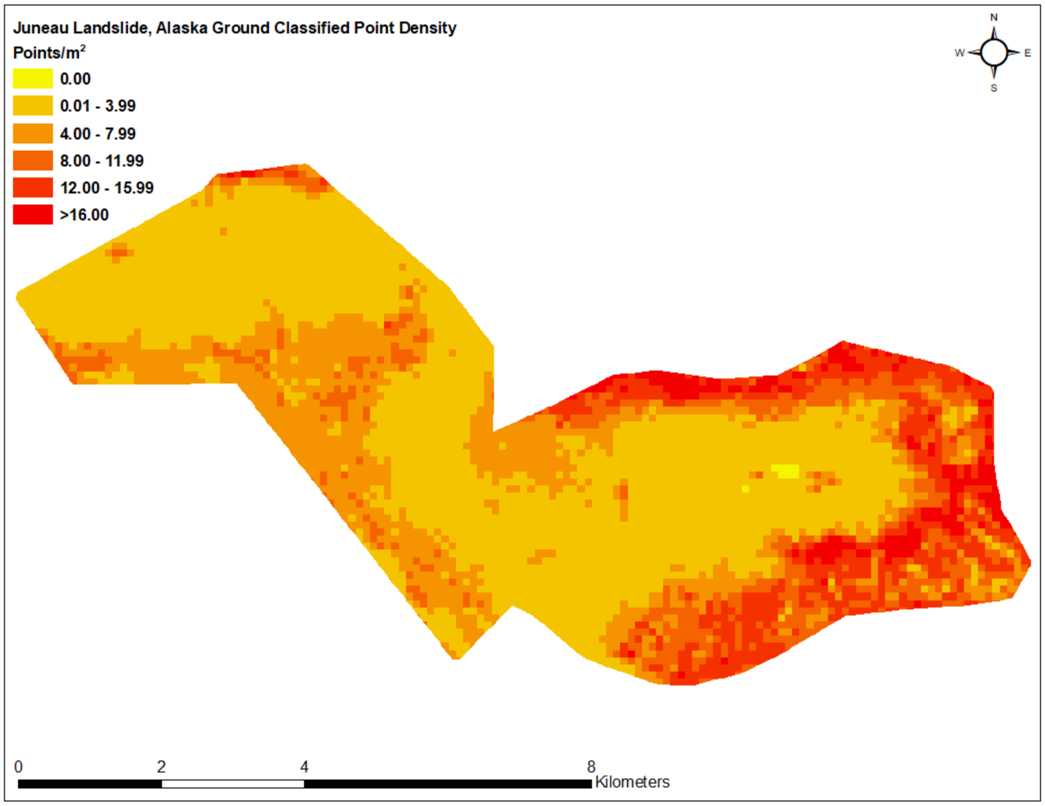


Figure 10: Ground point density map for the Juneau Landslide site (100 m x 100 m cells)

Lidar Accuracy Assessments

The accuracy of the lidar data collection can be described in terms of absolute accuracy (the consistency of the data with external data sources) and relative accuracy (the consistency of the dataset with itself). See Appendix A for further information on sources of error and operational measures used to improve relative accuracy.

Lidar Non-Vegetated Vertical Accuracy

Absolute accuracy was assessed using Non-Vegetated Vertical Accuracy (NVA) reporting designed to meet guidelines presented in the FGDC National Standard for Spatial Data Accuracy[2]. NVA compares known ground check point data that were withheld from the calibration and post-processing of the lidar point cloud to the triangulated surface generated by the classified 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.

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

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 Juneau Landslide survey, 23 ground check points were withheld from the calibration and post processing of the lidar point cloud, with resulting non-vegetated vertical accuracy of 0.032 meters as compared to classified LAS, and 0.036 meters as compared to the bare earth DEM, with 95% confidence (Figure 11, Figure 12).

NV5 Geospatial also assessed absolute accuracy using 15 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 13.

