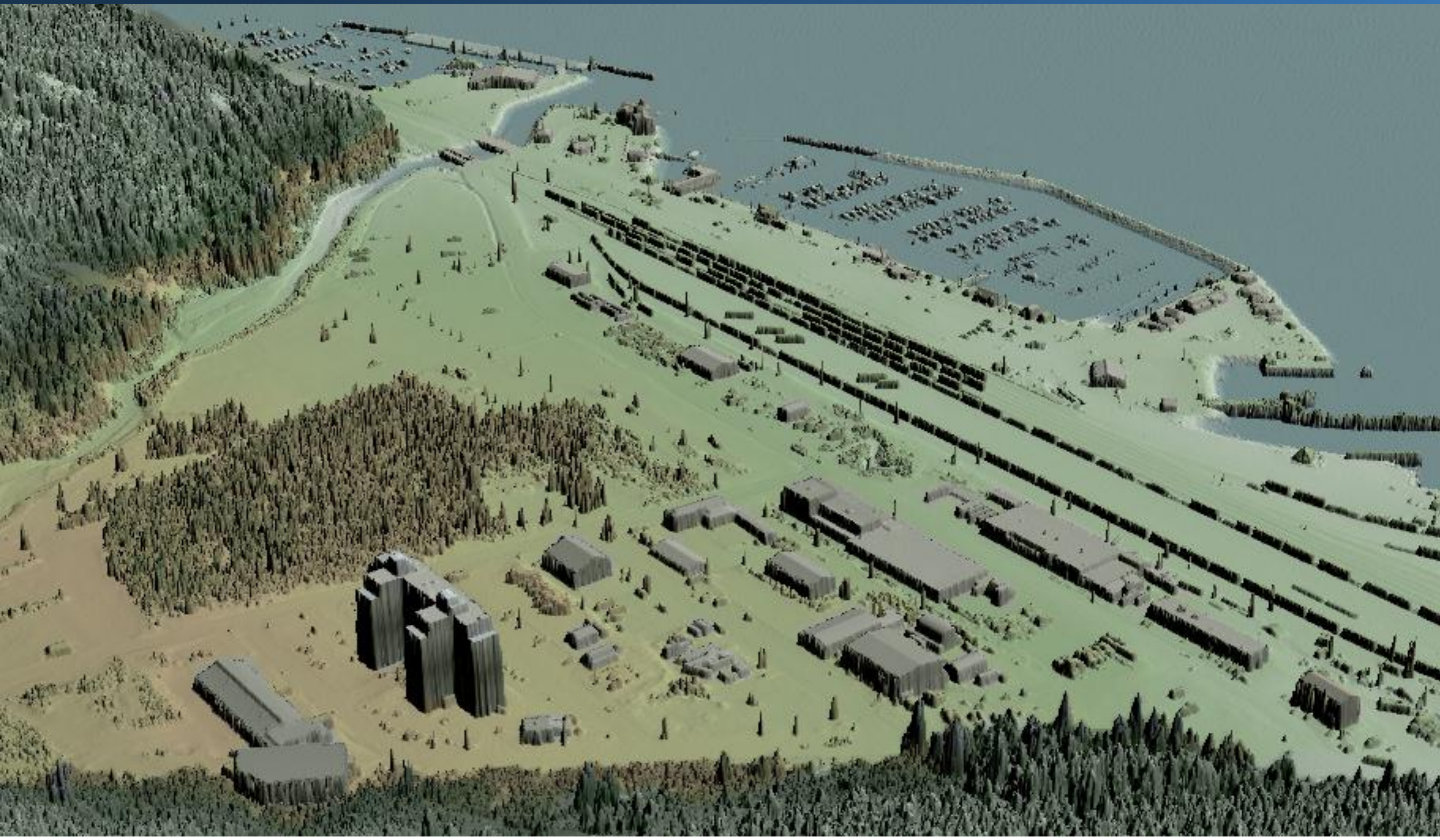
Applied
Remote Sensing
and Analysis

January 17, 2013



Whittier, Alaska LiDAR

Technical Data Report – Revision 3

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Cover Photo: View looking north over the Whittier, Alaska. Image created from a LiDAR-derived highest-hit model colored by elevation.

INTRODUCTION


View of Whittier, Alaska at the head of Passage Canal from the air

In July 2012, WSI (Watershed Sciences, Inc.) was contracted by the Alaska Department of Natural Resources/Division of Geological and Geophysical Surveys (DGGS) to collect Light Detection and Ranging (LiDAR) data in the fall of 2012 for Whittier, Alaska and the area surrounding Passage Canal. Data were collected to aid DGGS in assessing the topographic and geophysical properties of the area for hazard mitigation studies.

This report accompanies the delivered LiDAR data and documents data acquisition procedures, processing methods, and results of all accuracy assessments. Project specifics are shown in Table 1, the project area of interest (AOI) can be seen in Figure 1, and a complete list of contracted deliverables provided to DGGS can be found in Table 2.

Table 1: Acquisition dates, acreages, and data types collected on the Whittier, Alaska LiDAR site.

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
Whittier	32,502	35,292	October 21-25, 2012	LiDAR

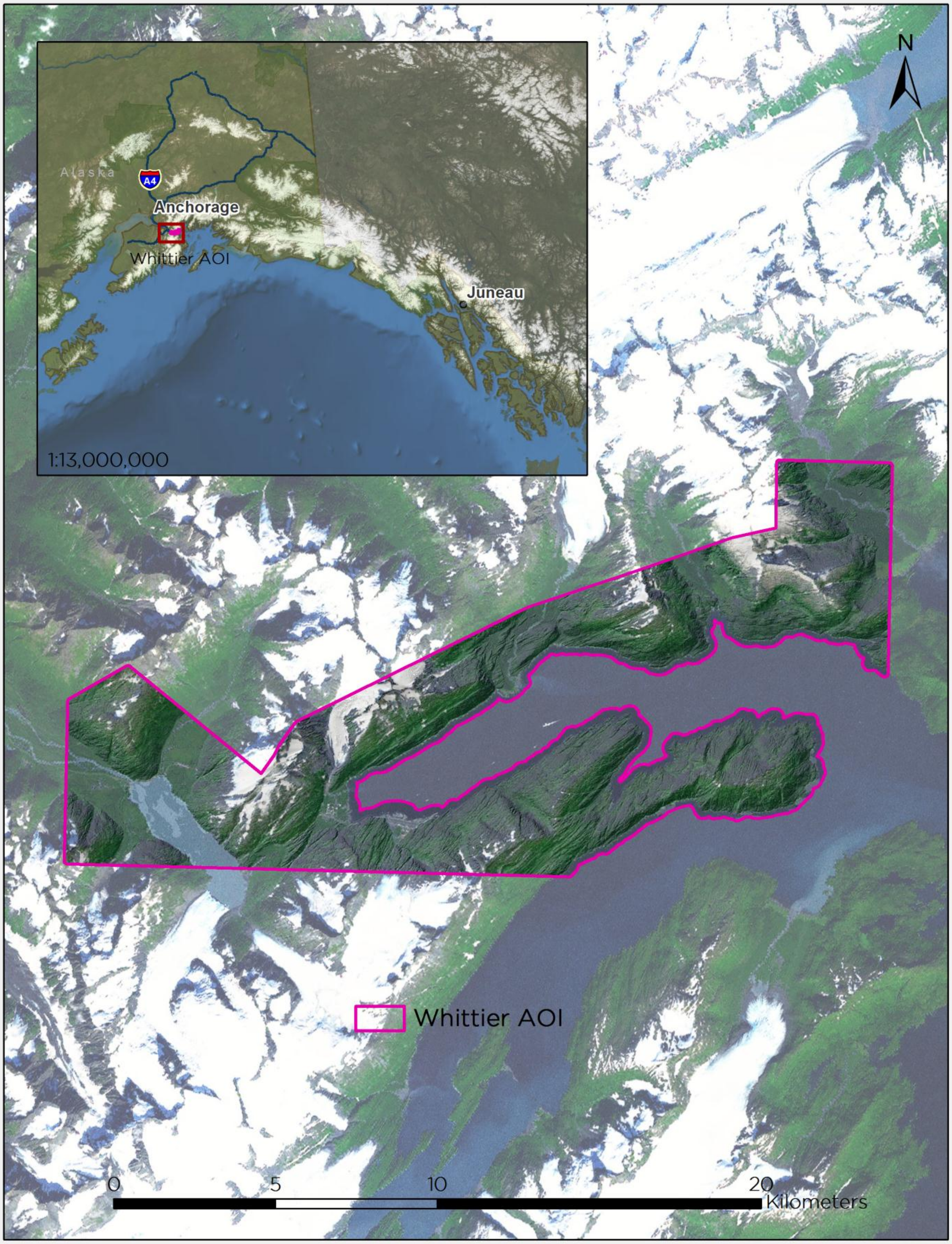


Figure 1: Location map of the Whittier, Alaska LiDAR site

Table 2: Products delivered to DGGS for the Whittier, Alaska LiDAR site

Whittier, Alaska LiDAR Products Projection: UTM Zone 6 North Horizontal Datum: NAD83 (CORS96) Vertical Datum: NAVD88 (GEOID09) Units: Meters	
LAS Files	LAS v 1.2 • All Returns • Ground Returns • RAW (unclassified) Returns
Rasters	1 Meter ESRI Grids • Highest Hit Model • Hydro-flattened Bare Earth Model • Vegetation Model 0.5 Meter GeoTiffs • Intensity Images
Vectors	Shapefiles (*.shp) • Site Boundary • LiDAR Index • DEM/DSM Index • Water’s edge breaklines

ALS50 LiDAR sensor installation ▶

Planning

In preparation for data collection, WSI reviewed the project area using Google Earth, and flightlines were developed using ALTM-NAV Planner (v.3.0) software. Careful planning by acquisition staff entailed adapting the pulse rate, flight altitude, scan angle, and ground speed to ensure complete coverage of the Whittier LiDAR study area at the target point density of ≥4 and ≥8 pulses per square meter. Efforts are taken to optimize flight paths by minimizing flight times while meeting all accuracy specifications.

