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Okanagan Lakes, British Columbia

Topobathymetric Lidar Technical Data Report

Prepared For:

Anna Warwick-Sears
Okanagan Basin Water Board
1450 KLO Road
Kelowna, BC, V1W 1G5
anna.warwick.sears@obwb.ca

Prepared By:

NV5 Geospatial Corvallis
1100 NE Circle Blvd, Ste. 126
Corvallis, OR 97330
PH: 541-752-1204

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Cover Photo: A photo taken by NV5 acquisition staff shows a scenic view over the Okanagan lakes project area.

Introduction

This photo taken by NV5 acquisition staff shows a view of the the Okanagan Lakes site in British Columbia.

In July 2021, NV5 Geospatial (NV5) was contracted by the Okanagan Basin Water Board (OBWB) to collect topobathymetric Light Detection and Ranging (lidar) data and digital imagery in the late summer and early fall of 2021 for the Okanagan Lakes sites in British Columbia. The Okanagan Lakes areas of interest extends south from just north of the town of Vernon down to the Canadian/United States border within the Okanagan Basin. The project area encompasses Okanagan Lake, Kalamalka Lake, Wood Lake, Ellison Lake, Skaha Lake, Vaseux Lake, and Osoyoos Lake. Traditional near-infrared (NIR) lidar was fully integrated with green wavelength return data (bathymetric) lidar in order to provide a seamless topobathymetric lidar dataset. Topobathymetric lidar data of the lakes were collected to supplement existing 2018 topographic lidar legacy data in order to create an integrated dataset of the two. The NV5 Geospatial newly acquired topobathymetric lidar will aid OBWB in assessing the nearshore bathymetry of the project area in order to support community planning and policies for flood construction levels.

This report accompanies the delivered topobathymetric lidar data and imagery, and documents contract specifications, data acquisition procedures, processing methods, and analysis of the final dataset including lidar accuracy, depth penetration, and density. Acquisition dates and acreage are shown in Table 1, a complete list of contracted deliverables provided to OBWB 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 Okanagan Lakes site

Project Site	Project Area Square Kilometers	Acquisition Dates	Data Type
Okanagan Lakes, British Columbia	573	09/10/2021 - 09/14/2021, 09/16/2021, 09/18/2021, 09/20/2021	Topobathymetric Lidar
		10/04/2021	NIR - Lidar
		09/16/2021	4 band (RGB-NIR) Digital Imagery

Deliverable Products

Table 2: Products delivered to OBWB for the Okanagan Lakes sites

Okanagan Lakes Lidar Products Projection: UTM Zone 11 North Horizontal Datum: NAD83(CSRS) (2002.00) Vertical Datum: CGVD2013(CGG2013a) Units: Meters	
Topobathymetric Lidar	
Points	LAZ v 1.4 PF6 • Raw Swaths • All Classified Returns • Ground and Bathymetric Bottom Classified Returns
Rasters	1.0 Meter Cloud Optimized GeoTiffs • Void Clipped Topobathymetric Bare Earth Digital Elevation Model (DEM)
Vectors	Shapefiles • Area of Interest • Lidar Tile Index • DEM Tile Index • Bathymetric Coverage Shape** • Water's Edge Breaklines • Ground Survey Points
4 Band (RGBI) Digital Imagery	
Rasters	10 cm GeoTiffs • Tiled Imagery Mosaics 10 cm MrSID Compression • AOI Imagery Mosaic
Vectors	Shapefiles • Imagery Tile Index • Area of Interest • Air Target Points

***NV5 delivered these Lidar-derived products in addition to contracted deliverables in order to provide a more complete and versatile dataset to OBWB.*

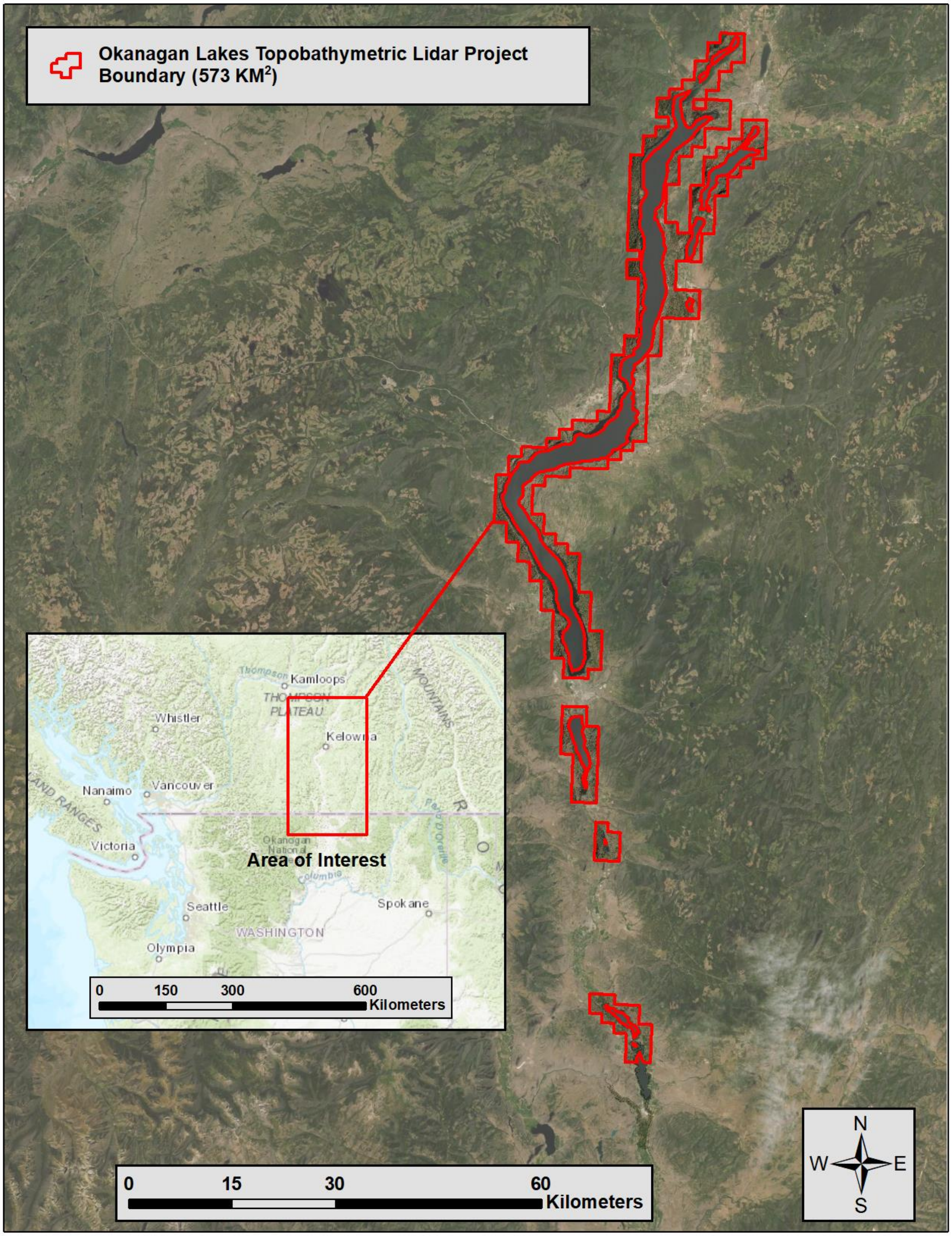


Figure 1: Location map of the Okanagan Lakes site in British Columbia

NV5's ground acquisition equipment set up over monument 99C040 in the Okanagan Lakes Lidar study area.

Planning

In preparation for data collection, NV5 reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Okanagan Lakes Lidar study area at the target combined point density of ≥4 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, potential air space restrictions, and water clarity conditions were reviewed.

Turbidity Measurements and Secchi Depth Readings

In order to assess water clarity conditions prior to and during lidar and digital imagery collection, NV5 collected turbidity measurements, secchi depth readings, and weather observations. Readings were collected at 31 locations throughout the project site between August 30 and September 21, 2021. Turbidity measurements were recorded three times at each location to confirm measurements. The table below provides turbidity and secchi depth results per site on each day of data collection.

Table 3: Water Clarity Observations for Lidar flights.

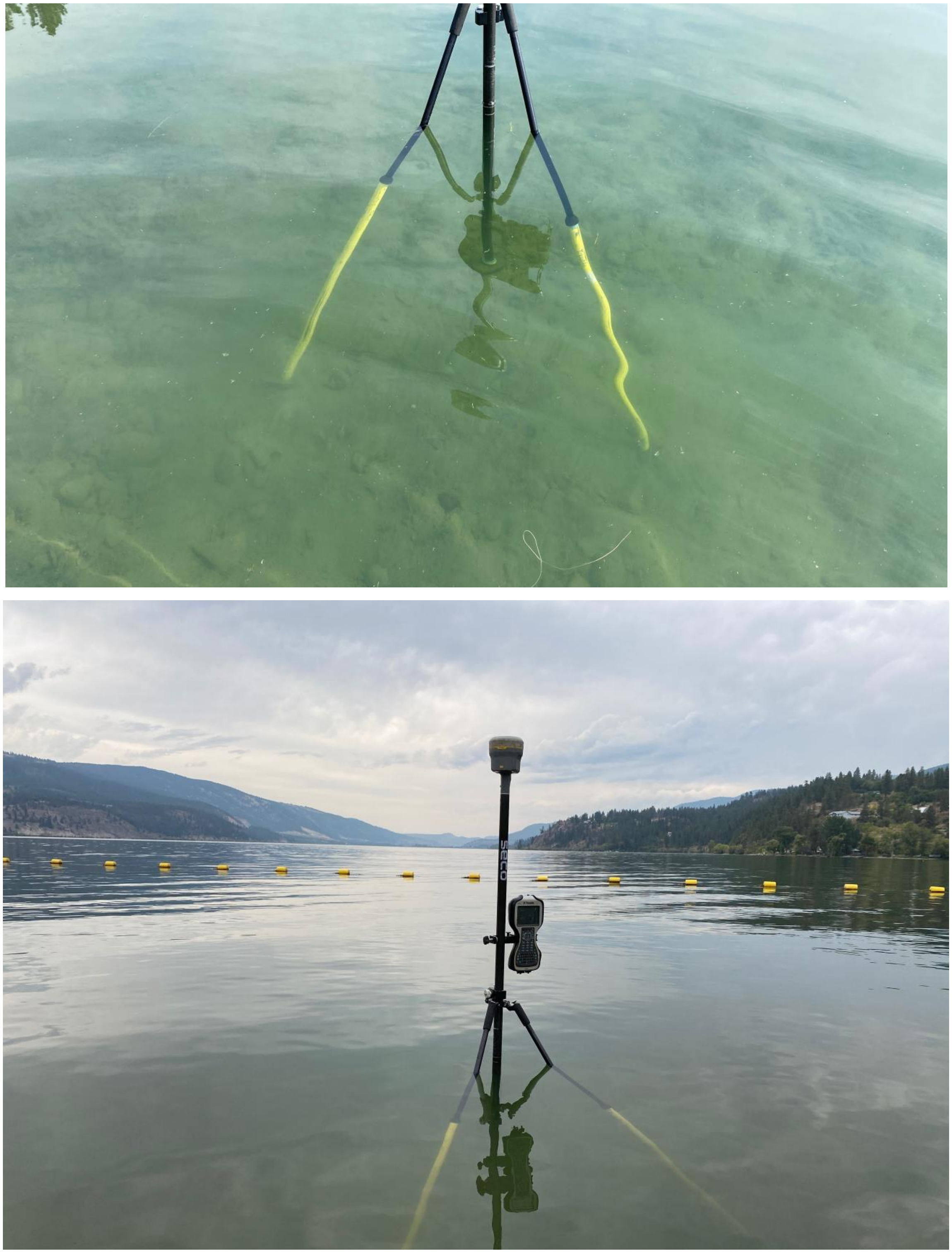
Turbidity, Secchi Depth, and Wind Speed Observations						
Date	Time	Location	Turbidity Read 1 (NTUs)	Turbidity Read 2 (NTUs)	Turbidity Read 3 (NTUs)	*Secchi Depth (m)
8/30/21	10:15	UWT01	1.12	1.22	0.81	4.25 m
8/31/21	9:15	UWT02	1.52	2.09	1.31	3.95 m
8/31/21	11:10	UWT03	2.01	2.66	2.09	3.45 m
9/01/21	9:40	UWT04	0.27	0.35	0.26	7.75 m
9/01/21	12:20	UWT05	0.25	0.31	0.29	6.50 m
9/02/21	9:00	UWT06	0.16	0.16	0.45	7.90 m
9/02/21	12:00	UWT07	0.74	0.24	0.82	5.50 m
9/03/21	8:15	UWT08	0.37	0.78	0.47	3.70 m
9/03/21	8:40	TURB_09	0.46	0.44	1.28	4.25 m
9/08/21	8:35	UWT09	0.10	0.00	0.24	8.50 m
9/08/21	9:30	UWT05	0.10	0.34	0.01	8.50 m
9/10/21	13:40	TURB_11	0.55	0.49	1.46	2.50 m
9/10/21	16:45	TURB_12	1.95	0.94	1.95	2.30 m
9/11/21	14:35	TURB_13	0.29	0.00	0.33	3.80 m
9/12/21	12:05	SECCHI_14 & TURB_14	0.04	0.04	0.01	4.50 m
9/12/21	15:15	TURB_15	0.11	0.09	0.23	1.75 m
9/13/21	15:50	TURB_16	0.18	0.12	0.10	2.70 m
9/13/21	17:20	TURB_17	0.30	0.18	0.76	1.20 m
9/13/21	18:15	TURB_18	0.37	0.46	0.36	1.45 m
9/14/21	9:25	TURB_19	8.15	7.94	7.73	0.80 m
9/14/21	16:00	TURB_20	0.31	0.28	0.35	3.75 m
9/14/21	17:05	TURB_21	0.37	0.48	0.45	1.10 m
9/15/21	12:17	TURB_22	0.48	0.06	0.20	0.85 m
9/15/21	13:00	TURB_23	6.64	6.00	5.88	1.10 m
9/15/21	13:50	TURB_24	2.35	0.89	1.60	1.40 m
9/15/21	14:34	TURB_25	0.36	0.47	0.32	1.25 m
9/16/21	11:10	TURB_16	0.31	0.24	0.33	2.70 m
9/16/21	12:55	TURB_26	0.18	0.16	0.36	1.85 m