Table 9: Absolute accuracy results

Absolute Vertical Accuracy			
	NVA, as compared to classified LAS	NVA, as compared to bare earth DEM	Ground Control Points
Sample	23 points	23 points	15 points
95% Confidence (1.96*RMSE)	0.032 m	0.036 m	0.032 m
Average	0.003 m	0.004 m	-0.002 m
Median	0.004 m	0.008 m	0.003 m
RMSE	0.016 m	0.018 m	0.016 m
Standard Deviation (1σ)	0.016 m	0.018 m	0.017 m

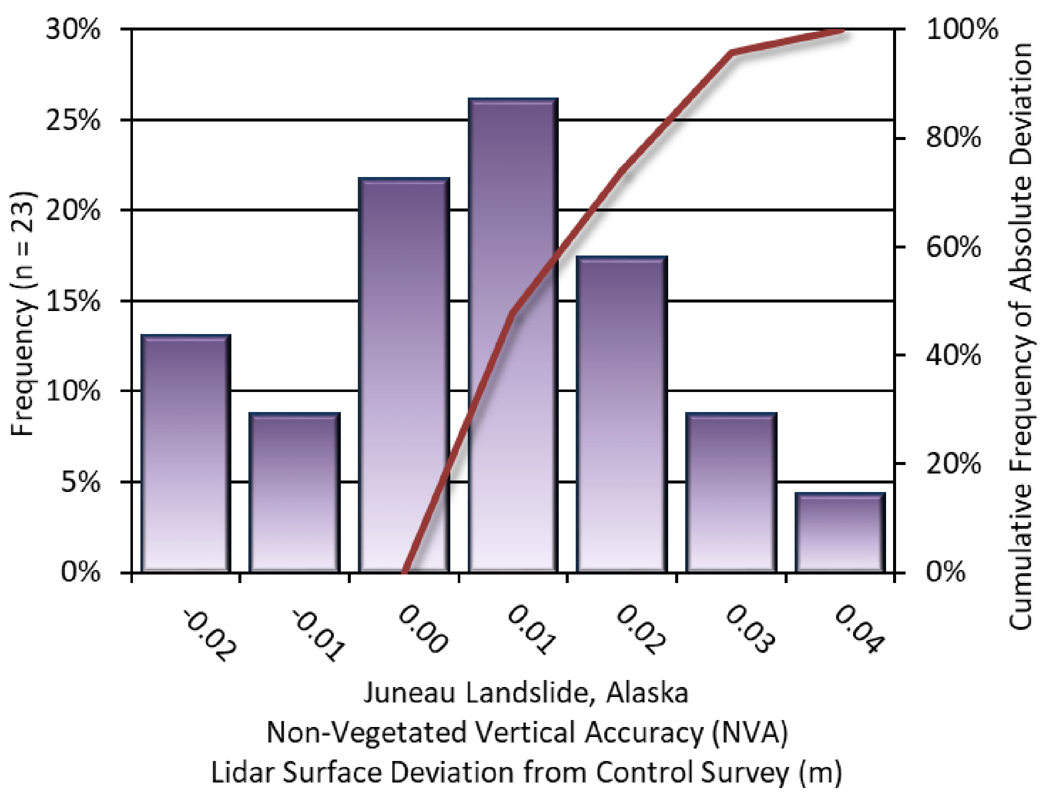

Figure 11: Frequency histogram for lidar classified LAS deviation from ground check point values (NVA)