Factors such as satellite constellation availability and weather windows must be considered. Any weather hazards and conditions affecting the flight were continuously monitored due to their impact on the daily success of airborne and ground operations. In addition, a variety of logistical considerations require review: private property access, potential air space restrictions, and availability of company resources (both staff and equipment).

Ground Survey

Ground survey data is used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on final LiDAR data. Ground professionals set permanent survey monuments and collect real time kinematic (RTK) surveys to support the airborne LiDAR acquisition process.

Monumentation

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

Monument locations were selected with consideration for satellite visibility, field crew safety, and optimal location for RTK coverage. One existing NGS monument was utilized and seven new monuments were established for the Whittier, Alaska LiDAR project (Table 3, Figure 2). New monumentation was set using 5/8" rebar topped with stamped 2" aluminum caps or using surveyor's PK nails. McClintock Land Associates (MLA, Alaska PLS# 6726) of Eagle River, Alaska placed and certified the monuments. Monuments CP2A and CP2B were occupied during LiDAR acquisition.

Table 3: Monuments established for the Whittier, Alaska LiDAR acquisition. Coordinates are on the NAD83 (CORS96) datum, epoch 2002.00

Monument ID	Monumentation	Latitude	Longitude	Ellipsoid (meters)
NGS "ENDING"	NGS Monument	60° 49' 06.47610"	-148° 58' 32.47893"	19.122
CP1A	Aluminum Cap	60° 49' 08.36346"	-148° 58' 42.70293"	19.565
CP1B	Aluminum Cap	60° 50' 14.52996"	-148° 58' 51.22088"	19.201
CP1C	PK Nail	60° 46' 58.93372"	-148° 50' 28.42096"	43.855
CP2A*	Aluminum Cap	60° 46' 45.38882"	-148° 43' 05.08990"	17.198
CP2B*	Aluminum Cap	60° 46' 34.25870"	-148° 40' 52.62625"	15.884
CP2C	PK Nail	60° 46' 44.78149"	-148° 39' 17.35414"	73.507
CP3A	Aluminum Cap	60° 49' 26.66622"	-148° 25' 18.62735"	17.690

*Occupied during acquisition.

To correct the continuous onboard measurements of the aircraft position recorded throughout the missions, WSI concurrently conducted multiple static Global Navigation Satellite System (GNSS) ground surveys (1 Hz recording frequency) over each monument. After the airborne survey, the static GPS data were triangulated with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS[1]) for precise positioning. Multiple independent sessions over the same monument were processed to confirm antenna height measurements and to refine position accuracy.

RTK

For the RTK check point data collection, a Trimble R7 base unit was positioned at a nearby monument to broadcast a kinematic correction to a roving Trimble R8 GNSS receiver. All RTK measurements were made during periods with a Position Dilution of Precision (PDOP) of ≤ 3.0 with at least six satellites in view of the stationary and roving receivers. When collecting RTK data, the rover would record data while stationary for five seconds, then calculate the pseudorange position using at least three one-second epochs. Relative errors for the position must be less than 1.5 cm horizontal and 2.0 cm vertical in order to be accepted.

RTK positions were collected on paved roads and other hard surface locations such as gravel or stable dirt roads that also had good satellite visibility. RTK measurements were not taken on highly reflective surfaces such as center line stripes or lane markings on roads due to the increased noise seen in the laser returns over these surfaces. The distribution of RTK points depended on ground access constraints and may not be equitably distributed throughout the study area. See Figure 2 for the distribution of RTK in this project.

All static surveys were collected with Trimble model R7 GNSS receivers equipped with a Zephyr Geodetic Model 2 RoHS antenna. A Trimble model R8 GNSS receiver was used to collect RTK. All GNSS measurements were made with dual frequency L1-L2 receivers with carrier-phase correction. See Table 4 for Trimble unit specifications.

Table 4: Trimble equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R7 GNSS	Zephyr GNSS Geodetic Model 2	TRM57971.00	Static
Trimble R8	Integrated Antenna R8 Model 2	TRM_R8_GNSS	RTK

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

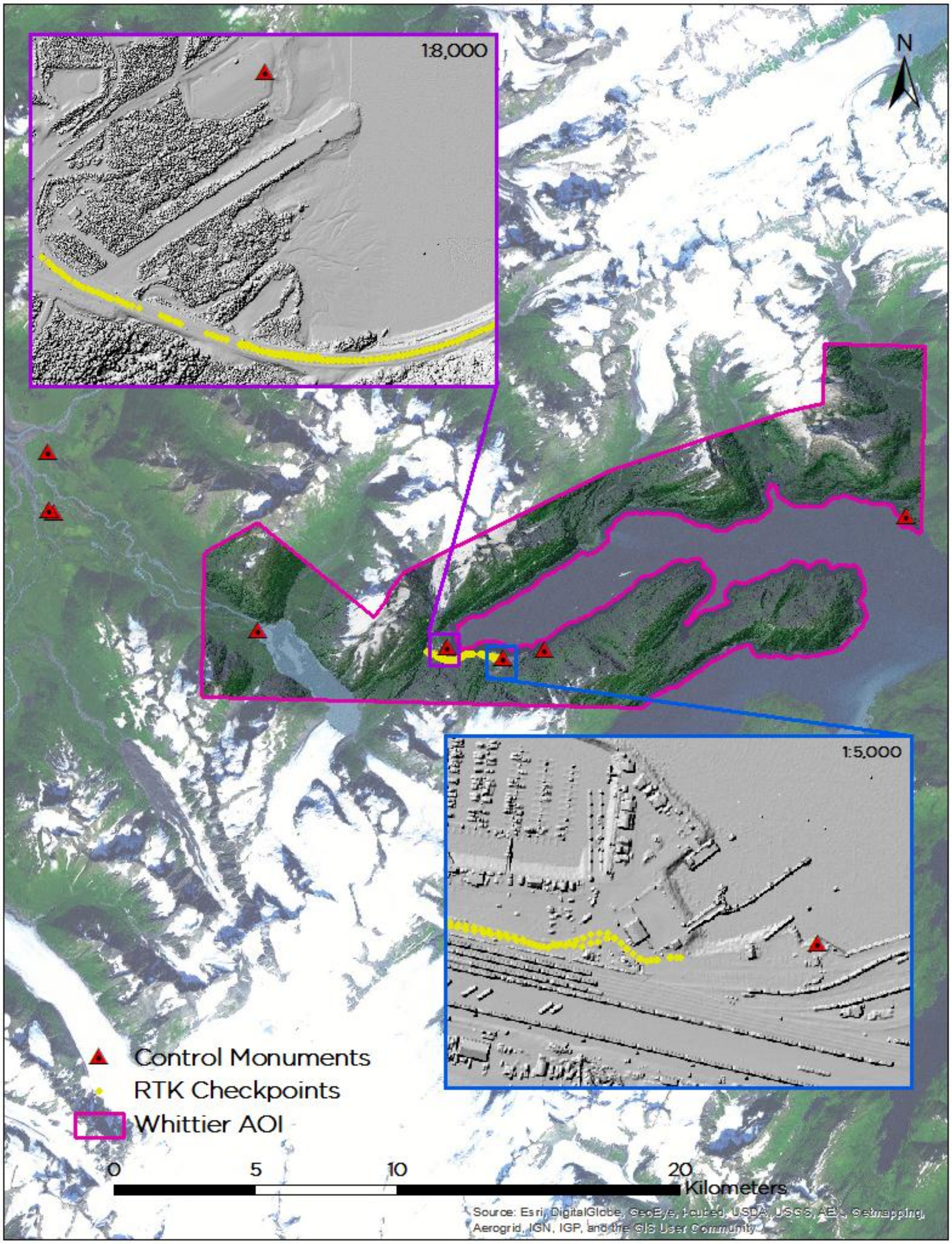


Figure 2: Basestation and RTK checkpoint location map

Airborne Survey

LiDAR

The LiDAR survey was accomplished with a Leica ALS50 Phase II system mounted in a Cessna Caravan. Table 5 summarizes the settings used to yield an average pulse density of ≥4 and 8 pulses/m^2 over the Whittier, Alaska LiDAR terrain. Areas below 1600 feet in elevation, including the City of Whittier, were collected at a higher pulse density (≥8 pulses/m^2), with areas above 1600 feet in elevation collected at ≥4 pulses/m^2. It is not uncommon for some types of surfaces (e.g. dense vegetation or water) to return fewer pulses to the sensor than the laser originally emitted. These discrepancies between native and delivered density will vary depending on terrain, land cover, and the prevalence of water bodies.