Date	Time	Location	Turbidity Read 1 (NTUs)	Turbidity Read 2 (NTUs)	Turbidity Read 3 (NTUs)	*Secchi Depth (m)
9/16/21	16:10	SECCHI_14 & TURB_14	0.07	0.30	0.46	4.90 m
9/17/21	12:15	TURB_27	0.24	0.06	0.46	7.00 m
9/18/21	15:40	TURB_28	0.11	0.18	0.24	1.70 m
9/18/21	16:25	TURB_29	0.49	0.24	0.28	2.20 m
9/18/21	17:55	TURB_19	12.73	11.78	11.66	0.75 m
9/20/21	11:00	TURB_29	0.28	0.39	0.53	2.65 m
9/20/21	16:35	TURB_30	0.61	0.52	0.52	2.00 m
9/21/21	10:20	TURB_19	11.07	11.86	11.25	0.80 m
9/21/21	13:20	TURB_31	0.76	0.40	0.36	3.15 m

Table 4: Secchi Depth and Turbidity Locations. Coordinates are on the NAD83 (CSRS) datum, UTM Zone 11N

Secchi Depth and Turbidity Locations				
Location	**X**	**Y**	**Z**	**Reading Type**
UWT01	332038.391	5575481.152	341.842	Secchi Depth
UWT02	329750.146	5554423.251	391.369	Secchi Depth
UWT03	330565.000	5553057.384	391.421	Secchi Depth
UWT04	318924.521	5528804.654	341.868	Secchi Depth
UWT05	308666.913	5516508.557	341.944	Secchi Depth
UWT06	309566.767	5492477.413	341.902	Secchi Depth
UWT07	312872.074	5470015.254	337.953	Secchi Depth
UWT08	320247.555	5432251.463	277.933	Secchi Depth
UWT09	321279.101	5532382.769	341.838	Secchi Depth
TURB_09	320144.546	5434816.847	277.947	Secchi Depth and Turbidity
TURB_11	338304.467	5566704.31	392.737	Secchi Depth and Turbidity
TURB_12	327578.719	5547285.774	391.219	Secchi Depth and Turbidity
TURB_14	311609.034	5522094.361	343.009	Secchi Depth and Turbidity
TURB_15	329364.342	5553606.720	394.411	Secchi Depth and Turbidity

Location	X	Y	Z	Reading Type
TURB_16	308532.971	5498175.411	343.778	Secchi Depth and Turbidity
TURB_17	316499.575	5462351.788	327.62	Secchi Depth and Turbidity
TURB_18	312773.147	5469324.991	338.538	Secchi Depth and Turbidity
TURB_19	327848.679	5541182.057	425.056	Secchi Depth and Turbidity
TURB_20	321281.783	5434689.348	278.207	Secchi Depth and Turbidity
TURB_21	321784.983	5431718.644	278.283	Secchi Depth and Turbidity
TURB_22	321168.404	5423039.579	276.757	Secchi Depth and Turbidity
TURB_23	322066.536	5424668.201	278.335	Secchi Depth and Turbidity
TURB_24	321276.971	5426357.312	277.673	Secchi Depth and Turbidity
TURB_25	322422.722	5420828.723	275.155	Secchi Depth and Turbidity
TURB_26	308458.657	5498100.935	342.291	Secchi Depth and Turbidity
TURB_27	321606.45	5542826.524	342.189	Secchi Depth and Turbidity
TURB_28	326790.368	5562885.898	342.292	Secchi Depth and Turbidity
TURB_29	331573.513	5567446.515	342.182	Secchi Depth and Turbidity
TURB_30	325658.127	5568122.342	342.719	Secchi Depth and Turbidity
TURB_31	331562.844	5567442.689	342.112	Secchi Depth and Turbidity
SECCHI_14	311627.589	5522058.737	344.598	Secchi Depth and Turbidity



NV5 field survey photos showing water clarity conditions and ground survey equipment set up over submerged shallow water targets at two location within the Okanagan Lakes Area of Interest.

Airborne Survey

Lidar

The lidar survey was accomplished using Leica Chiroptera/Hawkeye 4X and Riegl VQ1560ii-S green and NIR laser systems mounted in a Cessna Caravan and Cessna Stationair, respectively. The green wavelength laser (ʎ=532 nm) is capable of collecting high resolution topography data, as well as penetrating the water surface with minimal spectral absorption by water. The NIR wavelength laser (ʎ=1064 nm) adds additional topography data and aids in water surface modeling. The recorded waveform enables range measurements for all discernible targets for a given pulse. The typical number of returns digitized from a single pulse range from 1 to 12 for the Okanagan Lakes project area. It is not uncommon for some types of surfaces (e.g., dense vegetation or water) to return fewer pulses to the lidar sensor than the laser originally emitted. The discrepancy between first return and overall delivered density will vary depending on terrain, land cover, and the prevalence of water bodies. All discernible laser returns were processed for the output dataset. Table 5 summarizes the settings used to yield an average pulse density of ≥4 pulses/m^2 over the Okanagan Lakes project area.

All areas were surveyed with an opposing flight line side-lap of ≥20% (≥40% 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.

Leica Chiroptera CH4x and HawkEye HE4X Lidar Sensor System

Table 5: Lidar specifications and survey settings

Lidar Survey Settings & Specifications				
Acquisition Dates	09/10/2021 – 09/14/2021, 09/16/2021, 09/18/2021, 09/20/2021			10/04/2021
Aircraft Used	Cessna Caravan			Cessna Stationair
Sensor	Leica			Riegl
Laser	Chiroptera 4X NIR	Chiroptera 4X Green	Hawkeye 4X Green	VQ1560ii-S
Maximum Returns	15	15	15	15
Resolution/Density	Average 4 pulses/m^2	Average 4 pulses/m^2	Average 4 pulses/m^2	Average 5 pulses/ m^2
Nominal Pulse Spacing	0.50 m	0.50 m	0.50 m	0.45 m
Survey Altitude (AGL)	500 m	500 m	500 m	1500 m
Survey speed	145 knots	145 knots	145 knots	145 knots
Field of View	40º	40º	40º	58.5º
Scan Frequency	37 Rotations Per Second	37 Rotations Per Second	37 Rotations Per Second	Uniform Point Spacing
Target Pulse Rate	250 kHz	35 kHz	10 kHz	914 kHz
Pulse Length	2.5 ns	2.5 ns	2.0 ns	3.0 ns
Laser Pulse Footprint Diameter	0.1 m	1.6 m	2.88 m	0.345 m
Central Wavelength	1,064 nm	515 nm	515 nm	1,064 nm
Pulse Mode	Multiple Pulses in Air	Multiple Pulses in Air	Multiple Pulses in Air	Multiple Times Around
Beam Divergence	0.25 mrad	4 mrad	7.2 mrad	0.25 mrad
Swath Width	364 m	364m	364m	1680 m
Swath Overlap	25%	25%	25%	30%
Intensity	16-bit	16-bit	16-bit	16-bit
Accuracy	$RMSE_Z$ (Non-Vegetated) ≤ 20 cm			
	NVA (95% Confidence Level) ≤ 39.2 cm			
	VVA (95th Percentile) ≤ 60 cm			

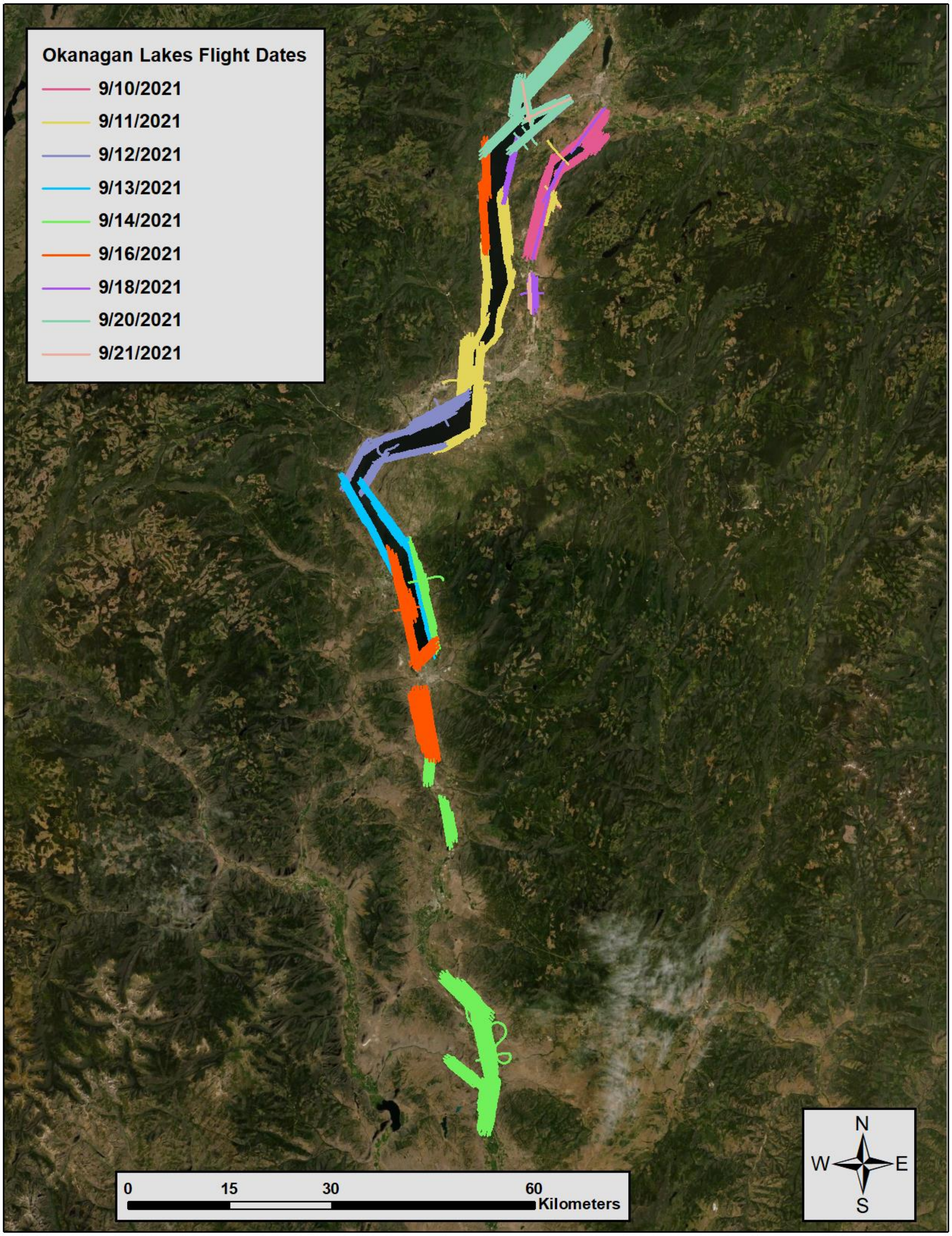


Figure 2: Flightline Index Map

Digital Imagery

Aerial imagery was collected by Peregrine Aerial Surveys using a DMC III digital mapping camera (Table 5). The DMC III is a large format, aerial camera manufactured by Leica. The system is gyro-stabilized and simultaneously collects panchromatic and multispectral (RGB, NIR) imagery.

Table 5: Camera manufacturer's specifications

DMC III	
Focal Length	92 mm
Spectral Bands	RGB NIR
Pixel Size	3.9 µm
Image Size	25,728 x 14,592 pixels
Frame Rate	1.8 seconds
FOV	57° x 34°
Date Format	8bit TIFF

For the Okanagan Lakes site, 840 images were collected with 60% along track overlap and 30% sidelap between frames. The acquisition flight parameters were designed to yield a native pixel resolution of ≤ 10 cm. Orthophoto specifications particular to the Okanagan Lakes project are in Table 6.