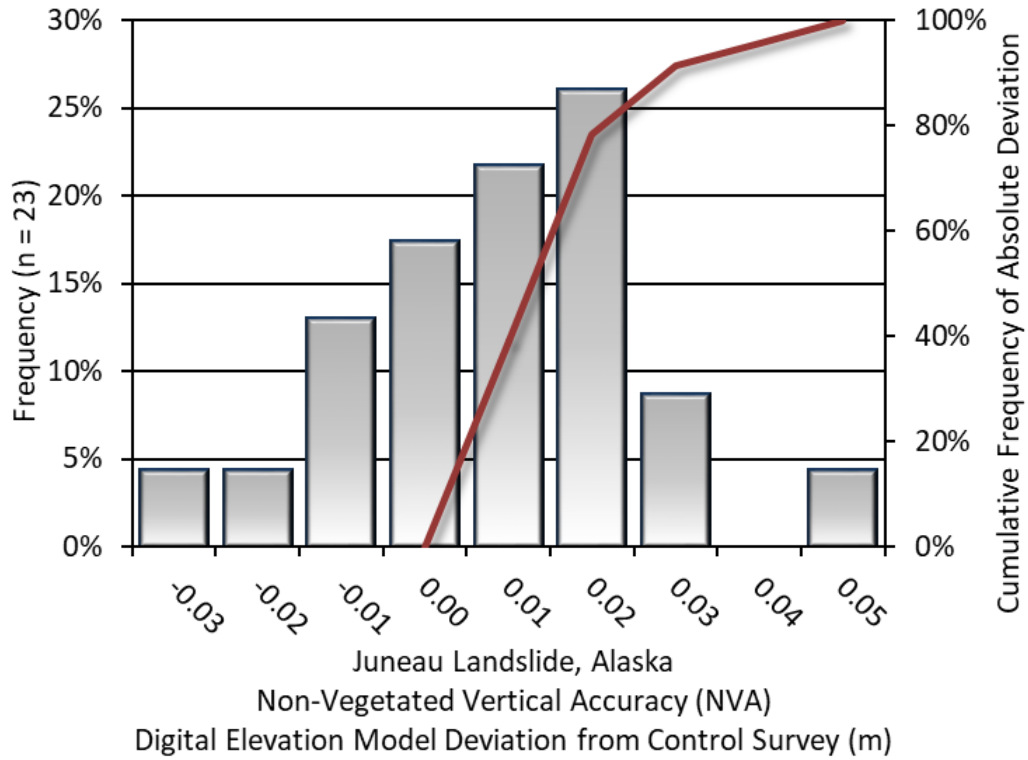

Figure 12: Frequency histogram for the lidar bare earth DEM surface deviation from ground check point values (NVA)

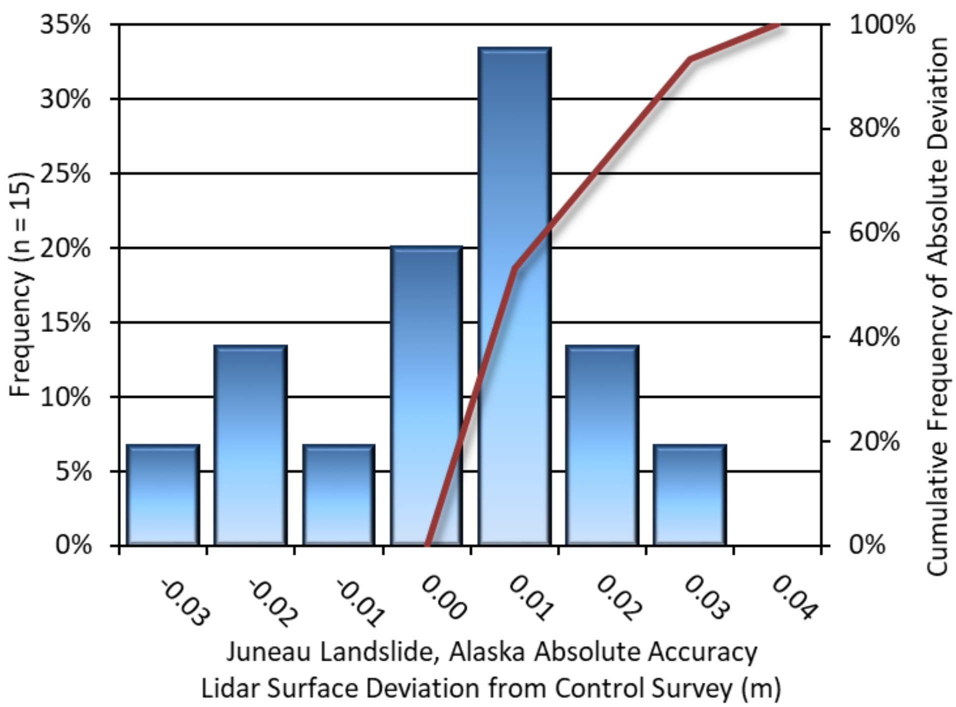

Figure 13: Frequency histogram the for lidar surface deviation from ground control point values

Lidar Vegetated Vertical Accuracy

NV5 Geospatial 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 Juneau Landslide survey, 6 vegetated check points were collected, with resulting vegetated vertical accuracy of 0.104 meters as compared to the classified LAS, and 0.088 meters as compared to the bare earth DEM evaluated at the 95th percentile (Table 10, Figure 14, Figure 15).