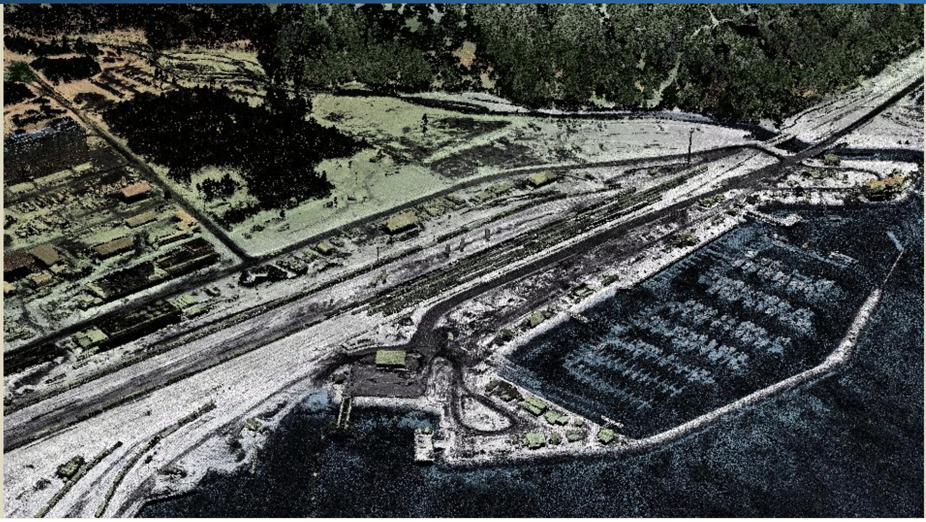
Table 5: LiDAR survey settings and specifications for the Whittier, Alaska LiDAR site

LiDAR Survey Settings & Specifications		
Sensor	Leica ALS50	Leica ALS50
Terrain	Below 1600-ft elevation	Above 1600-ft elevation
Resolution/Density	Average 8 pulses/m^2	Average 4 pulses/m2
Survey Altitude (AGL)	900 m	1200 m
Target Pulse Rate	93-106 kHz	75-88 kHz
Sensor Configuration	Single Pulse in Air (SPiA)	Single Pulse in Air (SPiA)
Laser Pulse Diameter	21 cm	28 cm
Mirror Scan Rate	50.2 Hz	50.2 Hz
Field of View	28^o	28^o
GPS Baselines	≤13 nm	≤13 nm
GPS PDOP	≤3.0	≤3.0
GPS Satellite Constellation	≥6	≥6
Maximum Returns	4	4
Intensity	8-bit	8-bit
Accuracy	$RMSE_Z$ ≤ 15 cm	$RMSE_Z$ ≤ 15 cm

To reduce laser shadowing and increase surface laser painting, all areas were surveyed with an opposing flight line side-lap of ≥50% (≥100% overlap). The Leica laser systems record up to four range measurements (returns) per pulse. All discernible laser returns were processed for the output dataset.

To accurately solve for laser point position (geographic coordinates x, y, 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. 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/sensor position and attitude data are indexed by GPS time.

View looking southwest over the harbor in Whittier. Image created from a LiDAR point cloud colored by elevation.



LiDAR Data

Upon the LiDAR data's arrival to the office, WSI processing staff initiates a suite of automated and manual techniques to process the data into the requested deliverables. Processing tasks include GPS control computations, kinematic corrections, calculation of laser point position, calibration for optimal relative and absolute accuracy, and classification of ground and non-ground points (Table 6). Processing methodologies are tailored for the landscape and intended application of the point data. A full description of these tasks can be found in Table 7.

Table 6: ASPRS LAS classification standards applied to the Whittier, Alaska LiDAR dataset

Classification Number	Classification Name	Classification Description
2	Ground	Lowest elevation returns at ground level.
3	Low Vegetation	Returns considered low vegetation (less than 20 cm).
4	Medium Vegetation	Vegetation with heights greater than 20 cm.
6	Buildings	Buildings and man-made structures
7	Low points/Noise	Low points and/or noise
9	Water	Water surface returns.
10	Ignored ground	Ground points within 1 meter of breaklines
11	Withheld	Laser returns that have intensity values of 0 or 255.
12	Mobile	Temporary placed structures (cars, boats, docks, bouys).
13	Utilities	Man-made, non-habitable structures (fences, powerlines).

Originally, a snow classification was assigned to classification number 10. This classification was reserved for points that demonstrated snow level differences in areas of mission overlap, with the higher snow level being classified as snow, and the lower level being considered ground. This senario is most common with acquisitions that span multiple weeks. Because acquisition of the Whittier site was fully completed in five consecutive days, there were no detectable snow level changes. Therefore, no snow classification was necessary. Classification number 10 was reassigned to contain the ignored ground class, which are ground points within 1 meter of breaklines as indicated in the USGS LiDAR guidelines[1]. These are classified as ignored ground to make a better hydro-flattened model.

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.	Waypoint GPS v.8.3 Trimble Business Center v.2.80 Blue Marble Desktop v.2.5
Develop a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with attitude data. Sensor head position and attitude are calculated throughout the survey. The SBET data are used extensively for laser point processing.	IPAS TC v.3.1
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. 1.2) format. Data are converted to orthometric elevations (NAVD88) by applying a Geoid12 correction.	ALS Post Processing Software v.2.74
Import raw laser points into manageable blocks (less than 500 MB) to perform manual relative accuracy calibration and filter erroneous points. Ground points are then classified for individual flight lines (to be used for relative accuracy testing and calibration).	TerraScan v.12.004
Using ground classified points per each flight line, the relative accuracy is tested. Automated line-to-line calibrations are then performed for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calibrations are calculated on ground classified points from paired flight lines and results are applied to all points in a flight line. Every flight line is used for relative accuracy calibration.	TerraMatch v.12.001
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 RTK survey data.	TerraScan v.12.004 TerraModeler v.12.002
Generate bare earth models as triangulated surfaces. Highest hit models were created as a surface expression of all classified points (excluding the noise and withheld classes). All surface models were exported as GeoTIFFs at a 1 meter pixel resolution.	TerraScan v.12.004 ArcMap v. 10.0 TerraModeler v.12.002

1. Heidemann, Hans Karl, 2012, Lidar base specification version 1.0: U.S. Geological Survey Techniques and Methods, book 11, chap. B4, 63 p

Feature Extraction

Water's edge breaklines

Lakes and other closed water bodies with a surface area >150 m^2 were flattened to a consistent water level. The hydro-flattening process eliminates artifacts in the digital terrain model caused by both increased variability in ranges or dropouts in laser returns due to the low reflectivity of water. As per the project specifications, water's edge breaklines were created for rivers and streams wider than 30m however these rivers were not hydro-flattened in the digital elevation model. Ground points within these polygons were classified to the appropriate water class.

Hydro-flattening of closed water bodies was performed through a combination of automated and manual detection and adjustment techniques designed to identify lake boundaries and water levels. Boundary polygons were developed using an algorithm which weights LiDAR-derived slopes, intensities, and return densities to detect the lake edge. The lake edges were then manually reviewed and edited as necessary.

Once polygons were developed, the lake elevations were computed from the filtered LiDAR returns. The elevation of each lake was computed as 5 centimeters above the minimum elevation of filtered water surface cells within the lake polygon. This approach ensures that all spurious returns off the water surface (both artificially high and low) were excluded from lake level assessment. Lake-boundary polygons were then incorporated into the final terrain model and enforced as hard breaklines. The initial ground classified points falling within lake polygons were reclassified as water (Figure 3).

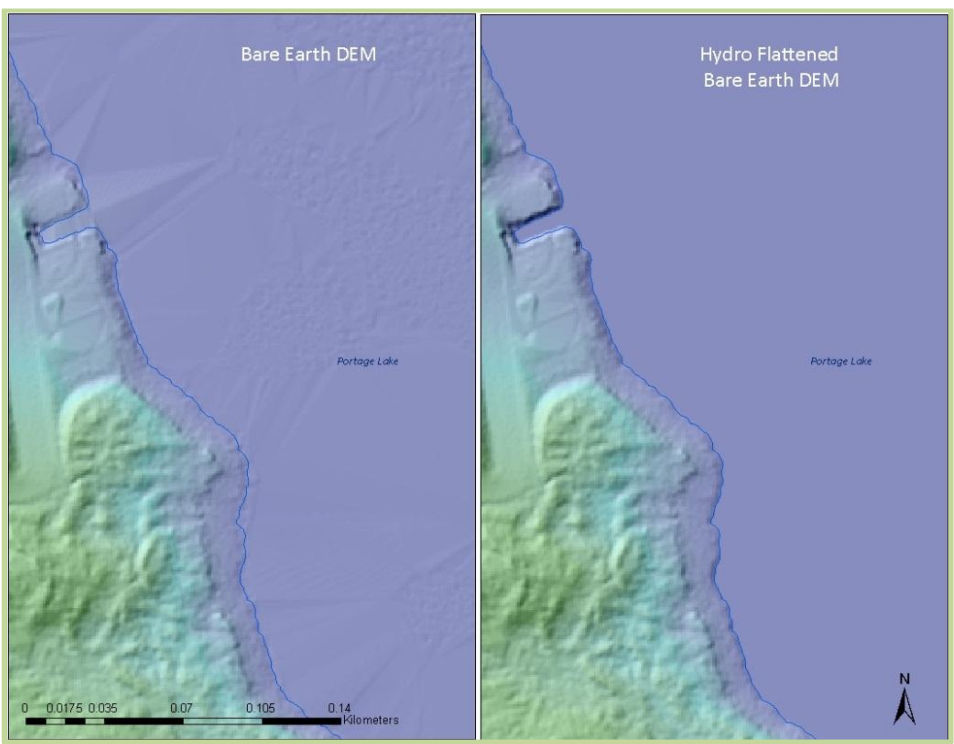
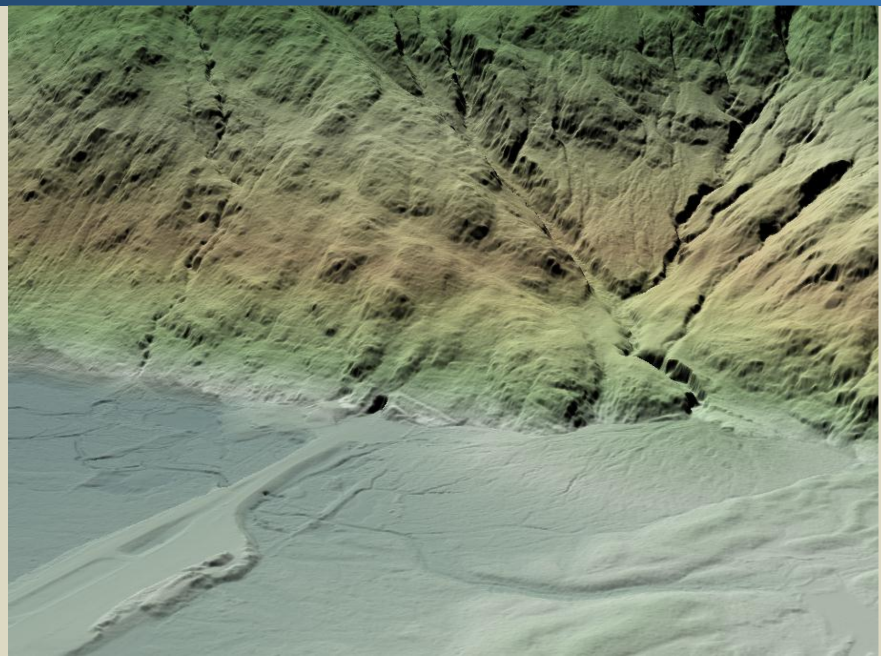


Figure 3: Comparison of Bare Earth and Hydro Flattened Bare Earth Model

View looking east towards the Whittier Tunnel. Image created from LiDAR derived bare-earth model colored by elevation.