Table 6: Project-specific orthophoto specifications

Digital Orthophotography Specifications	
Ground Sampling Distance (GSD)	≤10 cm pixel size
Along Track Overlap	≥60%
Cross Track Overlap	≥30%
Height Above Ground Level (AGL)	2,200 m
GPS PDOP	≤3.0
GPS Satellite Constellation	≥6

Ground Survey

Ground control surveys, including monumentation, aerial targets and ground survey points (GSPs), were conducted by NV5 ground survey staff to support the airborne acquisition. Ground control data were used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on final lidar data and orthoimagery products.

Base Stations

Monuments were used for collection of ground survey points using real time kinematic (RTK), post processed kinematic (PPK), and fast static (FS) survey techniques.

Base station locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage. NV5 utilized five existing NRCAN passive benchmarks, one BCACS station and established six new monuments for the Okanagan Lakes Lidar project (Table 6, Figure 3). New monumentation was set using 5/8" x 30" rebar topped with stamped 2 ½" aluminum caps. NV5's professional land surveyor, Evon Silvia, oversaw the ground survey work for the project.

Table 6: Monument positions for the Okanagan Lakes acquisition. Coordinates are on the NAD83 (CSRS) datum, epoch 2002.00

Monument ID	Province	Type	Latitude	Longitude	Ellipsoid (meters)
79C324	British Columbia	NRCAN BM	50° 23' 34.05667"	-119° 13' 11.50880"	430.852
79C438	British Columbia	NRCAN BM	49° 00' 33.32652"	-119° 24' 40.07234"	553.895
83C146	British Columbia	NRCAN BM	49° 35' 56.03174"	-119° 39' 24.98970"	395.226
85C081	British Columbia	NRCAN BM	50° 03' 56.79857"	-119° 22' 43.94212"	493.310
99C040	British Columbia	NRCAN BM	50° 09' 06.18349"	-119° 22' 13.80410"	419.875
BCSL	British Columbia	BCACS	49° 33' 55.55222"	-119° 38' 39.20938"	429.110
OBWB_01	British Columbia	NV5	49° 51' 50.68429"	-119° 32' 54.87173"	489.619
OBWB_02	British Columbia	NV5	49° 19' 44.45530"	-119° 33' 27.97966"	386.107
OBWB_03	British Columbia	NV5	50° 16' 16.87658"	-119° 17' 40.65732"	506.101
OBWB_04	British Columbia	NV5	50° 02' 30.00082"	-119° 26' 18.44279"	516.043
OBWB_05	British Columbia	NV5	49° 45' 43.46898"	-119° 45' 54.16814"	548.935
OBWB_06	Washington	NV5	48° 55' 59.58845"	-119° 24' 47.92459"	272.828

Ground Survey Points (GSPs)

Ground survey points were collected using real time kinematic (RTK), post-processed kinematic (PPK), and fast-static (FS) survey techniques. For RTK surveys, a roving receiver receives corrections from a nearby base station or Real-Time Network (RTN) via radio or cellular network, enabling rapid collection of points with relative errors less than 1.5 cm horizontal and 2.0 cm vertical. PPK and FS surveys compute these corrections during post-processing to achieve comparable accuracy. RTK and PPK surveys record data while stationary for at least five seconds, calculating the position using at least three one-second epochs. FS surveys record observations for up to fifteen minutes on each GSP in order to support longer baselines. All GSP measurements were made during periods with a Position Dilution of Precision (PDOP) of ≤ 3.0 with at least six satellites in view of the stationary and roving receivers. See Table 7 for NV5 ground survey equipment information.

Forested check points are collected using total stations in order to measure positions under dense canopy. Total station backsight and setup points are established using GNSS survey techniques.

GSPs were collected in areas where good satellite visibility was achieved on paved roads and other hard surfaces such as gravel or packed dirt roads. GSP measurements were not taken on highly reflective surfaces such as center line stripes or lane markings on roads due to the increased noise seen in the laser returns over these surfaces. GSPs were collected within as many flightlines as possible; however, the distribution of GSPs depended on ground access constraints and monument locations and may not be equitably distributed throughout the study area (Figure 3).

Table 7: NV5 Geospatial ground survey equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R7	Zephyr GNSS Geodetic Model 2 RoHS	TRM57971.00	Static
Trimble R8 Model 2	Integrated Antenna	TRMR8_GNSS	Rover
Trimble R10	Integrated Antenna	TRMR10	Rover
Trimble R10 Model 2	Integrated Antenna	TRMR10-2	Rover
Trimble R12	Integrated Antenna	TRMR12	Rover
Nikon NPL-322+ 5” P Total Station		n/a	VVA
Trimble M3 Total Station		n/a	VVA

Aerial Targets

Air target points (ATP) were collected throughout the project area prior to imagery acquisition to refine the exterior orientation parameters of the camera and conduct an accuracy assessment of the final orthophoto product . ATPs are typically collected over hard surface ground features or temporary vinyl chevrons. Hard surface points consist of high contrast, road markings such as stop bars and turn arrows and cement corners. Typically each corner of the road marking is surveyed, in this way only one point was used for aerial triangulation while the remaining points are used for quality assurance purposes. Each ATP was surveyed using Fast Static (FS) or RTK techniques.

Land Cover Class

In addition to ground survey points, land cover class check points were collected throughout the study area to evaluate vertical accuracy. Vertical accuracy statistics were calculated for all land cover types to assess confidence in the lidar derived ground models across land cover classes (Table 8, see Lidar Accuracy Assessments, page 27).

Table 8: Land Cover Types and Descriptions

Land Cover Type	Land Cover Code	Example	Description	Accuracy Assessment Type
Shrubbery	SH		Rangeland dominated by shrub and brush	VVA
Tall Grass	TG		Herbaceous grasslands in advanced stages of growth	VVA
Mixed Forest	FR		Forested areas dominated by mixed deciduous, and coniferous species	VVA
Bare Earth	BE		Areas of bare earth surface	NVA
Urban	UA		Areas dominated by urban development, including parks	NVA

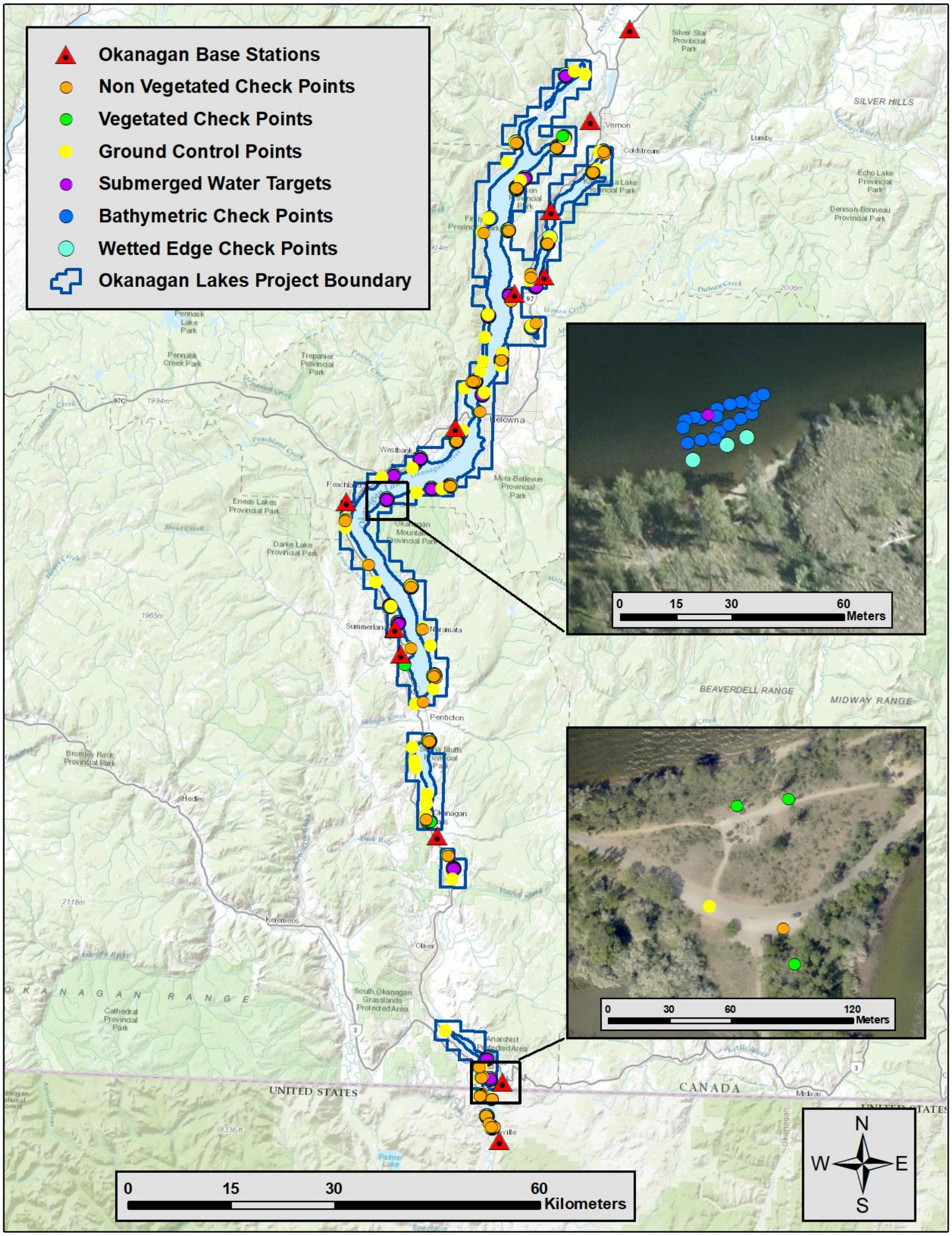
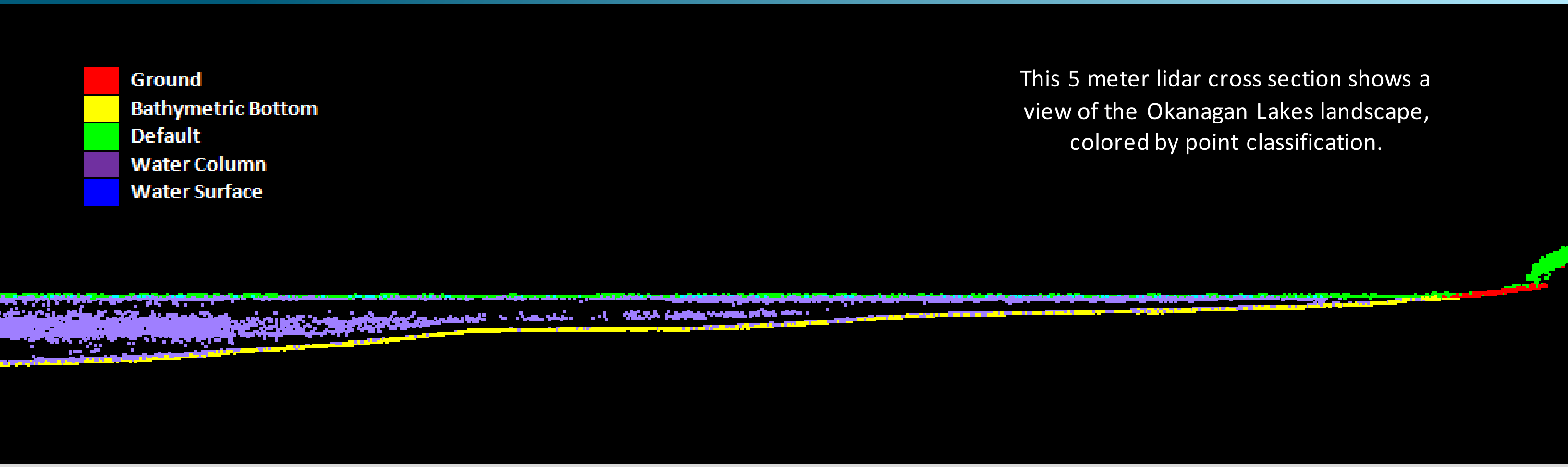


Figure 3: Ground survey location map



This 5 meter lidar cross section shows a view of the Okanagan Lakes landscape, colored by point classification.

Topobathymetric Lidar Data

Upon completion of data acquisition, NV5 processing staff initiated a suite of automated and manual techniques to process the data into the requested deliverables. Processing tasks include d 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 9).

Bathymetric refraction corrections were then applied using Las Monkey (NV5 Geospatial proprietary software). The resulting point cloud data were classified using both manual and automated techniques. Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 10.