Table 10: Vegetated vertical accuracy results

Vegetated Vertical Accuracy		
	VVA, as compared to classified LAS	VVA, as compared to bare earth DEM
Sample	6 points	6 points
95th Percentile	0.104 m	0.088 m
Average	0.038 m	0.022 m
Median	0.042 m	0.018 m
RMSE	0.062 m	0.051 m
Standard Deviation (1σ)	0.054 m	0.050 m

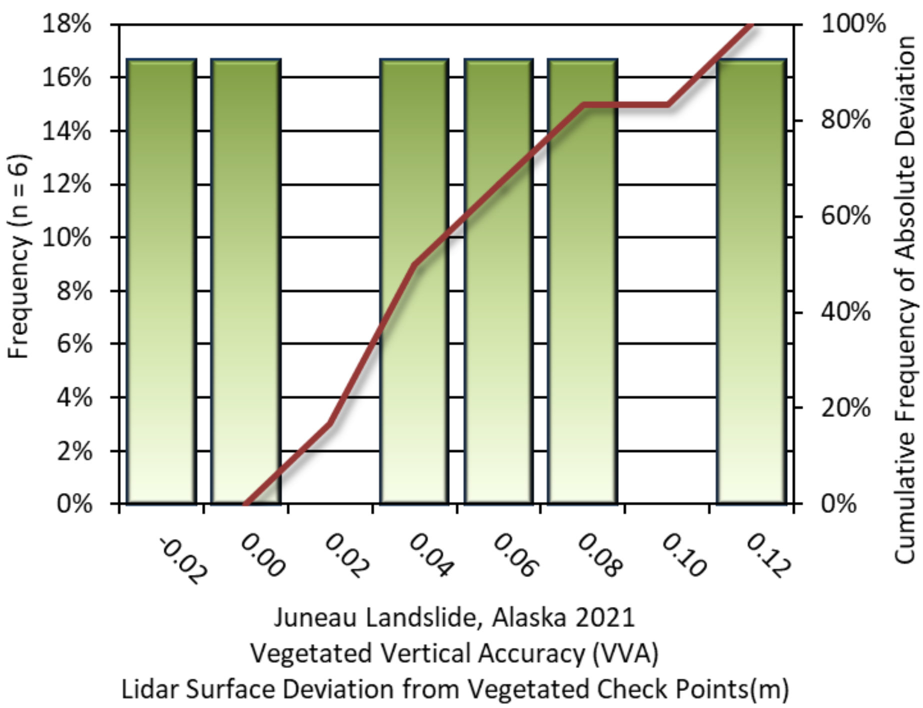

Figure 14: Frequency histogram for the lidar surface deviation from vegetated check point values (VVA)

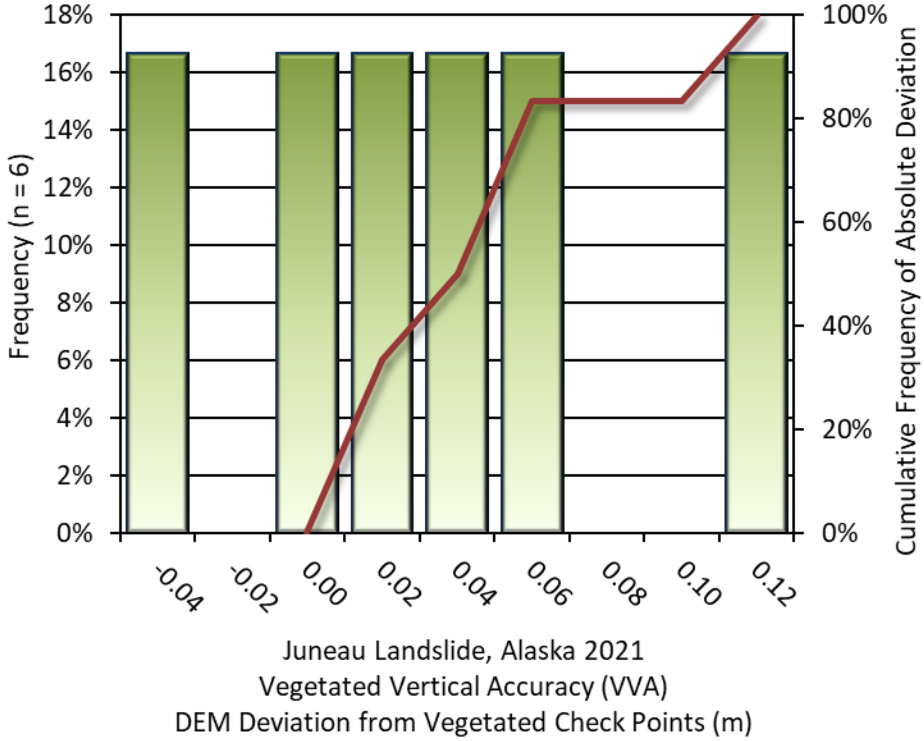

Figure 15: Frequency histogram for the lidar bare earth DEM deviation from vegetated check point values (VVA)

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 Juneau Landslide lidar project was 0.023 meters (Table 11, Figure 16).