LiDAR Density

The average first-return density for the entire LiDAR dataset for the Whittier, Alaska LiDAR was 13.87 points/m^2 (Table 8). As mentioned, areas below 1,600 feet in elevation, including the City of Whittier, were collected at a higher pulse density (≥8 pulses/m^2), with areas above 1,600 feet in elevation collected at ≥4 pulses/m^2. The pulse density distribution will vary within the study area due to laser scan pattern and flight conditions. Additionally, some types of surfaces (i.e. breaks in terrain, water, steep slopes) may return fewer pulses to the sensor (delivered density) than originally emitted by the laser (native density).

The statistical distribution of first returns for the overall dataset, the 4-point target areas, and the 8-point target areas can be seen in Figure 4, 5 and 6. The statistical distributions of classified ground points are shown in Figures 7, 8, and 9. Also presented are the spatial distribution of average first return densities and ground point densities (Figure 10) for each 100 m^2 cell.

Table 8: Average LiDAR point densities

Classification	Complete AOI	Above 1600 ft elevation	Below 1600 ft elevation
First-Return	13.87 points/m^2	10.64 points/m^2	13.88 points/m^2
Ground Classified	3.22 points/m^2	4.02 points/m^2	3.02 points/m^2

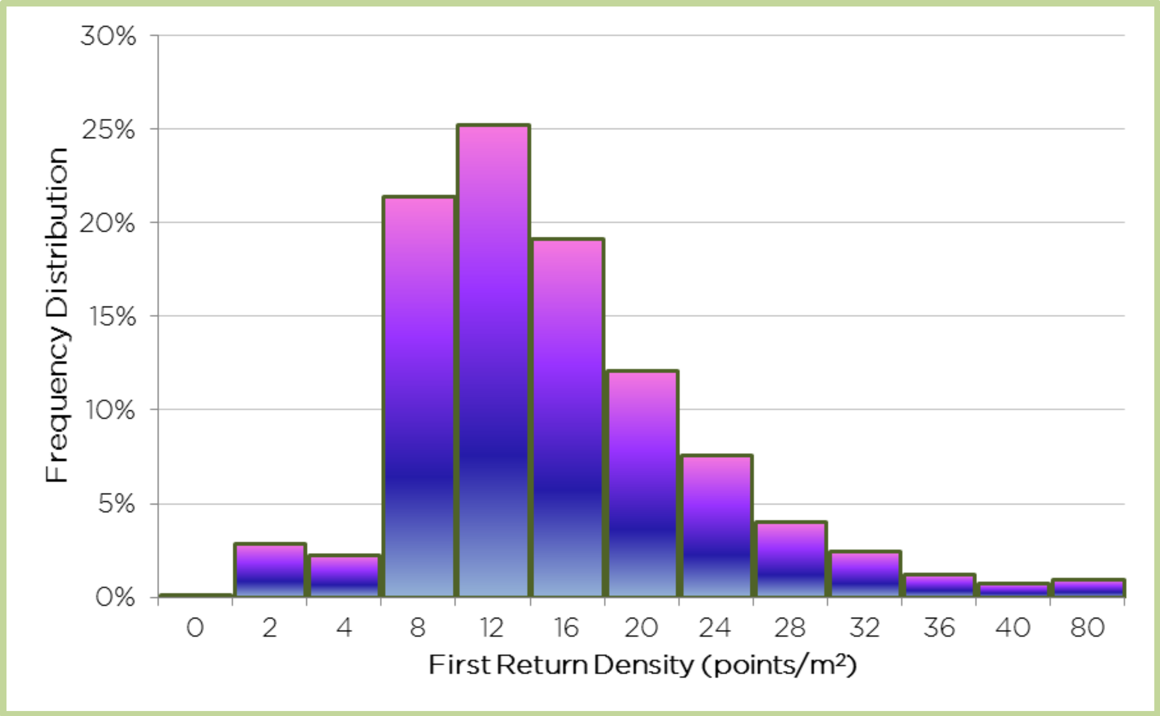


Figure 4: Frequency distribution of first return densities (native densities) of the entire 1m gridded study area

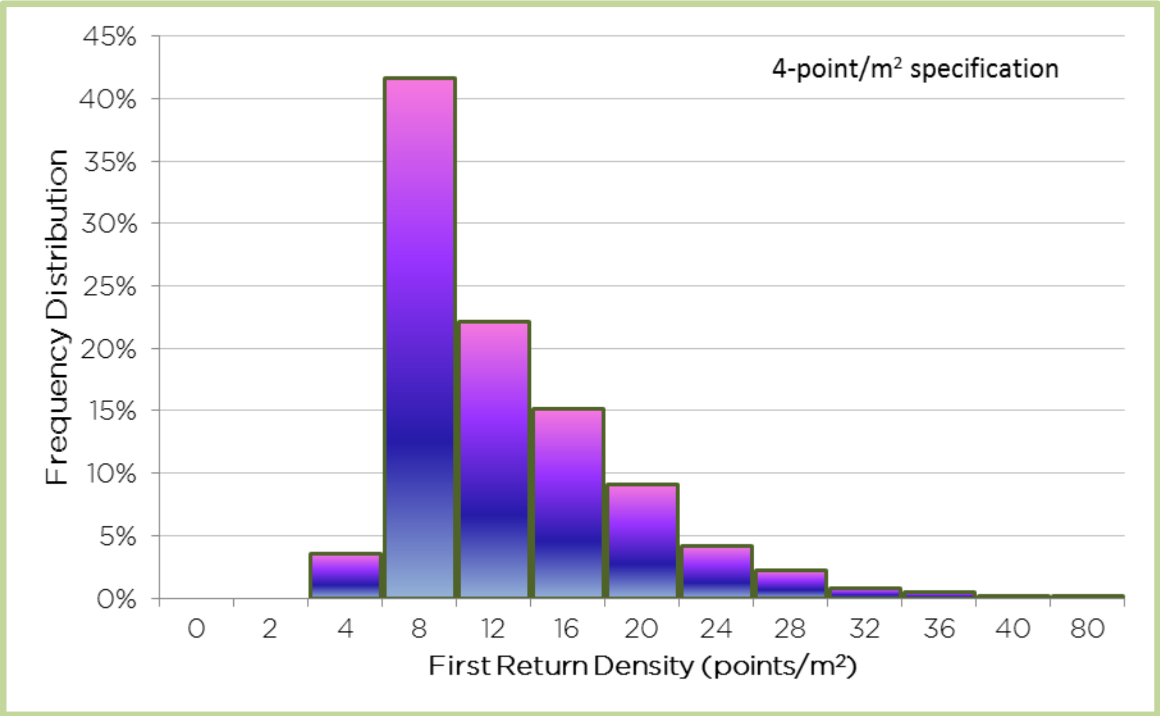


Figure 5: Frequency distribution of first return densities (native densities) of the 1m gridded study area above 1600-foot elevation.

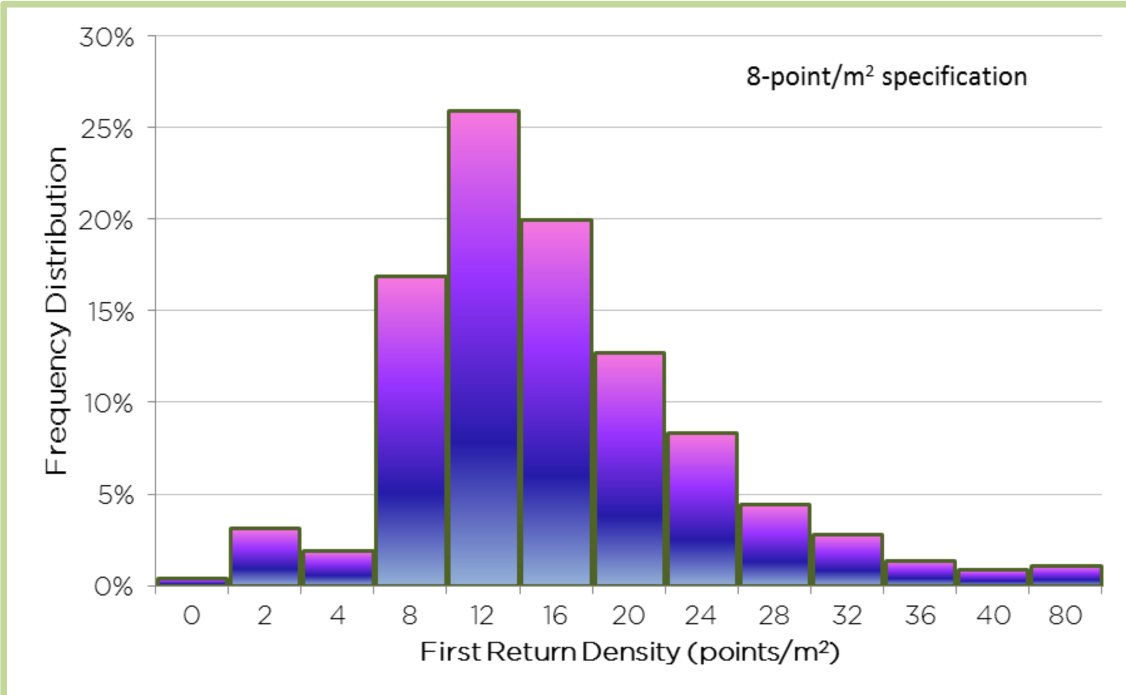


Figure 6: Frequency distribution of first return densities (native densities) of the 1m gridded study area below 1600-foot elevation