Table 9: ASPRS LAS classification standards applied to the Okanagan Lakes 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
7	NIR Laser Noise	NIR laser returns that are often associated with birds, scattering from reflective surfaces, or artificial points below the ground surface
40	Bathymetric Bottom	Refracted green laser returns that fall within the water's edge breakline which characterize the submerged topography.
41	Water Surface	Green laser returns that are determined to be water surface points using automated and manual cleaning algorithms.
45	Water Column	Refracted green laser returns that are determined to be water using automated and manual cleaning algorithms.
47	Green Laser Noise	Green laser returns that are often associated with birds, scattering from reflective surfaces, or artificial points below the bathymetric surface

Table 10: Lidar processing workflow

Lidar Processing Step	Software Used
Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS, PPP and static ground GPS data. Develop a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with sensor head position and attitude recorded throughout the survey.	Waypoint Inertial Explorer v.8.9 POSPac 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.	Lidar Survey Studio v.3.0.1 LasProjector v.1.3 (NV5 Proprietary Software) GeoRun v.6.1.1
Import raw laser points into manageable blocks to perform manual relative accuracy calibration and filter erroneous points. Classify ground points for individual flight lines.	TerraScan v.19
Using ground classified points per each flight line, test the relative accuracy. Perform automated line-to-line calibrations for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calculate calibrations on ground classified points from paired flight lines and apply results to all points in a flight line. Use every flight line for relative accuracy calibration.	BayesMap StripAlign v.2.19 TerraMatch v.19
Apply refraction correction to all subsurface returns.	Las Monkey v.2.6 (NV5 proprietary software)
Classify resulting data to ground and other client designated ASPRS classifications (Table 9). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.19 TerraModeler v.19
Generate bare earth models as triangulated surfaces. Export all surface models as Cloud Optimized GeoTiffs(.tif) format at a 1 meter pixel resolution.	TerraScan v.19 TerraModeler v.19 Las Product Creator v.3.0 (NV5 proprietary software) ArcMap v.10.3.1
Correct intensity values for depth.	Las Monkey v.2.6 (NV5 proprietary software)

Bathymetric Refraction

Following final SBET creation for the Leica Chiroptera 4X and Hawkeye 4X systems, NV5 Geospatial used Leica Lidar Survey Studio (LSS) to calculate laser point positioning by associating SBET positions to each laser point return time, scan angle, and intensity. Light travels at different speeds in air than in water and its direction of travel is changed or refracted when it enters the water column, so a refraction correction is needed to ensure correct positions of bathymetric data.

Water surface models and ray tracing were used to perform the refraction correction to all submerged sensor data from the Chiroptera 4X green laser channel and from the Hawkeye 4x sensor. Water surface models were made for each lake by creating a triangulated irregular network (TIN) based on elevation information from the co-acquired Chiroptera 4X NIR lidar point cloud and from water's edge survey points. The refraction correction was applied to submerged returns using NV5 Geospatial's proprietary software Las Monkey. Points were flagged to refract based on their position relative to the water surface TIN. Using the information from the trajectory files and water surface models, each point was spatially corrected for refraction through the water column based the angle of incidence of the laser to the model. The resulting point cloud was classified into its initial refracted scheme using automated techniques (Table 10).

Lidar Derived Products

Because hydrographic laser scanners penetrate the water surface to map submerged topography, this affects how the data should be processed and presented in derived products from the lidar point cloud. The following discusses certain derived products that vary from the traditional (NIR) specification and delivery format.

Topobathymetric DEMs

Creating digital elevation models (DEMs) presents a challenge with respect to interpolation of areas with no returns. Traditional DEMs are "unclipped", meaning areas lacking ground returns are interpolated from neighboring ground returns, with the assumption that the interpolation is close to reality. In bathymetric modeling, these assumptions are prone to error because a lack of bathymetric returns can indicate a change in elevation that the laser can no longer map due to increased depths. The resulting void areas may suggest greater depths, rather than similar elevations from neighboring bathymetric bottom returns. Therefore, NV5 Geospatial created a polygon of bathymetric voids to delineate areas outside of successfully mapped bathymetry. This shapefile was used to control the extent of the delivered clipped topobathymetric model and to avoid false triangulation across areas in the water with no returns.

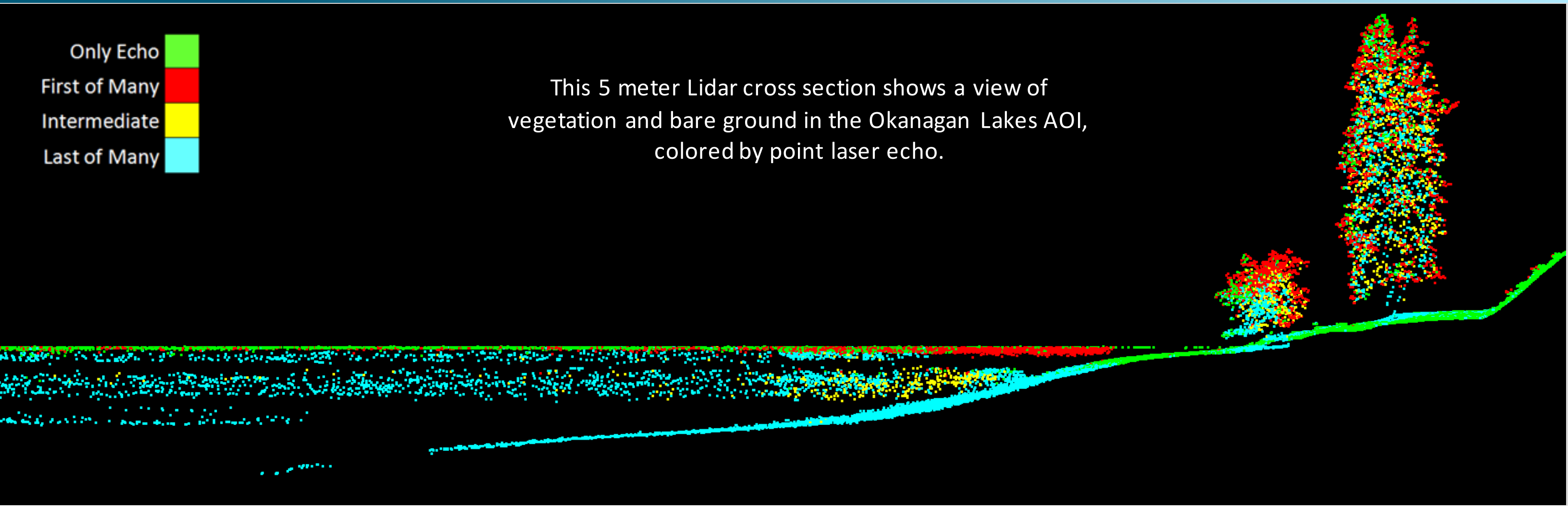
Digital Imagery

As with the lidar, the collected digital photographs went through multiple processing steps to create final orthophoto products. Initially, images were corrected for geometric distortion to yield level02 image files. Next, images were color balanced and levels were adjusted to exploit the full 14bit histogram and finally output as level03 pan-sharpened 8bit TIFF images. Camera position and orientation were calculated by linking the time of image capture to the smoothed best estimate of trajectory (SBET). Within Inpho's Match AT softcopy photogrammetric software, analytical aerial triangulation was performed using ground control, automatically generated tie points, and camera calibration information.

Adjusted images were orthorectified using the Lidar-derived ground model to remove displacement effects from topographic relief inherent in the imagery. The resulting orthos were mosaicked within Inpho's OrthoVista blending seams and applying automated project color-balancing. The final mosaics were inspected and edited for seam cutlines across above ground features such as buildings and other man-made features. Special care was taken to eliminate glare on the water surface. The processing workflow for orthophotos is summarized in Table 11.

Table 11: Orthophoto processing workflow

Orthophoto Processing Step	Software Used
Resolve GPS kinematic corrections for the aircraft position data using kinematic aircraft GPS (collected at 2 Hz) and PPP data.	Waypoint Inertial Explorer v.8.9
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.	Waypoint Inertial Explorer v.8.9
Create an exterior orientation file (EO) for each photo image with omega, phi, and kappa.	Waypoint Inertial Explorer v.8.9
Convert Level 00 raw imagery data into geometrically corrected Level 02 image files.	HxMap
Apply radiometric adjustments to Level 02 image files to create Level 03 Pan-sharpened TIFFs.	HxMap
Apply EO to photos, measure ground control points and perform aerial triangulation.	Inpho Match AT v10.0.2
Import DEM and orthorectify image frames	Inpho OrthoMaster v10.0.2
Mosaic orthorectified imagery blending automated and manually drawn seams between photos and applying global color balancing to the project.	Inpho OrthoVista/Seameditor v10.0.2



Bathymetric Lidar

An underlying principle for collecting hydrographic lidar data is to survey near-shore areas that can be difficult to collect with other methods, such as multi-beam sonar, particularly over large areas. In order to determine the capability and effectiveness of the bathymetric lidar, several parameters were considered; depth penetrations below the water surface, bathymetric return density, and spatial accuracy.

Mapped Bathymetry and Depth Penetration

To assist in evaluating performance results of the sensor, a polygon layer was created to delineate areas where bathymetry was successfully mapped.

This shapefile was used to control the extent of the delivered clipped topo-bathymetric model and to avoid false triangulation across areas in the water with no returns. Insufficiently mapped areas were identified by triangulating bathymetric bottom points with an edge length maximum of 4.56 meters. This ensured all areas of no returns (> 9 m^2), were identified as data voids. Overall NV5 sucessfully mapped 53% of the bathymetric bottom within the project area.

Table 12: Depth Penetration Statitics

Absolute Vertical Accuracy		
Depth	**Area M^2**	**Percent**
Shallow	566,359	0.8%
0.1 – 1 m	10,733,500	15.5%
1 – 2 m	9,914,150	14.3%
2 – 3 m	8,063,220	11.6%
3 – 4 m	6,233,680	9.0%
4 – 5 m	4,719,630	6.8%
5 – 6 m	3,953,570	5.7%
6 – 7 m	3,900,180	5.6%
7 – 8 m	4,268,280	6.1%
8 – 9 m	4,198,480	6.0%
9 – 10 m	3,573,870	5.1%
>10 m	9,331,370	13.4%
Total	69,456,289	100.0%

Lidar Point Density

First Return Point Density

The acquisition parameters were designed to acquire an average first-return density of 4 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 average first-return density of the Okanagan Lakes Lidar project was 10.17 points/m^2 (Table 13). The statistical distributions of all first return densities per 100 m x 100 m cell are portrayed in Figure 4.

Bathymetric and Ground Classified Point Densities

The density of ground classified lidar returns and bathymetric bottom returns were 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 have penetrated the canopy, resulting in lower ground density. Similarly, the density of bathymetric bottom returns was influenced by turbidity, depth, and bottom surface reflectivity. In turbid areas, fewer pulses may have penetrated the water surface, resulting in lower bathymetric density.

The ground and bathymetric bottom classified density of lidar data for the Okanagan Lakes project was 3.67 points/m^2 (Table 13). The statistical distributions ground classified and bathymetric bottom return densities per 100 m x 100 m boundary clipped cells are portrayed in Figure 5.

Additionally, for the Okanagan Lakes project, density values of only bathymetric bottom returns were calculated for areas containing at least one bathymetric bottom return. Areas lacking bathymetric returns (voids) were not considered in calculating an average density value. Within the successfully mapped area, a bathymetric bottom return density of 4.52 points/m^2 was achieved.