Table 11: Relative accuracy results

Relative Accuracy	
Sample	67 surfaces
Average	0.023 m
Median	0.023 m
RMSE	0.023 m
Standard Deviation (1σ)	0.005 m
1.96σ	0.010 m

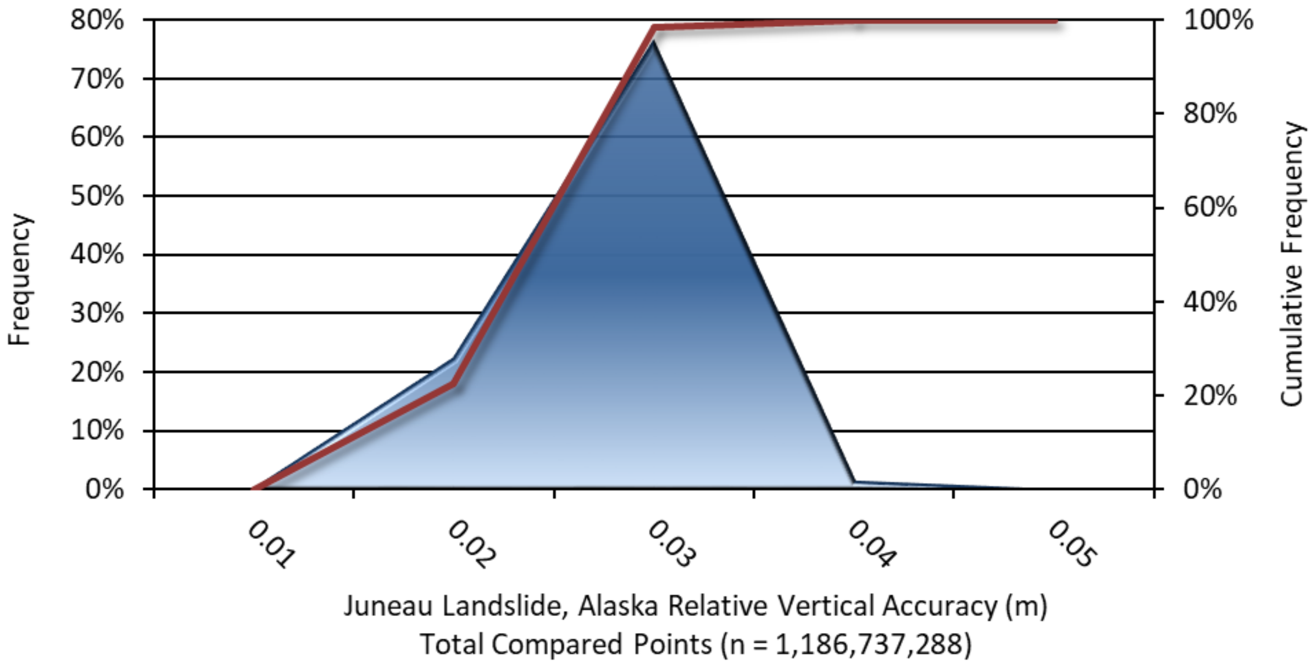

Figure 16: Frequency plot for relative vertical accuracy between flight lines

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 1,200 meters, an IMU error of 0.001 decimal degrees, and a GNSS positional error of 0.019 meters, this project was compiled to meet 0.073 m horizontal accuracy at the 95% confidence level.

Table 12: Horizontal Accuracy

Horizontal Accuracy	
$RMSE_r$	0.042 m
ACC_r	0.073 m

CERTIFICATIONS

NV5 Geospatial provided lidar services for the Juneau Landslide project as described in this report.

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

May 19, 2022

Steven Miller
Project Manager
NV5 Geospatial

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 on June 28, 2021 and August 21-22, 2021 for the airborne survey. The ground survey was performed by DOWL and under the supervision of their professional land surveyor staff.

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".