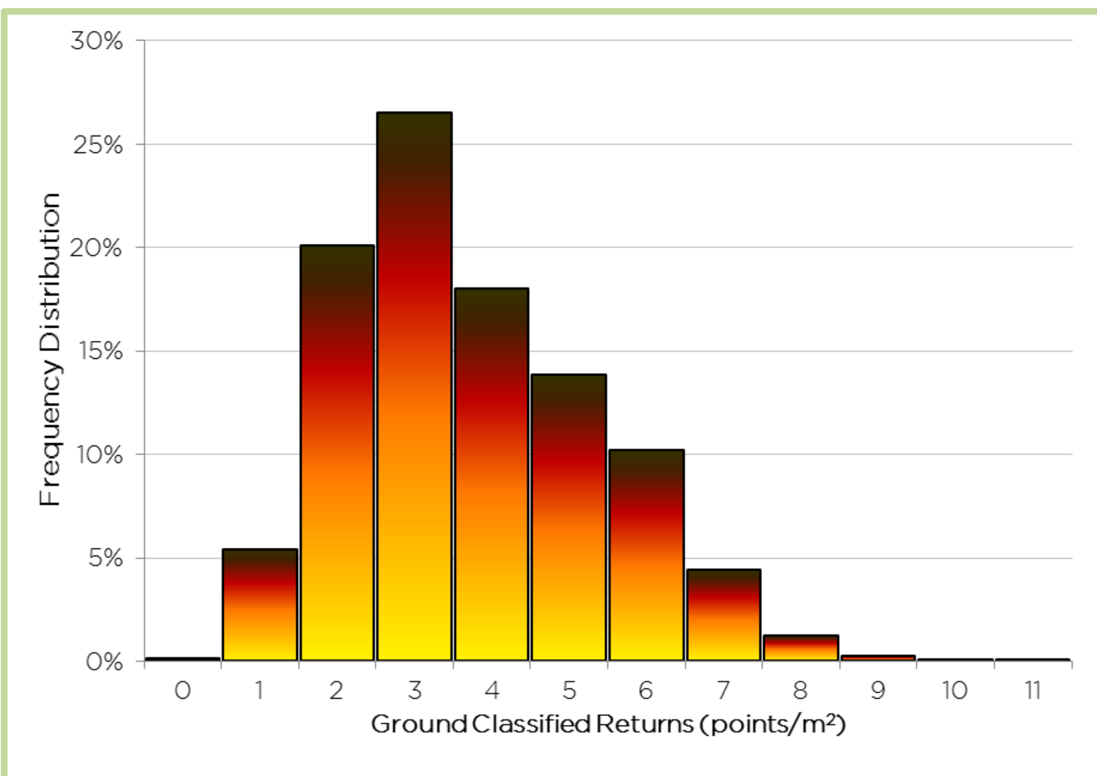


Figure 7: Frequency distribution of ground return densities of the entire 1m gridded study area

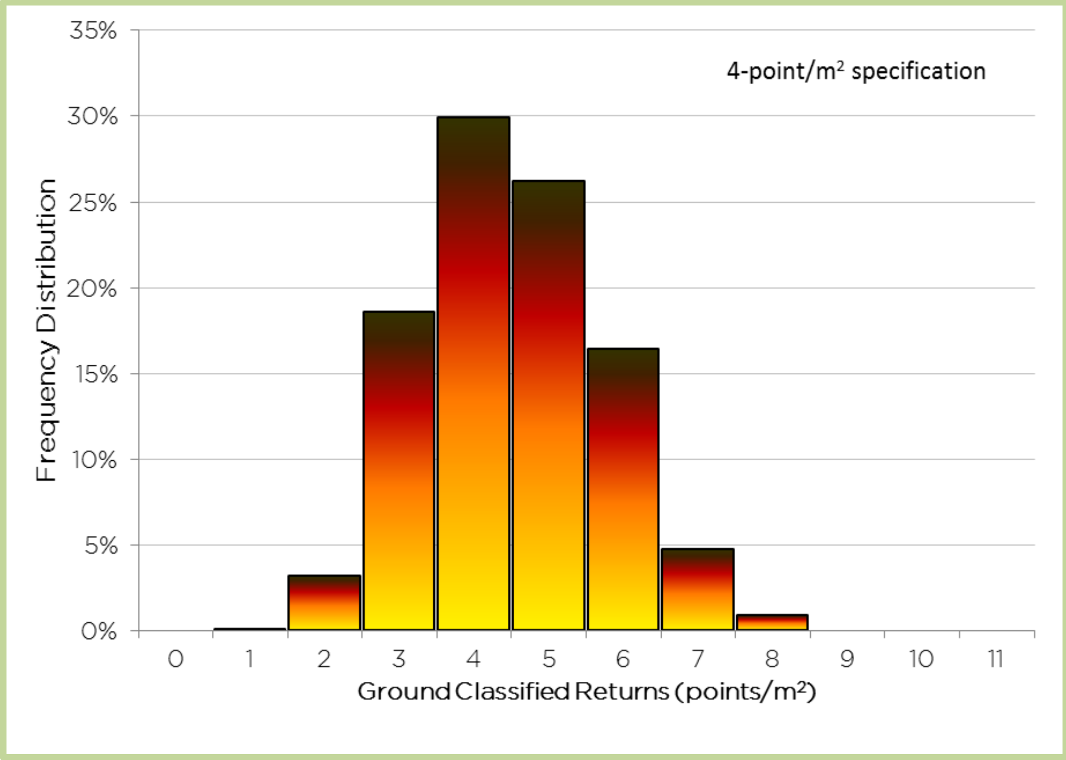


Figure 8: Frequency distribution of ground return densities of the 1m gridded study area above 1600-foot elevation

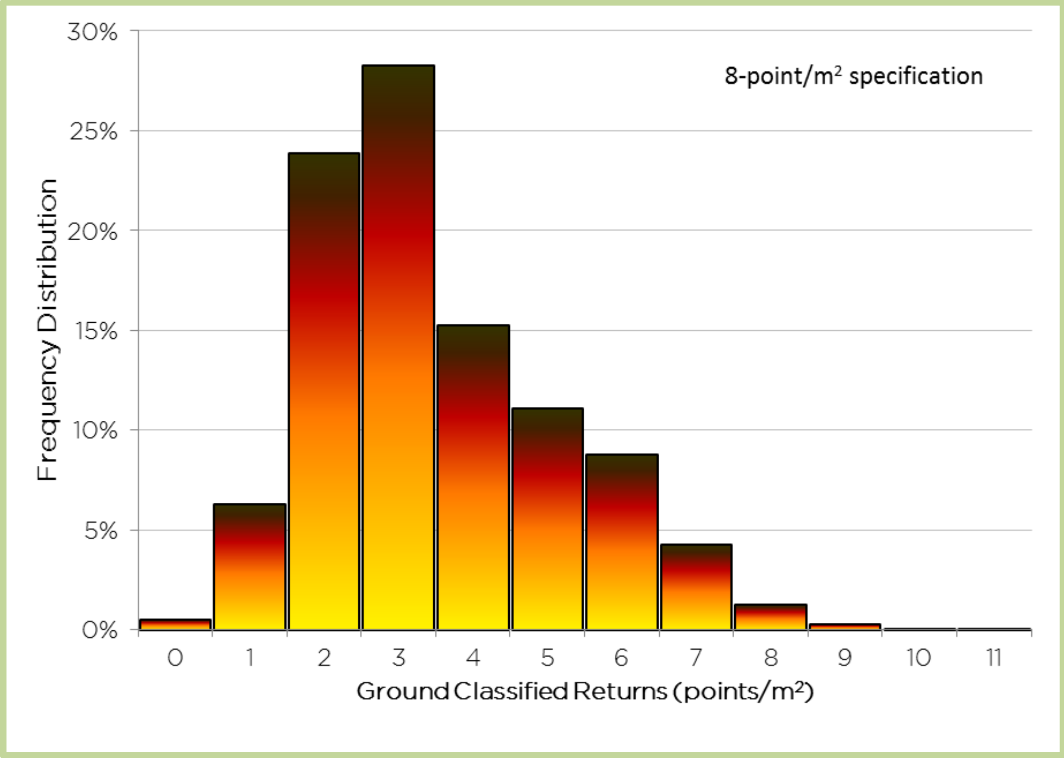


Figure 9: Frequency distribution of ground return densities of the 1m gridded study area below 1600-foot elevation