Table 13: Average Lidar point densities

Density Type	Point Density
First Returns	10.17 points/m^2
Ground and Bathymetric Bottom Classified Returns	3.67 points/m^2
Bathymetric Bottom Classified Returns	4.52 points/m^2

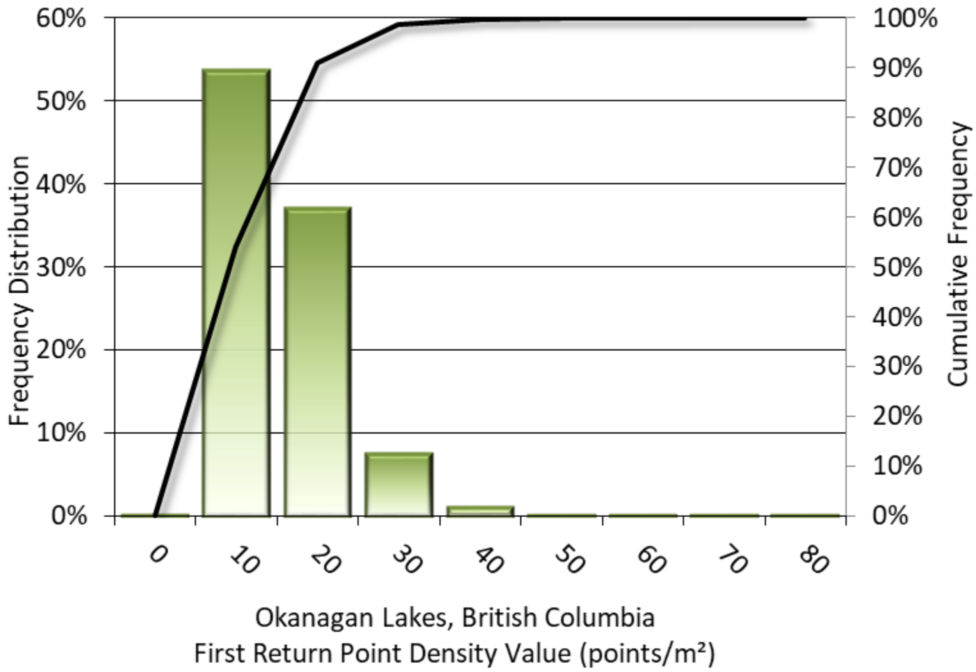


Figure 4: Frequency distribution of first return densities per 100 x 100 m cell

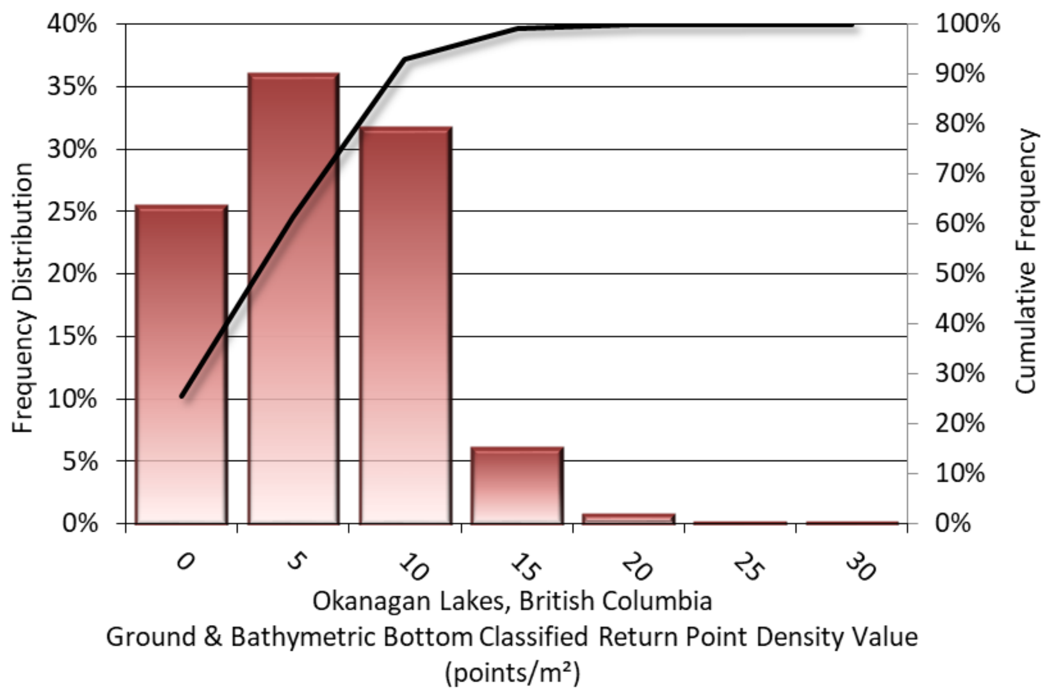


Figure 5: Frequency distribution of ground and bathymetric bottom classified return densities per 100 x 100 m cell

Lidar Accuracy Assessments

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

Lidar Non-Vegetated Vertical Accuracy

Absolute accuracy was assessed using Non-vegetated Vertical Accuracy (NVA) reporting designed to meet guidelines presented in the FGDC National Standard for Spatial Data Accuracy[1]. NVA compares known ground check point data that were withheld from the calibration and post-processing of the lidar point cloud to the triangulated surface generated by the 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 14.

The mean and standard deviation (sigma σ) of divergence of the ground surface model from ground check 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 Okanagan Lakes survey, 80 ground check points were withheld from the calibration and post-processing of the lidar point cloud, with resulting non-vegetated vertical accuracy of 0.050 meters as compared to the classified LAS, and 0.072 meters against the bare earth DEM, with 95% confidence (Figure 6 and Figure 7).

NV5 also assessed absolute accuracy using 55 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 14 and Figure 8.

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

Table 14: Absolute accuracy results

Absolute Vertical Accuracy			
	NVA, as compared to Classified LAS	NVA, as compared to Bare Earth DEM	Ground Control Points
Sample	80 points	80 points	55 points
95% Confidence (1.96*RMSE)	0.050 m	0.072 m	0.049 m
Average	-0.011 m	-0.013 m	-0.003 m
Median	-0.011 m	-0.012 m	0.001 m
RMSE	0.026 m	0.037 m	0.025 m
Standard Deviation (1σ)	0.023 m	0.034 m	0.025 m

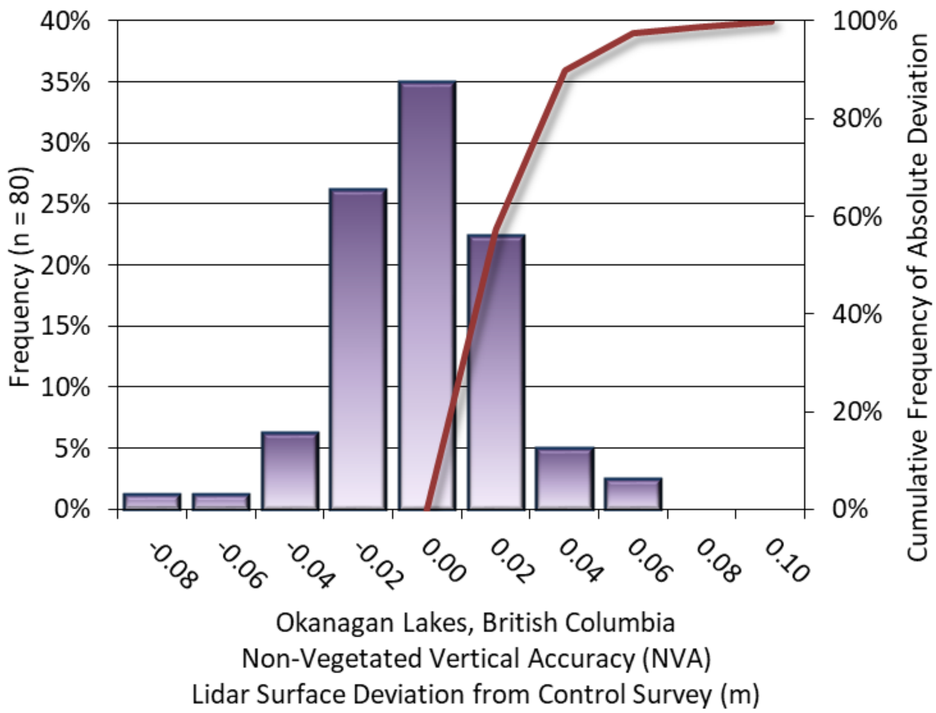

Figure 6: Frequency histogram for classified LAS deviation from ground check point values

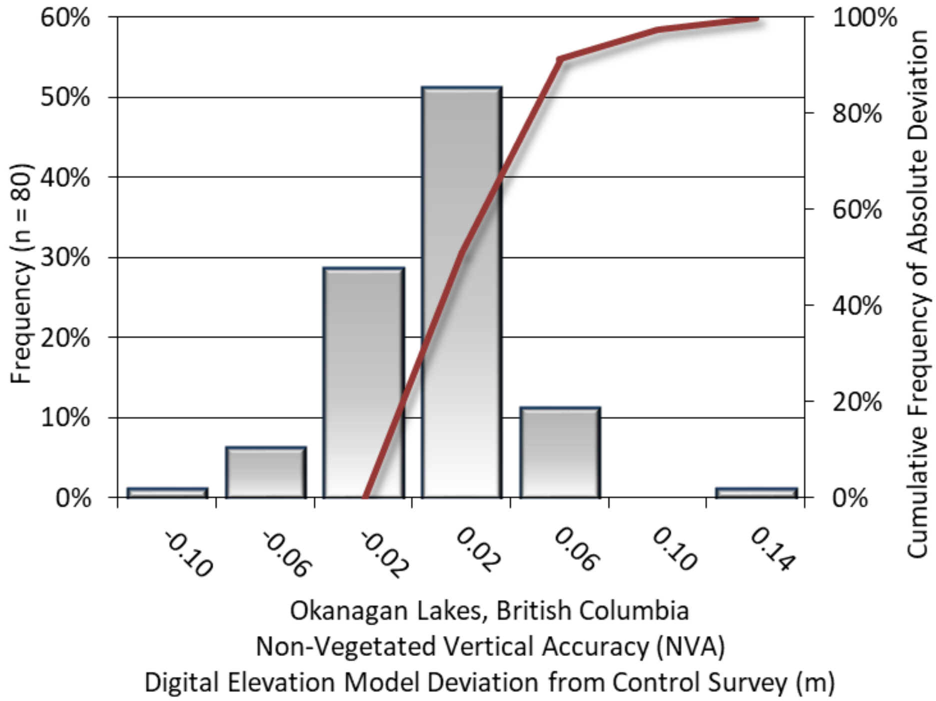

Figure 7: Frequency histogram for lidar bare earth DEM deviation from ground check point values

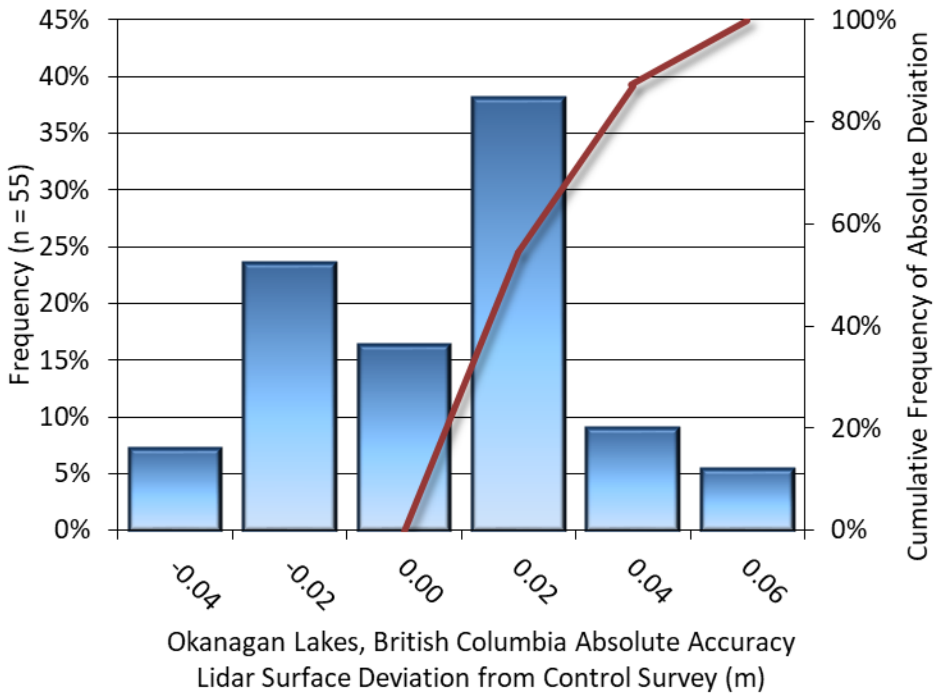

Figure 8: Frequency histogram for lidar surface deviation ground control point values

Lidar Bathymetric Vertical Accuracies

Traditional bathymetric (submerged and along the water's edge) check points were collected in order to assess the submerged surface vertical accuracy. NV5 ground survey staff also placed submerged shallow water physical targets around 1 meter depths throughout the AOI to further assess the depth accuracy of the two Leica topbathy sensors. Additionally, deep underwater targets were placed in depths of 10 meters or greater, however these proved to be too physically small at these depths to be captured by the laser in order for the depth accuracy to be assessed. Assessment of 390 submerged bathymetric check points resulted in a vertical accuracy of 0.108 meters, while assessment of 115 wetted edge check points resulted in a vertical accuracy of 0.086 meters, evaluated at 95% confidence interval (Figure 9 - Figure 10). Assessment of the submerged underwater targets resulted in a vertical accuracy of 0.093 meters evaluated at the 95% confidence level (Figure 12, Table 15).