May 19, 2022

Evon P. Silvia, PLS
NV5 Geospatial
Corvallis, OR 97330

Signed: May 19, 2022
COA: 125659

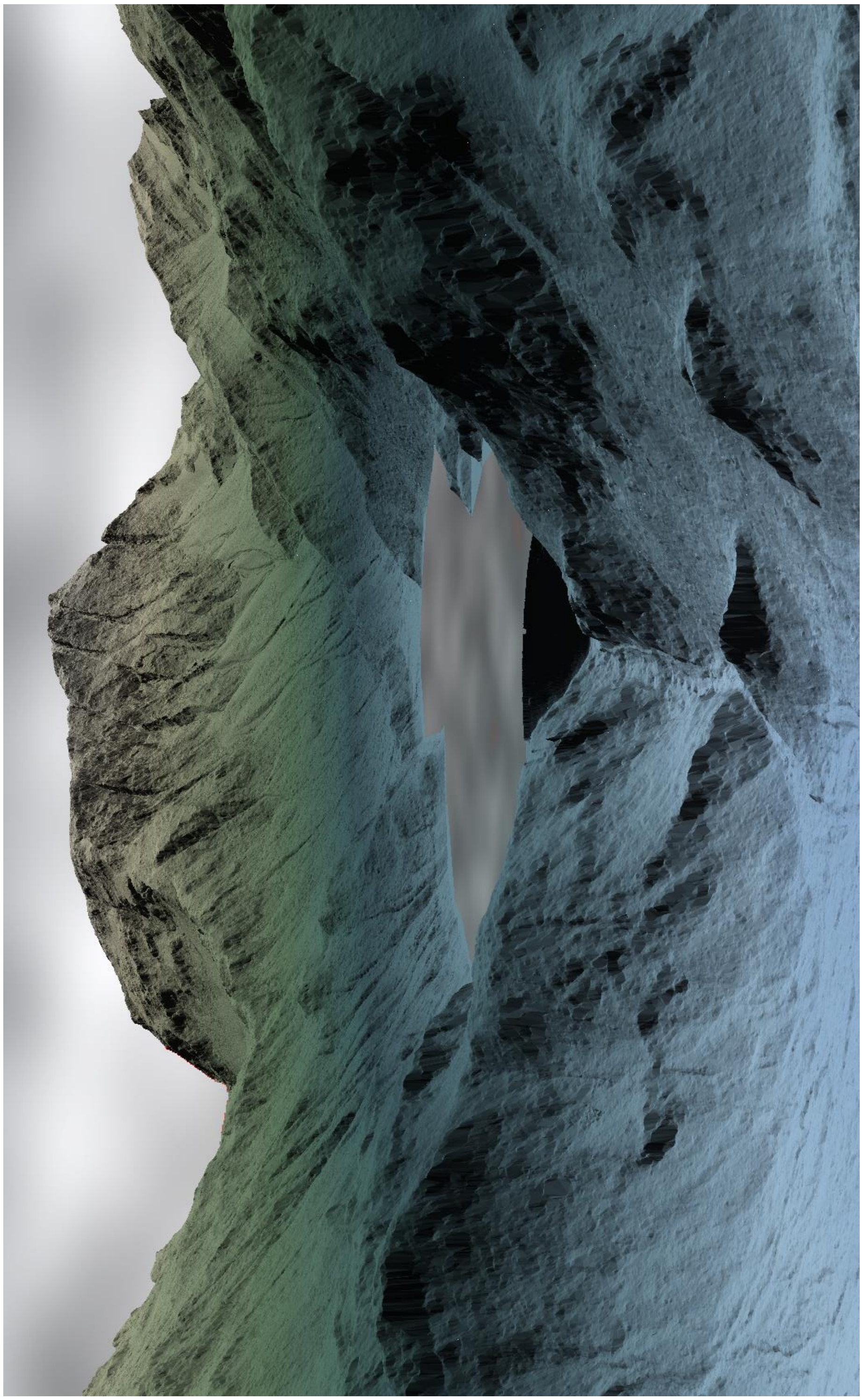

Figure 17: View looking west over Salmon Reservoir within the Juneau Landslide project area. The image was created from the lidar bare earth model colored by elevation.

GLOSSARY

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Relative Accuracy Calibration Methodology:

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

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

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

Lidar accuracy error sources and solutions:

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

Operational measures taken to improve relative accuracy:

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

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

Reduced Scan Angle: Edge-of-scan data can become inaccurate. The scan angle was reduced to a maximum of ±29.25° 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.