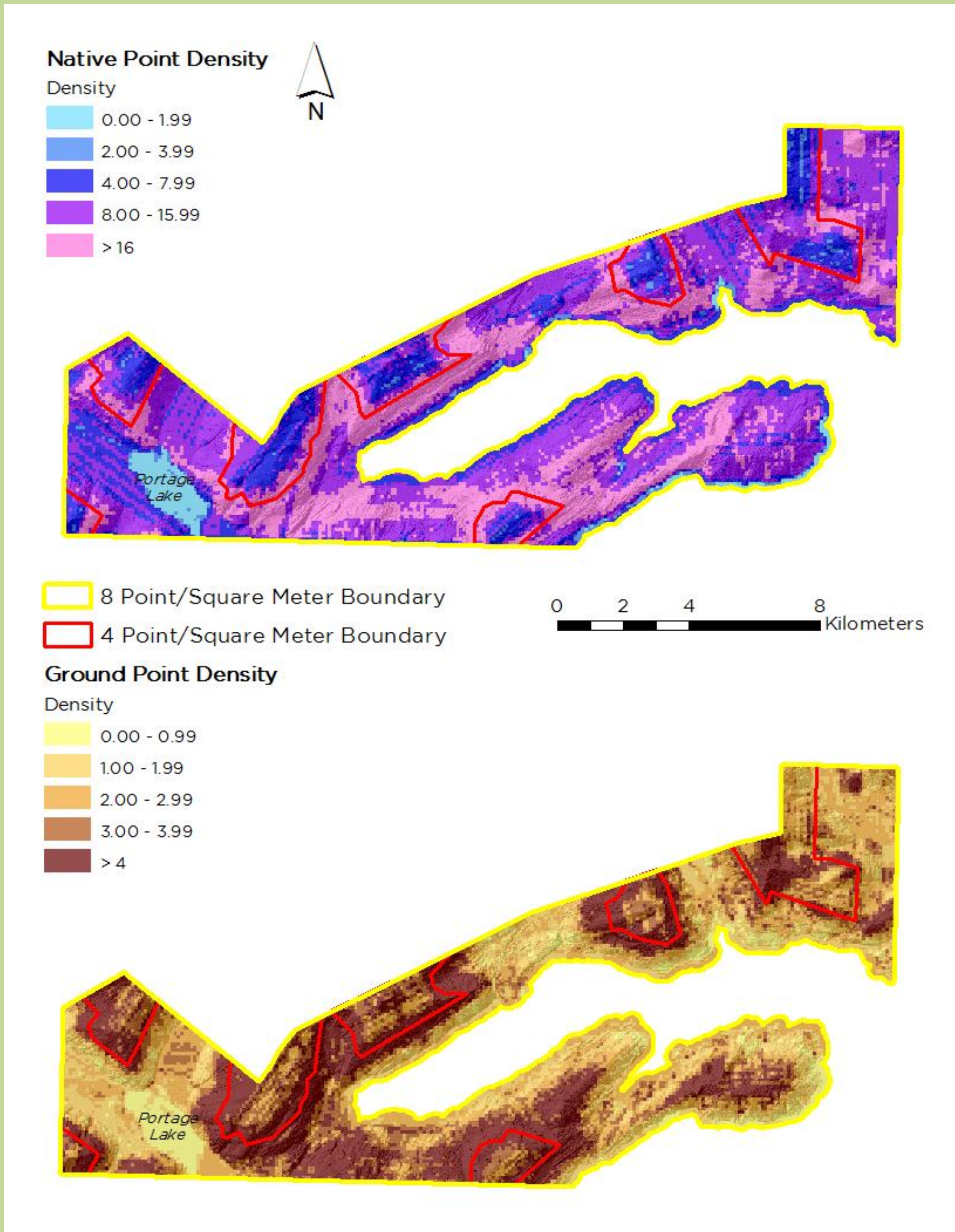


Figure 10: Native (first return) density and ground density maps for the Whittier, Alaska LiDAR site

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).

LiDAR Absolute Accuracy

Vertical absolute accuracy was primarily assessed from RTK ground check point (GCP) data collected on open, bare earth surfaces with level slope (<20°). Fundamental Vertical Accuracy (FVA) reporting is designed to meet guidelines presented in the National Standard for Spatial Data Accuracy (FGDC, 1998). FVA compares known RTK ground survey check points to the triangulated ground surface generated by the LiDAR points. FVA is a measure of the accuracy of LiDAR point data in open areas where the LiDAR system has a "very high probability" of measuring the ground surface and is evaluated at the 95% confidence interval (1.96 σ).

Absolute accuracy is described as the mean and standard deviation (sigma σ) of divergence of the ground surface model from ground survey point coordinates. 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 Whittier, Alaska LiDAR survey, WSI collected 385 RTK points resulting in an average accuracy of -0.002 meters (Table 9, Figure 11). McClintock Land Associates (MLA) of Eagle River, Alaska collected blind check points as an independent accuracy assessment. The complete MLA report can be seen in Appendix A.

Table 9: Absolute and relative accuracies

Statistic	Absolute Accuracy	Relative Accuracy
Sample	385 points	439 surfaces
Average	-0.002 m	0.063 m
Median	- 0.001 m	0.063 m
RMSE	0.022 m	0.065 m
1σ	0.022 m	0.010 m
2σ	0.043 m	0.019 m

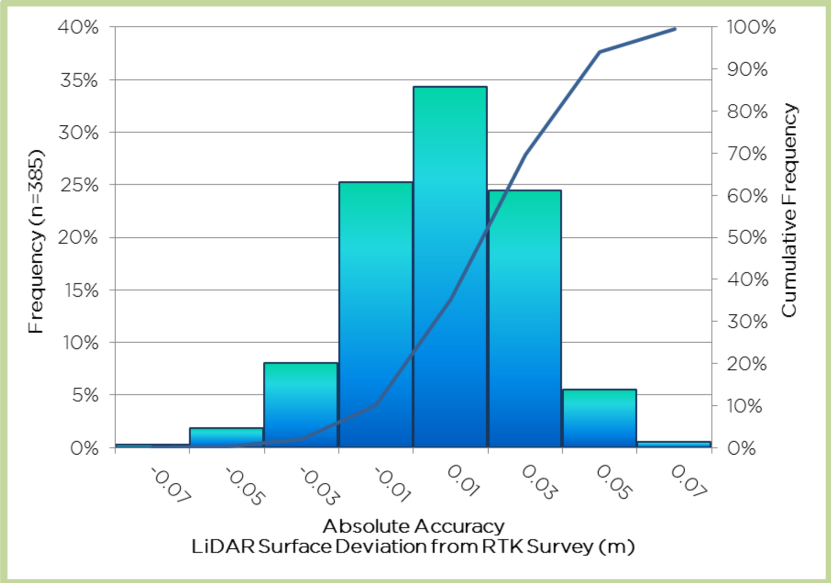


Figure 11: Frequency histogram for LiDAR surface deviation from WSI RTK values

LiDAR Relative Accuracy

Relative 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 divergence is low (<0.10 meters). The relative accuracy is computed by comparing the ground surface model of each individual flight line with its neighbors in overlapping regions. See Appendix B and C for further information on sources of error and operational measures used to improve relative accuracy. The average relative accuracy for the Whittier, Alaska LiDAR was 0.063 meters (Table 9, Figure 12).