Table 15: Bathymetric Vertical Accuracy for the Okanagan Lakes Project

Bathymetric Vertical Accuracy			
	Submerged Bathymetric Check Points	**Wetted Edge Bathymetric Check Points**	**Submerged Shallow Water Targets**
Sample	390 points	115 points	34 points
95% Confidence (1.96*RMSE)	0.108 m	0.086 m	0.093 m
Average Dz	0.014 m	-0.004 m	0.011 m
Median	0.017 m	-0.006 m	0.012 m
RMSE	0.055 m	0.044 m	0.047 m
Standard Deviation (1σ)	0.053 m	0.044 m	0.047 m

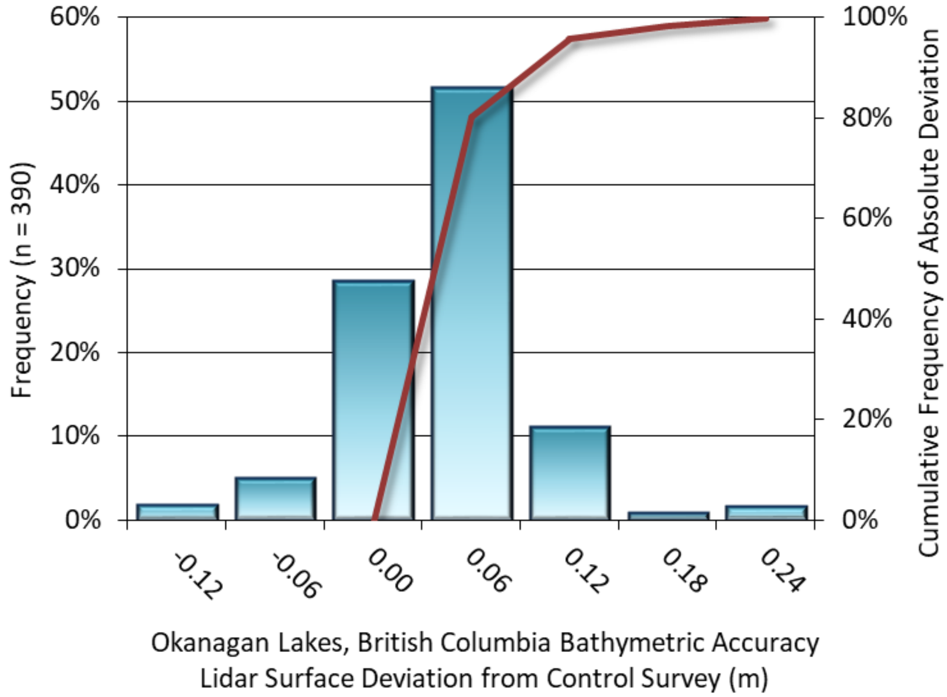

Figure 9: Frequency histogram for lidar surface deviation from submerged check point values

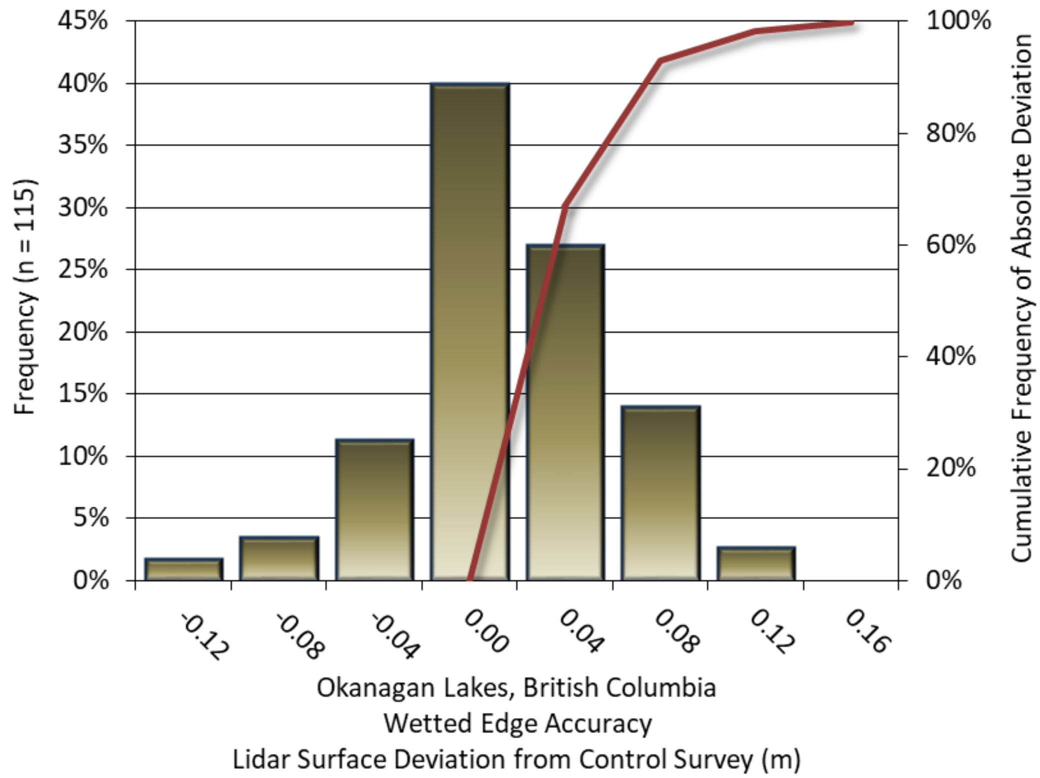

Figure 10: Frequency histogram for lidar surface deviation from wetted edge check point values

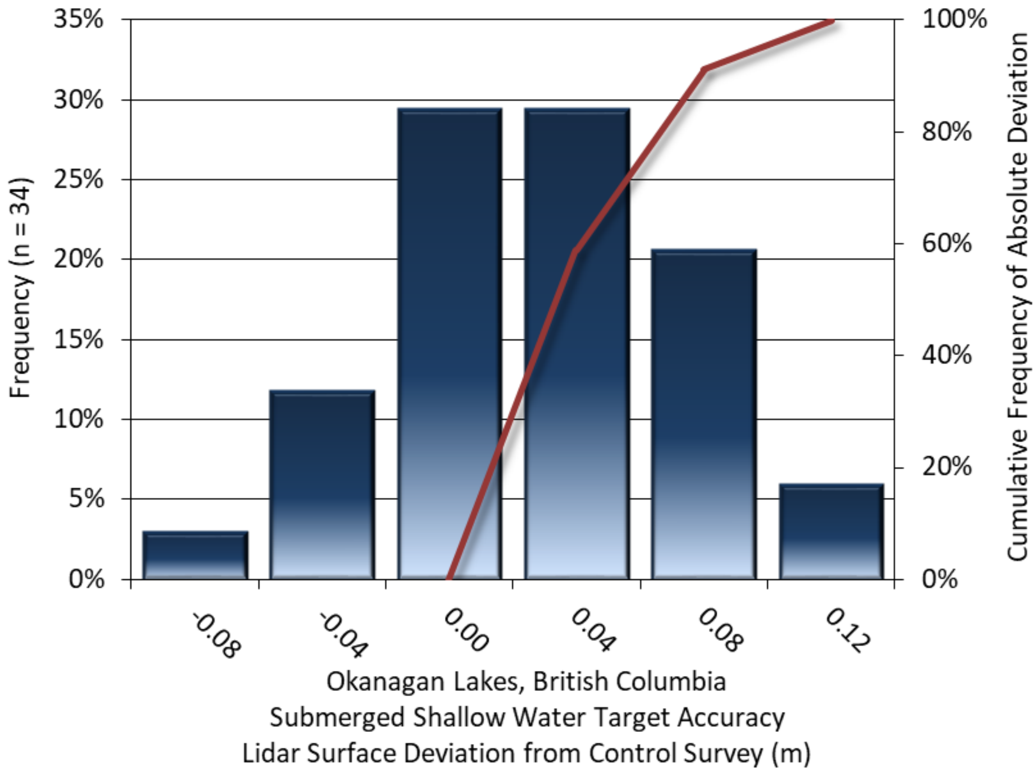

Figure 11: Frequency histogram for lidar surface deviation from submerged shallow water target point values

Lidar Vegetated Vertical Accuracies

NV5 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. VVA is evaluated at the 95th percentile (Table 16, Figure 12, Figure 13).

Table 16: Vegetated Vertical Accuracy for the Okanagan Lakes Project

Vegetated Vertical Accuracy (VVA)		
	VVA, as compared to Classified LAS	VVA, as compared to Bare Earth DEM
Sample	38 points	38 points
Average Dz	0.026 m	0.029 m
Median	0.016 m	0.021 m
RMSE	0.058 m	0.064 m
Standard Deviation (1σ)	0.053 m	0.057 m
95th Percentile	0.103 m	0.107 m

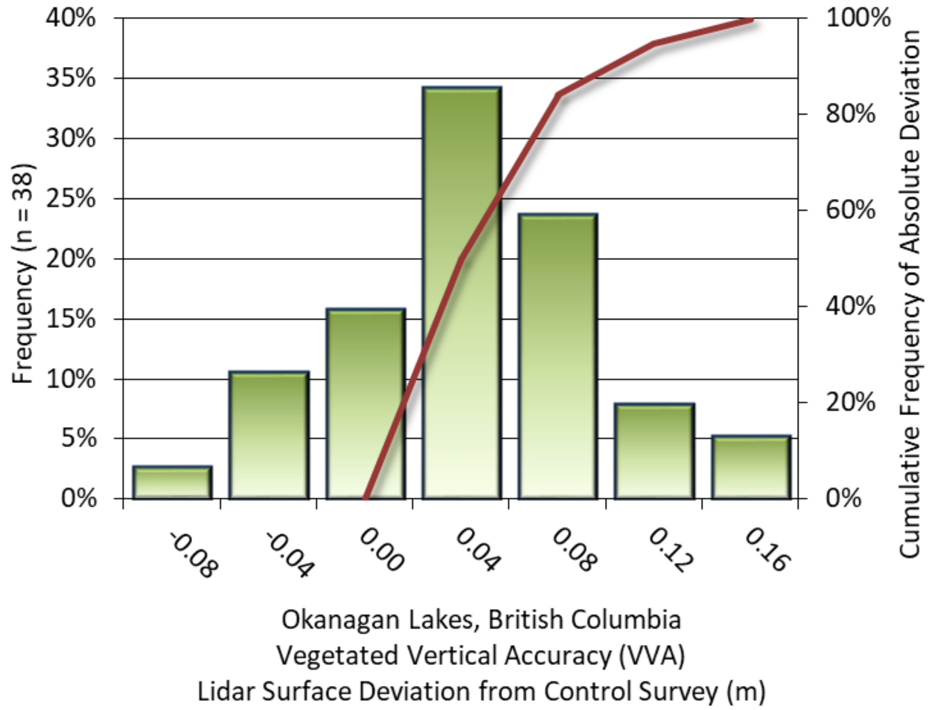

Figure 12: Frequency histogram for lidar surface deviation from all land cover class point values (VVA)

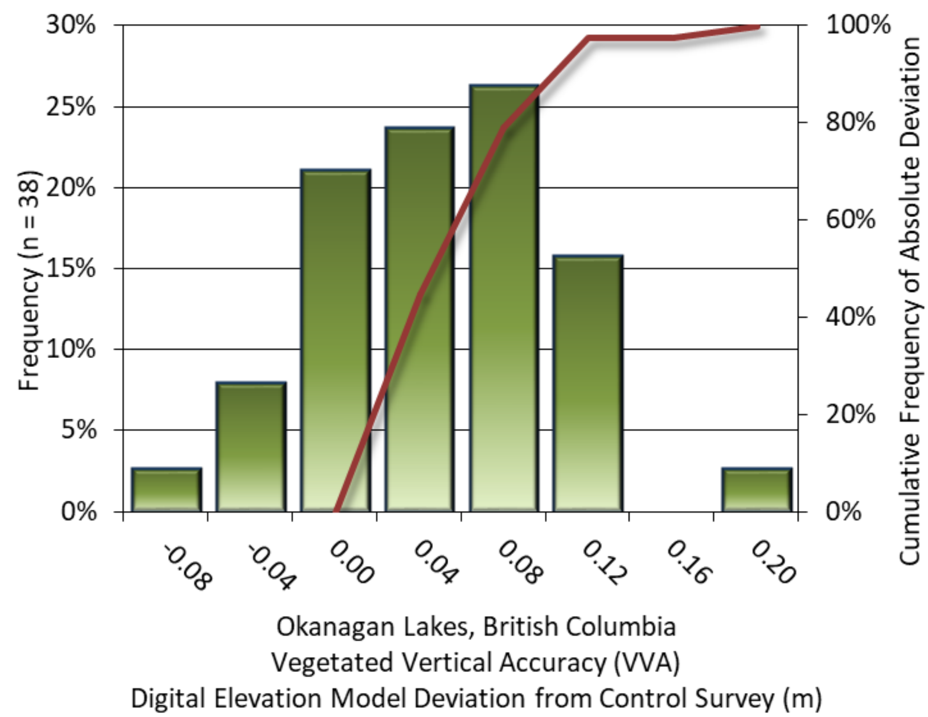

Figure 13: Frequency histogram for lidar bare earth DEM deviation from all land cover class point values (VVA)

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 Okanagan Lakes Lidar project was 0.048 meters (Table 17, Figure 14).