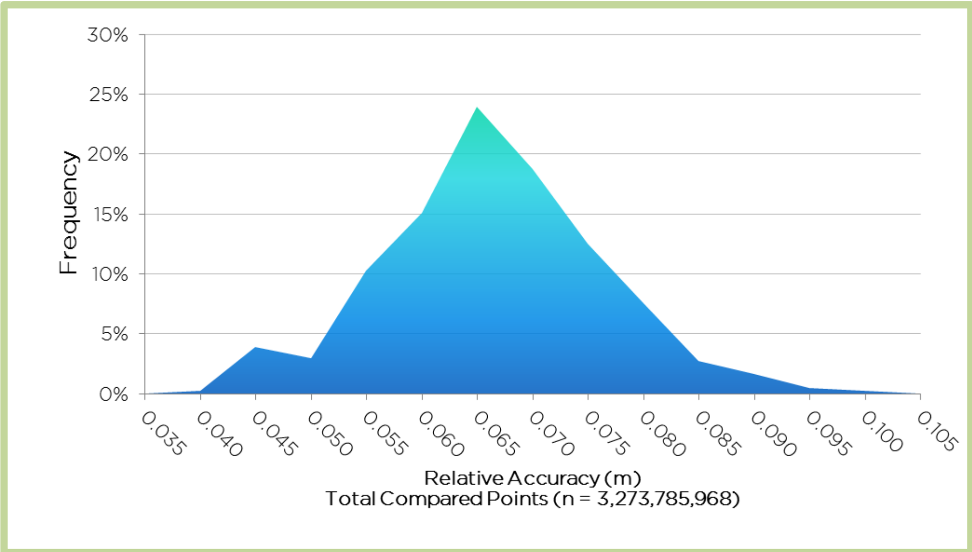


Figure 12: Frequency plot for relative accuracy between flight lines

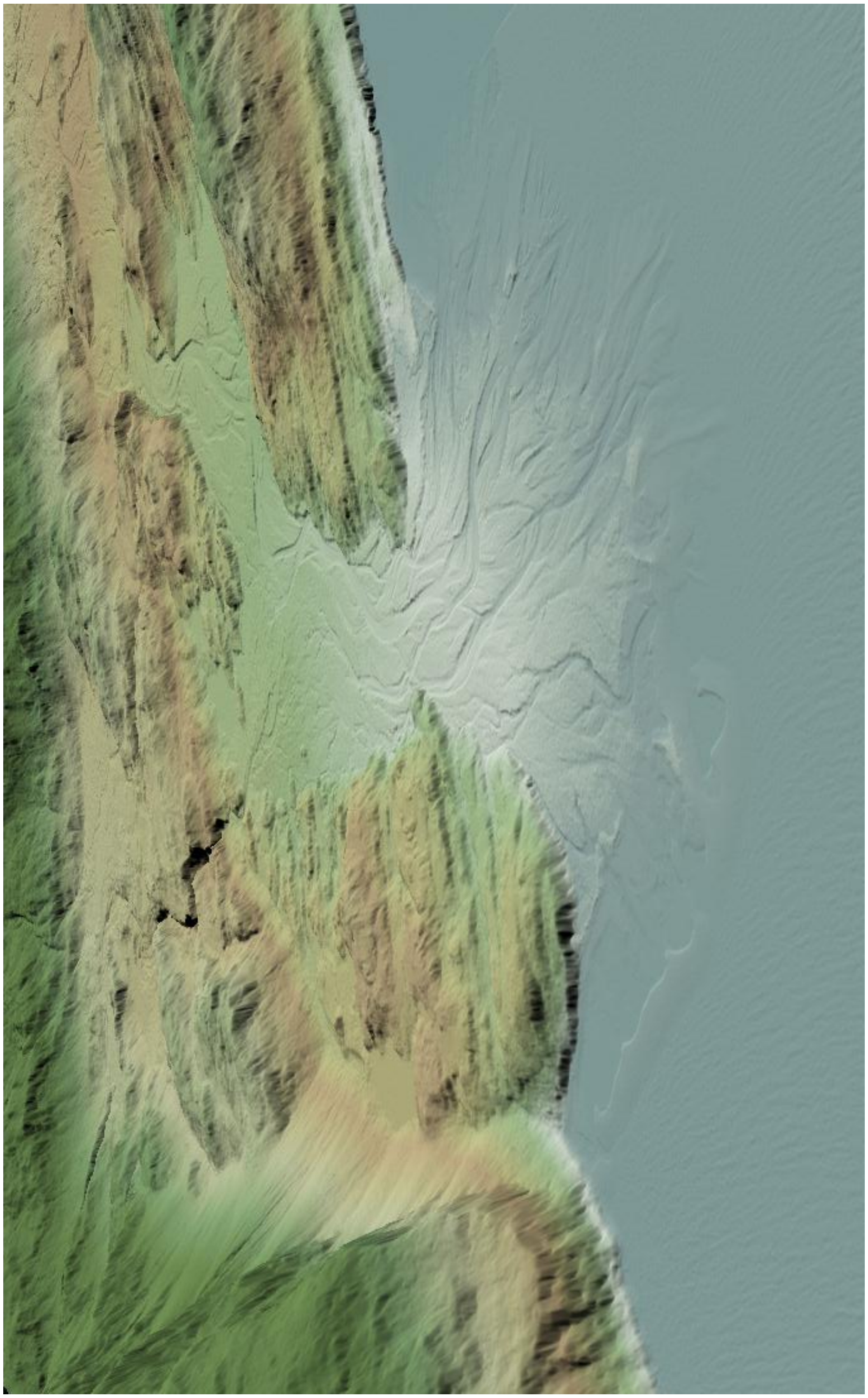


Figure 13: View looking north towards the mouth of Billings Creek. Image created from LiDAR derived bare-earth model colored by elevation.

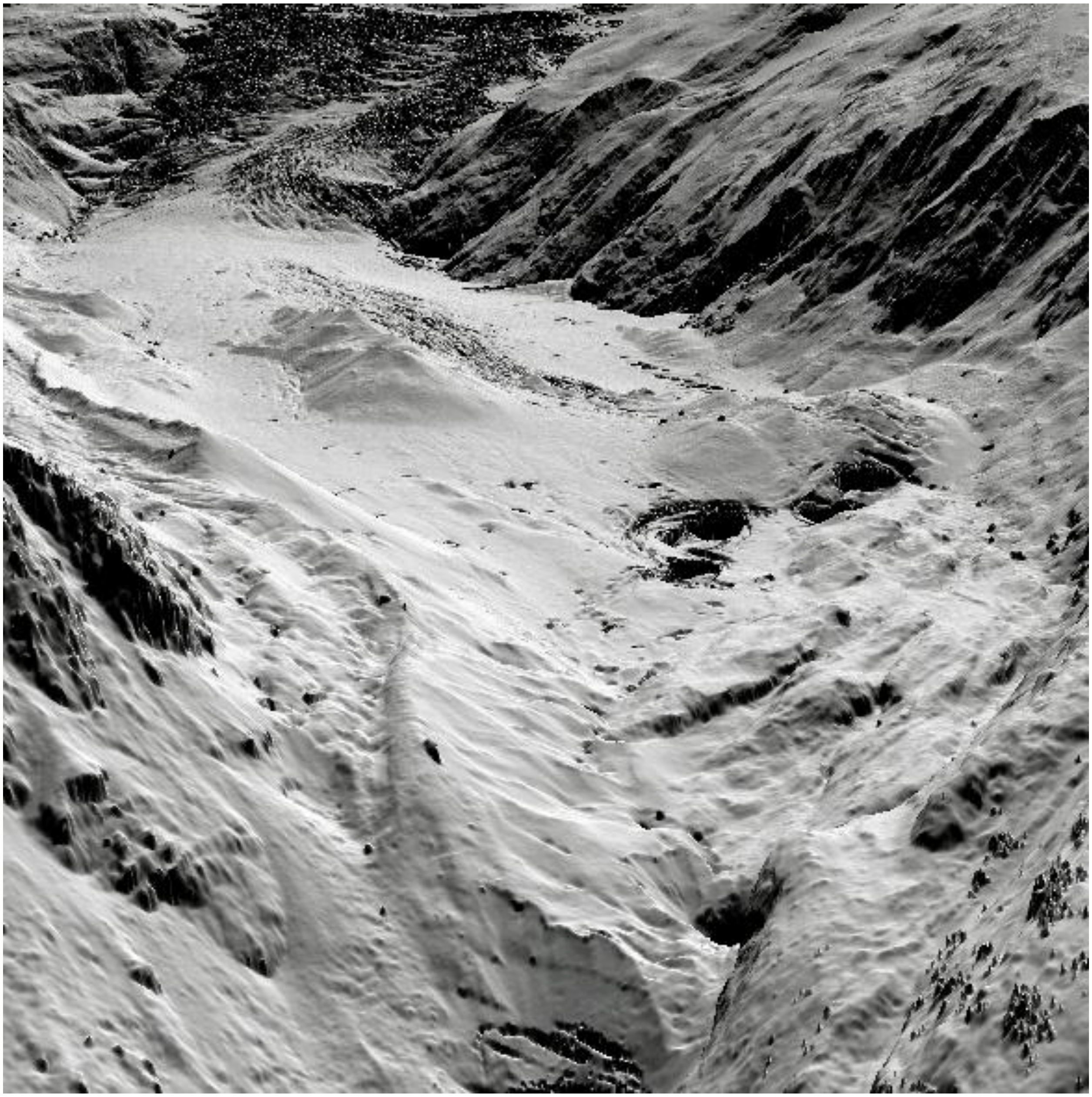


Figure 14: View looking north up Learnard Glacier. Image created from LiDAR derived highest-hit model.

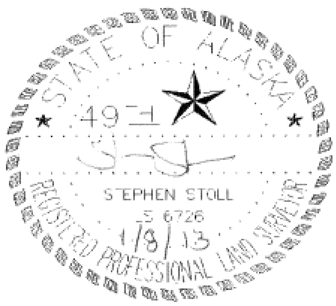
Figure 15: View looking north at the Meadows near Poe Bay. Image created from a LiDAR point cloud colored by elevation.

WHITTIER LIDAR MAPPING CONTROL SHEET

The project reference frame is NAD_83(2011)(EPOCH:2010.0000) & the elevations are [NAVD88 (computed using GEOID 12A)]; and all based on an averaged OPUS solution of five independent occupations of Control Point 2B, a rebar and alcap set by MLA for this project, which constrains a GNSS Network of Static occupations processed using Topcon Tools v8.2. Coordinates shown are Alaska State Plane, Zone 4, expressed in meters.

PT NO	NORTHING	EASTING	ELEVATION	DESCRIPTION
100	759708.755	555731.74	8.604	FOUND NGS STATION "ENDING" 3-1/4" BRASS CAP ON 2" IRON PIPE
101	759764.752	555576.318	9.049	CP1A, SET 2" ALCAP ON 5/8"REBAR
102	761810.34	555415.786	8.734	CP1B, SET 2" ALCAP ON 5/8"REBAR
103	755883.658	563116.791	33.199	CP1C, SET PK NAIL IN PAVEMENT
104	755589.247	569832.098	6.573	CP2A, SET 2" ALCAP ON 5/8"REBAR
105	755284.548	571843.253	5.293	CP2B, SET 2" ALCAP ON 5/8"REBAR
106	755639.423	573278.22	62.943	CP2C, SET PK NAIL IN PAVEMENT
107	760931.148	585847.687	7.289	CP3A, SET 2" ALCAP ON 5/8"REBAR

I HEREBY CERTIFY THAT I AM LICENSED TO PRACTICE LAND SURVEYING IN THE STATE OF ALASKA AND THAT THE INFORMATION CONTAINED HEREON IS TRUE AND ACCURATE TO THE BEST OF MY KNOWLEDGE.



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-sigma (σ) Absolute Deviation: Value for which the data are within two standard deviations (approximately 95th percentile) of a normally distributed data set.

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.

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

Pulse Returns: For every laser pulse emitted, the Leica ALS 60 system can record *up to four* wave forms reflected back to the sensor. Portions of the wave form that return earliest 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.

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).

Intensity Values: The peak power ratio of the laser return to the emitted laser. It is a function of surface reflectivity.

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

Spot Spacing: Also a measure of LiDAR resolution, measured as the average distance between laser points.

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.

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

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

DTM / DEM: These often-interchanged terms refer to models made from laser points. The digital elevation model (DEM) refers to all surfaces, including bare ground and vegetation, while the digital terrain model (DTM) refers only to those points classified as ground.

Real-Time Kinematic (RTK) Survey: GPS surveying is 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.

Whittier LiDAR Project

Watershed Sciences, Inc.
McClintock Land Associates, Inc.