Table 17: Relative accuracy results

Relative Accuracy	
Sample	520 surfaces
Average	0.048 m
Median	0.048 m
RMSE	0.051 m
Standard Deviation (1σ)	0.013 m
1.96σ	0.026 m

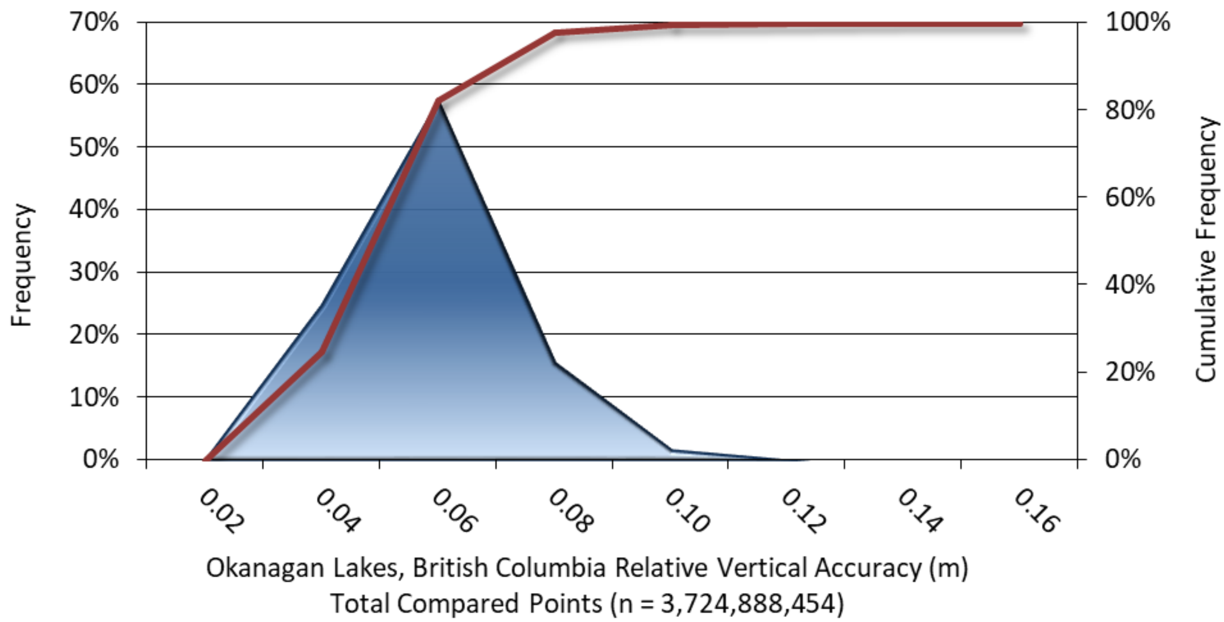

Figure 14: Frequency plot for relative vertical accuracy between flight lines

Lidar Horizontal Accuracy

Lidar horizontal accuracy was calculated using the Linear Horizontal Error Propagation Model put forth by GeoBC in Version 5.1 of Specifications for Airborne Lidar for the Province of British Columbia[2]. It is a function of Global Navigation Satellite System (GNSS) derived positional error, flying altitude, IMU derived attitude error, and laser beam divergence.

$$\boldsymbol{RMSEr} = \sqrt{(\theta_{laser}\ x\ AGL)^2 + \left(\sigma_{GNSS_{xy}}\right)^2 + \left(\sigma_{IMUrp}\ x\ AGL\right)^2}$$

RMSEr = Horizontal LiDAR point accuracy over flat terrain (metres) at 63% probability

$\theta laser$ = Laser beam divergence (rad)

AGL = Aircraft altitude above ground level at Nadir position (metres)

$\sigma GNSSxy$ ≅ RMSEr = Average 2D positional precision of the GNSS system (metres) at 63% probability

$\sigma IMUrp$ = Average 3D angular accuracy of the drift corrected IMU in roll and pitch orientation (rad)

Figure 15: Linear Horizontal Error propagation Model

Table 18: Horizontal Accuracy

Horizontal Accuracy				
	Chiroptera 4X NIR	Chrioptera 4X Green	Hawkeye 4X	VQ-1560-ii
$RMSE_r$	0.13 m	2.00 m	3.60 m	0.38 m
$\theta laser$	0.25 mrads	4 mrads	7.2 mrads	0.25 mrads
AGL	500 m	500 m	500 m	1,500 m
$\sigma GNSSxy$	0.005 m	0.005 m	0.008 m	0.019 m
$\sigma IMUrp$	0.002 mrads	0.002 mrads	0.002 mrads	0.002 mrads

[2] GeoBC, Specifications for Airborne Lidar for the Province of British Columbia Version 5.1, APRIL 2021. https://www2.gov.bc.ca/assets/gov/data/geographic/digital-imagery/geobc_lidar_specifications_v51.pdf

Photo Analytical Aerial Triangulation Report

Overview

Aerial triangulation was performed in six blocks to support photogrammetric mapping efforts of the Okanagan area Lakes in southern British Columbia. The block consisted of thirty flight lines of 840 images flown at a scale of 1:800 on Sepetember 16th, 2021. Block adjustments were made to ground control established by NV5 referencing UTM11N, NAD83(CSRS)V4e2002 horizontal datum and CGVD 2013 CGG2013a vertical datum. Digital imagery along with ground control and camera calibration data were used as input to Inpho's Match AT softcopy photogrammetry program. The sensor used was a Leica DMC III, large format, aerial mapping camera. Of the 161 total surveyed air target points, 87 were used for aerial triangulation and 52 were withheld from the block adjustment as check points for accuracy assessment, remaining air target points were either deemed misfits or redundant due to their proximity to other ground control.

Control Points

Air target points used in the aerial triangulation adjustment are listed with their location in Table 19, and RMSE values can be found in Table 20.

Table 19: Location of air target points used as control for aerial triangulation adjustment

Control Point Coordinates (m) – 87 Total Points				Control Point Residuals (m) - 87 Total Points			
Point ID	X	Y	Z	X	Y	Z	Block ID
AT014	327808.700	5541494.846	436.221	0.000	0.000	0.000	Ellison Lake
AT007	328039.136	5547114.605	392.457	0.006	0.057	-0.029	Kalamalka and Wood Lake
AT011	327379.151	5547295.975	400.984	-0.008	-0.027	-0.001	Kalamalka and Wood Lake
AT012	327379.295	5547295.531	400.990	0.002	-0.017	-0.031	Kalamalka and Wood Lake
AT025	338469.941	5566760.114	394.956	-0.029	0.003	0.089	Kalamalka and Wood Lake
AT027	337446.412	5564277.325	443.487	-0.049	0.053	-0.142	Kalamalka and Wood Lake
AT028	337445.327	5564234.604	443.411	0.017	-0.054	-0.121	Kalamalka and Wood Lake
AT029	337444.836	5564234.967	443.379	-0.016	-0.018	-0.111	Kalamalka and Wood Lake
AT032	330602.709	5554262.621	393.877	0.018	0.013	0.129	Kalamalka and Wood Lake
AT033	330599.177	5554264.471	393.888	0.060	-0.010	0.216	Kalamalka and Wood Lake
AT093	310761.287	5480956.008	347.940	0.019	-0.011	-0.046	Skaha Lake
AT094	310760.576	5480958.997	348.017	-0.017	0.010	-0.048	Skaha Lake

Control Point Coordinates (m) – 87 Total Points				Control Point Residuals (m) - 87 Total Points			
Point ID	**X**	**Y**	**Z**	**X**	**Y**	**Z**	**Block ID**
AT095	310831.985	5478039.371	419.534	0.002	-0.002	-0.015	Skaha Lake
AT096	310832.500	5478037.315	419.535	-0.001	0.028	-0.028	Skaha Lake
AT118	313242.312	5468966.197	348.246	0.034	-0.025	0.027	Skaha Lake
AT119	313242.389	5468968.020	348.238	-0.026	0.005	0.057	Skaha Lake
AT120	312652.273	5473363.817	341.746	-0.005	-0.011	0.030	Skaha Lake
AT121	312652.791	5473364.073	341.759	-0.006	0.006	0.024	Skaha Lake
AT124	315772.412	5464300.150	330.557	0.029	0.015	-0.05	Vaseux Lake
AT127	316272.959	5460810.766	329.233	0.028	0.001	-0.001	Vaseux Lake
AT132	316050.962	5463683.543	332.136	-0.030	0.003	-0.032	Vaseux Lake
AT134	316050.496	5463681.513	332.152	0.010	-0.031	0.070	Vaseux Lake
AT135	316049.860	5463682.784	332.172	-0.031	0.031	0.030	Vaseux Lake
AT137	316017.233	5463752.202	330.997	-0.007	-0.018	-0.018	Vaseux Lake
AT047	317163.577	5426940.135	404.054	0.007	-0.034	0.078	Osoyoos Lake
AT048	317162.867	5426939.545	404.026	-0.027	0.040	0.129	Osoyoos Lake
AT049	317162.972	5426940.819	403.999	-0.008	-0.012	0.06	Osoyoos Lake
AT050	318598.657	5425236.363	358.201	0.023	-0.030	0.078	Osoyoos Lake
AT051	318598.320	5425233.956	358.193	-0.004	-0.005	0.139	Osoyoos Lake
AT139	320967.923	5433667.653	279.832	-0.029	0.033	-0.031	Osoyoos Lake
AT140	320967.314	5433667.660	279.865	-0.03	0.047	0.004	Osoyoos Lake
AT141	320967.282	5433670.840	279.902	-0.042	0.025	-0.036	Osoyoos Lake
AT142	315137.190	5438875.045	285.460	-0.046	0.038	-0.09	Osoyoos Lake
AT150	322693.601	5421375.323	286.586	0.025	0.020	0.020	Osoyoos Lake
AT152	322204.283	5418406.005	289.151	0.029	-0.001	0.010	Osoyoos Lake
AT154	322006.769	5422431.030	280.731	0.034	0.005	-0.085	Osoyoos Lake
AT155	322009.033	5422422.216	280.858	0.024	-0.036	-0.065	Osoyoos Lake
AT158	320613.006	5429654.764	279.847	0.031	-0.005	-0.112	Osoyoos Lake
AT162	321936.957	5424797.172	279.044	0.008	-0.04	-0.058	Osoyoos Lake
AT164	321939.141	5424795.877	279.021	0.006	-0.042	-0.041	Osoyoos Lake
AT001	336335.946	5578954.501	349.705	0.021	-0.018	-0.009	Okanagan Lake
AT002	336336.472	5578959.771	349.683	0.031	0.020	-0.020	Okanagan Lake
AT004	336333.756	5578954.696	349.679	-0.035	-0.036	-0.008	Okanagan Lake
AT005	335035.619	5580783.766	354.390	0.030	-0.001	-0.199	Okanagan Lake
AT013	325799.210	5545752.401	551.107	0.012	-0.052	0.052	Okanagan Lake
AT015	332670.265	5568893.062	344.724	-0.013	0.014	-0.006	Okanagan Lake
AT016	332669.983	5568892.219	344.726	0.002	0.033	0.020	Okanagan Lake
AT017	332669.297	5568893.566	344.723	-0.011	-0.029	-0.062	Okanagan Lake
AT021	312397.428	5517298.033	376.585	-0.099	-0.025	0.163	Okanagan Lake

Control Point Coordinates (m) – 87 Total Points				Control Point Residuals (m) - 87 Total Points			
Point ID	X	Y	Z	X	Y	Z	Block ID
AT022	312410.383	5517298.950	375.110	0.085	-0.018	0.067	Okanagan Lake
AT023	313418.420	5517582.123	379.889	0.092	0.064	0.002	Okanagan Lake
AT035	324547.547	5555258.588	350.842	-0.004	-0.06	-0.097	Okanagan Lake
AT036	317808.133	5526064.659	344.557	0.010	-0.027	0.029	Okanagan Lake
AT037	317807.614	5526064.957	344.553	-0.016	-0.031	0.031	Okanagan Lake
AT054	321523.155	5543085.798	379.349	-0.019	0.035	-0.070	Okanagan Lake
AT055	321523.187	5543086.352	379.378	-0.007	0.033	-0.060	Okanagan Lake
AT058	320481.885	5554830.205	448.527	0.004	0.025	0.002	Okanagan Lake
AT061	321851.660	5557060.803	343.452	-0.038	0.008	-0.050	Okanagan Lake
AT062	321863.053	5557034.976	343.545	0.001	0.035	-0.082	Okanagan Lake
AT065	325762.324	5560492.239	389.221	-0.003	-0.021	-0.229	Okanagan Lake
AT067	320495.047	5521246.743	354.900	0.059	0.058	0.115	Okanagan Lake
AT069	320497.413	5521248.779	355.115	-0.021	0.001	0.007	Okanagan Lake
AT072	322234.195	5531934.625	568.293	0.045	0.027	0.143	Okanagan Lake
AT073	322279.118	5532012.019	565.903	-0.023	0.008	0.014	Okanagan Lake
AT074	323510.472	5537421.285	366.126	0.046	0.051	-0.019	Okanagan Lake
AT076	323622.199	5537426.289	393.491	-0.043	0.031	0.035	Okanagan Lake
AT078	325654.343	5568113.916	342.797	-0.029	0.028	0.126	Okanagan Lake
AT080	328422.798	5567093.693	451.817	-0.005	0.026	-0.212	Okanagan Lake
AT081	328421.549	5567093.281	451.816	-0.071	0.026	-0.131	Okanagan Lake
AT082	328421.961	5567092.095	451.813	0.006	-0.067	-0.188	Okanagan Lake
AT084	305160.309	5504162.544	450.372	0.023	-0.064	0.067	Okanagan Lake
AT085	310921.223	5486359.603	342.717	-0.017	-0.012	0.023	Okanagan Lake
AT086	310920.690	5486356.792	342.701	0.024	-0.016	-0.042	Okanagan Lake
AT087	310921.768	5486356.588	342.686	0.005	0.015	-0.029	Okanagan Lake
AT089	312554.850	5486508.407	355.496	-0.049	-0.010	0.208	Okanagan Lake
AT099	313640.969	5490410.078	343.772	0.014	-0.026	0.070	Okanagan Lake
AT100	313209.063	5494836.165	429.394	0.014	-0.010	0.000	Okanagan Lake
AT101	313208.302	5494838.206	429.297	0.012	-0.031	0.021	Okanagan Lake
AT102	313208.793	5494838.336	429.324	-0.004	-0.014	-0.038	Okanagan Lake
AT105	312011.601	5497404.048	343.795	-0.010	-0.023	0.217	Okanagan Lake
AT106	312011.945	5497406.301	343.814	0.013	-0.02	0.116	Okanagan Lake
AT107	311973.615	5497322.069	344.367	0.008	0.004	0.070	Okanagan Lake
AT108	311337.732	5502642.972	523.147	-0.049	0.074	0.211	Okanagan Lake
AT109	311338.871	5502640.580	523.159	0.044	-0.035	-0.035	Okanagan Lake
AT112	324519.527	5540015.474	367.930	0.004	0.000	0.017	Okanagan Lake
AT114	320481.249	5534763.305	383.275	-0.008	0.021	-0.081	Okanagan Lake