QUALITY CONTROL REVIEW SUMMARY

Max. Positive Elev. Deviation:	0.37	meters
Max. Negative Elev. Deviation:	-0.24	meters
Elevation Deviation Range:	0.60	meters
Elevation Deviation Mean:	0.01	meters
Elevation Deviation RMSE	**0.08**	**meters**

Root Mean Square Error)

Number of Check Points Used: 120.00

CHECK POINTS			SURVEYED		LiDAR	
Point Number	Northing (Meters)	Easting (Meters)	Elevation (Meters)	DESCRIPTOR	Elevation (Meters)	Deviation (Meters)
103	755883.658	563116.791	33.199	PK CP1C	33.239	-0.04
510	754360.054	576988.988	3.712	OG STATIC	3.439	0.27
511	756339.122	580557.27	4.699	OG STATIC	4.679	0.02
601	760930.881	585844.758	6.742	OG	6.784	-0.04
602	760936.815	585844.333	5.351	OG	5.274	0.08
603	760946.366	585848.376	4.686	OG	4.744	-0.06
604	760966.156	585838.504	4.191	OG	4.223	-0.03
605	758827.304	584055.183	4.453	OG	4.374	0.08
606	758851.296	584086.258	5.448	OG	5.285	0.16
610	761631.748	583042.264	3.186	OG	3.186	0.00
611	760646.064	579897.804	4.989	OG	4.860	0.13
612	760646.684	579940.631	7.037	OG	7.250	-0.21
613	757486.174	579904.161	6.15	OG	6.170	-0.02
614	757515.984	579909.922	3.974	OG	4.210	-0.24
615	757544.187	579909.417	4.248	OG	4.211	0.04
616	756436.7	578343.954	3.593	OG	3.629	-0.04
617	756439.426	578345.611	4.146	OG	4.069	0.08
618	758243.479	578925.961	3.99	OG	3.935	0.06
619	758259.072	578936.09	4.687	OG	4.726	-0.04
620	758542.853	577458.123	6.623	OG	6.257	0.37
621	758542.83	577458.107	6.6	OG	6.277	0.32
622	758077.001	576582.185	3.236	OG	3.261	-0.02
623	758068.585	576549.666	9.241	OG	9.181	0.06
624	757130.894	575497.662	8.885	OG	8.969	-0.08
625	757151.929	575477.784	8.534	OG	8.630	-0.10
626	757132.005	575485.882	7.875	OG	7.969	-0.09
627	760947.567	576206.208	4.416	OG	4.447	-0.03
628	760929.085	576159.048	3.358	OG	3.326	0.03
629	759466.623	574293.105	4.554	OG	4.713	-0.16
630	759406.294	574276.719	2.702	OG	2.712	-0.01
631	757033.262	571051.576	2.943	OG	3.043	-0.10
634	755711.307	569682.417	13.464	OG	13.538	-0.07
635	755720.542	569676.541	13.743	OG	13.808	-0.06
636	755724.817	569664.817	14.136	OG	14.208	-0.07
637	755724.57	569651.452	14.561	OG	14.588	-0.03
638	755267.053	569425.218	16.527	OG	16.573	-0.05

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CHECK POINTS			SURVEYED Elevation (Meters)	DESCRIPTOR	LiDAR Elevation (Meters)	Deviation (Meters)
Point Number	Northing (Meters)	Easting (Meters)				
639	755261.179	569439.574	16.571	OG	16.614	-0.04
640	755256.247	569450.451	16.728	OG	16.774	-0.05
641	755248.474	569461.733	16.948	OG	16.954	-0.01
642	755342.973	571174.145	6.937	OG	6.976	-0.04
643	755350.327	571187.145	6.697	OG	6.726	-0.03
644	755351.039	571200.56	6.623	OG	6.666	-0.04
645	755339.357	571197.557	7.013	OG	7.046	-0.03
646	754702.536	571389.706	22.238	OG	22.217	0.02
647	754734.666	571388.793	21.218	OG	21.228	-0.01
648	754784.87	571386.433	18.607	OG	18.589	0.02
649	754792.823	571402.283	19.015	OG	18.929	0.09
650	755246.962	572600.854	32.761	OG	32.765	0.00
651	755252.906	572619.751	32.414	OG	32.425	-0.01
652	756290.884	574097.714	41.127	OG	41.165	-0.04
653	756287.771	574090.096	44.102	OG	43.885	0.22
654	755648.792	573288.679	61.613	OG	61.616	0.00
655	755608.131	573254.101	62.15	OG	62.175	-0.02
660	755526.327	562901.012	40.202	OG	40.278	-0.08
661	755530.659	562903.54	40.052	OG	40.068	-0.02
662	755535.446	562905.957	39.904	OG	39.968	-0.06
663	755573.009	562914.39	39.044	CL	39.008	0.04
664	755557.783	562906.856	39.473	CL	39.458	0.02
665	755541.82	562899.192	39.985	CL	39.948	0.04
666	755529.943	562892.976	40.279	CL	40.238	0.04
667	755513.551	562884.712	40.667	CL	40.658	0.01
668	756665.78	564746.371	43.863	OG	43.781	0.08
669	756668.373	564738.584	43.854	OG	43.801	0.05
670	756670.442	564732.075	43.848	OG	43.741	0.11
671	756672.831	564724.512	43.844	OG	43.771	0.07
672	756666.59	564722.322	43.963	OG	43.881	0.08
673	756664.205	564729.013	43.972	OG	43.921	0.05
674	756660.826	564728.006	44.055	OG	43.981	0.07
675	756657.65	564726.957	44.125	OG	44.061	0.06
676	756654.246	564725.994	44.18	OG	44.141	0.04
677	756651.031	564725.286	44.246	OG	44.201	0.05
678	756647.459	564724.267	44.323	OG	44.251	0.07
679	756644.281	564732.074	44.326	OG	44.261	0.06
680	756639.059	564721.179	44.458	OG	44.422	0.04
681	756642.666	564711.513	44.399	OG	44.352	0.05
682	756645.751	564703.244	44.441	OG	44.422	0.02
683	756655.366	564700.391	44.286	OG	44.241	0.05
684	756661.675	564681.52	44.254	OG	44.171	0.08
685	756672.625	564649.002	44.19	OG	44.161	0.03
694	756140.634	563031.919	35.745	OG	35.666	0.08
695	756140.653	563031.924	35.736	OG	35.666	0.07
696	756135.402	563011.907	35.029	OG	34.966	0.06
697	756127.983	563000.086	34.834	OG	34.745	0.09

Whittier LiDAR Project

Watershed Sciences, Inc.
McClintock Land Associates, Inc.

CHECK POINTS			SURVEYED		LiDAR	
Point Number	Northing (Meters)	Easting (Meters)	Elevation (Meters)	DESCRIPTOR	Elevation (Meters)	Deviation (Meters)
698	756080.764	561723.439	27.185	OG	27.198	-0.01
699	756070.554	561724.992	27.281	OG	27.247	0.03
700	756060.7	561726.274	26.787	OG	26.767	0.02
701	756050.806	561727.092	26.777	OG	26.757	0.02
702	756048.516	561731.52	26.844	OG	26.917	-0.07
703	756053.8	561731.235	26.848	OG	26.907	-0.06
704	756062.314	561730.537	26.983	OG	27.078	-0.09
705	756068.919	561729.998	27.127	OG	27.238	-0.11
706	756316.948	561395.995	26.498	OG	26.446	0.05
707	756316.15	561404.759	26.495	OG	26.456	0.04
708	756314.737	561415.029	26.519	OG	26.456	0.06
709	756313.571	561425.447	26.537	OG	26.506	0.03
710	756309.832	561424.641	26.525	OG	26.446	0.08
711	756310.93	561415.163	26.52	OG	26.466	0.05
712	756312.143	561407.085	26.518	OG	26.466	0.05
713	756313.421	561396.376	26.491	OG	26.446	0.04
714	754573.808	563705.329	41.167	OG	41.194	-0.03
715	754589.33	563705.167	40.626	OG	40.674	-0.05
716	754603.681	563703.812	40.254	OG	40.265	-0.01
717	754616.539	563700.412	39.862	OG	39.915	-0.05
718	754630.265	563695.712	39.429	OG	39.505	-0.08
719	754626.614	563692.723	39.599	OG	39.645	-0.05
720	754612.106	563695.804	40.066	OG	40.115	-0.05
721	754590.871	563698.898	40.671	OG	40.664	0.01
722	754577.512	563700.188	41.084	OG	41.154	-0.07
723	754566.551	563701.288	41.493	OG	41.554	-0.06
724	756592.658	561767.443	27.97	OG	28.017	-0.05
725	756593.047	561762.291	27.801	OG	27.827	-0.03
726	756592.044	561753.667	27.328	OG	27.377	-0.05
727	756589.85	561743.011	26.961	OG	27.007	-0.05
728	756587.664	561734.03	26.684	OG	26.737	-0.05
729	756585.548	561727.283	26.535	OG	26.567	-0.03
730	756583.055	561717.731	26.401	OG	26.437	-0.04
731	755886.926	563113.49	33.205	OG	33.189	0.02
732	755881.253	563111.395	33.213	OG	33.179	0.03
733	755878.8	563108.133	33.231	OG	33.249	-0.02
734	755876.482	563114.611	33.196	OG	33.209	-0.01

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Laser Noise

For any given target, laser noise is the breadth of the data cloud per laser return (i.e., last, first, etc.). Lower intensity surfaces (roads, rooftops, still/calm water) experience higher laser noise. The laser noise range for this survey was approximately 0.02 meters.

Relative Accuracy

Relative accuracy refers to the internal consistency of the data set - 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).

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.

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 RTK 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, thus we also consider the skew and kurtosis of distributions when evaluating error statistics.

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 is employed to maintain a constant above ground level (AGL). Laser horizontal errors are a function of flight altitude above ground (i.e., ~ 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 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 ±15^{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 19 km (11.5 miles) at all times.

Ground Survey: Ground survey point accuracy (i.e. <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 RTK 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 most nadir portion of one flight line coincides with the edge (least nadir) 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 are opposing. 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.