Control Point Coordinates (m) – 87 Total Points				Control Point Residuals (m) - 87 Total Points			
Point ID	X	Y	Z	X	Y	Z	Block ID
AT115	320476.134	5534759.238	383.498	-0.031	0.004	-0.161	Okanagan Lake

Table 20: RMSE for air target points used as control for aerial triangulation adjustment

Control Point RMSE - 87 Total Points Meters		
X	Y	Z
0.030	0.032	0.116

Check Points

Air target check points withheld from the aerial triangulation adjustment are listed with their location and residuals in Table 21, RMSE values can be found in Table 22.

Table 21: Location of air target check points withheld from aerial triangulation adjustment

Check Point Coordinates (m) - 52 Total Points				Check Point Residuals (m) -52 Total Points			
Point ID	X	Y	Z	X	Y	Z	Block ID
AT008	327980.487	5547115.317	392.276	-0.054	0.053	0.003	Kalamalka and Wood Lake
AT009	327980.483	5547115.93	392.286	-0.041	-0.029	-0.004	Kalamalka and Wood Lake
AT010	327396.654	5547286.339	399.702	-0.001	0.032	-0.027	Kalamalka and Wood Lake
AT026	338472.543	5566759.156	395.042	-0.183	0.063	0.170	Kalamalka and Wood Lake
AT030	337964.035	5564612.537	460.917	0.024	0.099	-0.170	Kalamalka and Wood Lake
AT031	337961.726	5564609.131	460.837	-0.217	0.022	0.042	Kalamalka and Wood Lake
AT034	330601.065	5554273.833	394.469	0.177	-0.112	0.167	Kalamalka and Wood Lake
AT053	312930.821	5480930.041	339.754	0.154	-0.014	-0.009	Skaha Lake
AT091	312354.203	5481060.021	339.945	0.021	-0.006	-0.062	Skaha Lake
AT092	310788.894	5480908.357	346.164	-0.007	-0.042	-0.167	Skaha Lake
AT116	313221.699	5468989.067	347.640	-0.005	-0.026	0.022	Skaha Lake
AT117	313227.124	5468988.794	347.722	-0.008	-0.032	-0.022	Skaha Lake
AT122	312651.559	5473365.981	341.785	-0.043	0.121	0.016	Skaha Lake
AT125	315779.590	5464301.836	330.574	0.058	0.012	-0.046	Vaseux Lake
AT128	316263.677	5460802.043	329.164	-0.039	-0.038	0.042	Vaseux Lake

Check Point Coordinates (m) - 52 Total Points				Check Point Residuals (m) -52 Total Points			
Point ID	**X**	**Y**	**Z**	**X**	**Y**	**Z**	**Block ID**
AT129	316371.890	5460888.975	330.231	-0.064	-0.075	-0.026	Vaseux Lake
AT133	316051.763	5463681.974	332.099	0.072	0.034	-0.233	Vaseux Lake
AT136	316019.184	5463752.509	330.993	0.072	-0.016	-0.145	Vaseux Lake
AT052	318546.820	5425260.065	354.089	0.063	-0.047	0.100	Osoyoos Lake
AT138	320974.550	5433660.563	279.579	0.016	0.111	-0.020	Osoyoos Lake
AT143	315109.838	5438860.827	285.461	-0.133	0.118	-0.232	Osoyoos Lake
AT151	322693.814	5421368.472	286.722	-0.040	0.047	0.016	Osoyoos Lake
AT153	322205.114	5418414.857	289.256	-0.009	0.079	-0.074	Osoyoos Lake
AT156	321240.204	5426387.719	280.412	0.032	-0.029	-0.204	Osoyoos Lake
AT157	321248.173	5426394.623	280.118	-0.026	0.009	-0.132	Osoyoos Lake
AT159	320609.139	5429674.017	280.338	0.014	0.044	0.030	Osoyoos Lake
AT160	322144.155	5428876.231	279.718	-0.207	0.047	0.160	Osoyoos Lake
AT163	321939.539	5424801.899	279.004	-0.013	-0.088	-0.068	Osoyoos Lake
AT003	336334.294	5578959.969	349.707	-0.016	-0.022	0.002	Okanagan Lake
AT018	332673.400	5568890.923	344.710	-0.007	-0.05	0.106	Okanagan Lake
AT020	312366.929	5517293.992	379.768	0.094	0.033	0.294	Okanagan Lake
AT038	317810.982	5526070.309	344.530	0.003	0.025	0.033	Okanagan Lake
AT039	317810.457	5526070.595	344.526	-0.037	0.008	0.002	Okanagan Lake
AT056	321458.543	5543073.175	388.706	0.087	-0.029	0.051	Okanagan Lake
AT057	321457.331	5543072.750	388.742	-0.020	-0.024	-0.061	Okanagan Lake
AT060	320481.134	5554826.832	448.348	-0.023	0.058	0.086	Okanagan Lake
AT063	321271.932	5557296.325	349.295	0.014	0.001	-0.064	Okanagan Lake
AT064	321271.501	5557296.735	349.311	0.015	0.035	-0.044	Okanagan Lake
AT066	325773.632	5560517.549	390.695	0.110	-0.029	-0.227	Okanagan Lake
AT068	320466.688	5521247.754	353.683	-0.175	0.121	0.133	Okanagan Lake
AT070	320970.033	5531764.715	390.148	-0.110	0.051	0.064	Okanagan Lake
AT071	320969.137	5531765.643	390.133	-0.167	0.125	0.115	Okanagan Lake
AT075	323622.402	5537426.878	393.500	-0.079	0.067	0.011	Okanagan Lake
AT079	328441.479	5567096.210	452.095	-0.020	-0.082	-0.253	Okanagan Lake
AT083	305166.079	5504160.823	450.353	0.032	-0.046	0.302	Okanagan Lake
AT090	312555.803	5486505.385	355.493	0.031	-0.125	0.105	Okanagan Lake
AT097	313865.834	5488528.020	418.233	0.056	-0.117	0.147	Okanagan Lake
AT098	313868.763	5488527.162	418.141	0.043	-0.09	0.023	Okanagan Lake
AT103	312008.582	5497366.257	344.120	0.014	-0.039	-0.027	Okanagan Lake
AT104	312009.901	5497368.119	344.126	0.026	-0.044	0.048	Okanagan Lake
AT111	311300.370	5502667.954	520.482	-0.027	0.014	0.048	Okanagan Lake
AT113	324410.623	5539867.652	350.866	-0.058	-0.006	-0.065	Okanagan Lake

Table 22: RMSE for air target points withheld from aerial triangulation adjustment

Check Point RMSE - 52 Total Points Meters		
X	Y	Z
0.070	0.065	0.128

Anomalies and Misfits

Twenty two ATPs were omitted from processing due to their close proximity to other ATPs. ATP redundancy can be useful when points fails QAQC measures or are obscured by shadow or object lean.

CERTIFICATIONS

NV5 Geospatial provided lidar services for the Okanagan Lakes project as described in this report.

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

Shauna Gutierrez
Shauna Gutierrez (Mar 9, 2022 12:34 PST) Mar 9, 2022

Shauna Gutierrez
Project Manager
NV5 Geospatial

I, Evon P. Silvia, PLS, as a Professional Land Surveyor registered in the United States of America, confirm that the methodologies and ground survey point collection were performed using commonly accepted Standard Practices. Field work conducted for this report was conducted between August 30 and September 29, 2021.

Evon P. Silvia Mar 9, 2022

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

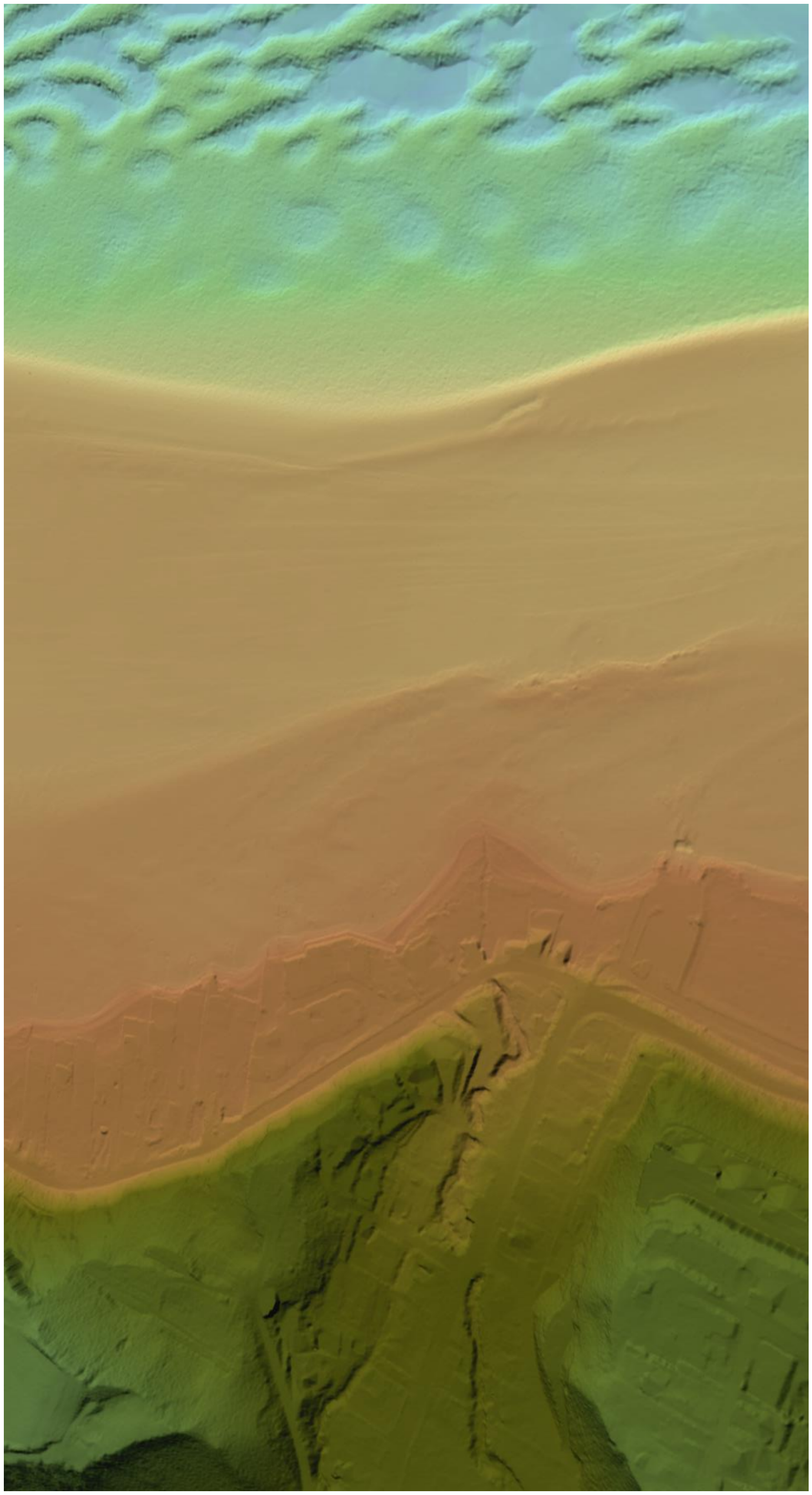

Figure 16: View looking east over Okanagan Lakes. The image was created from the lidar bare earth model colored by elevation.

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

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

Lidar accuracy error sources and solutions:

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

Operational measures taken to improve relative accuracy:

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

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

Reduced Scan Angle: Edge-of-scan data can become inaccurate. The scan angle was reduced to a maximum of ±20 – 29.25^{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.