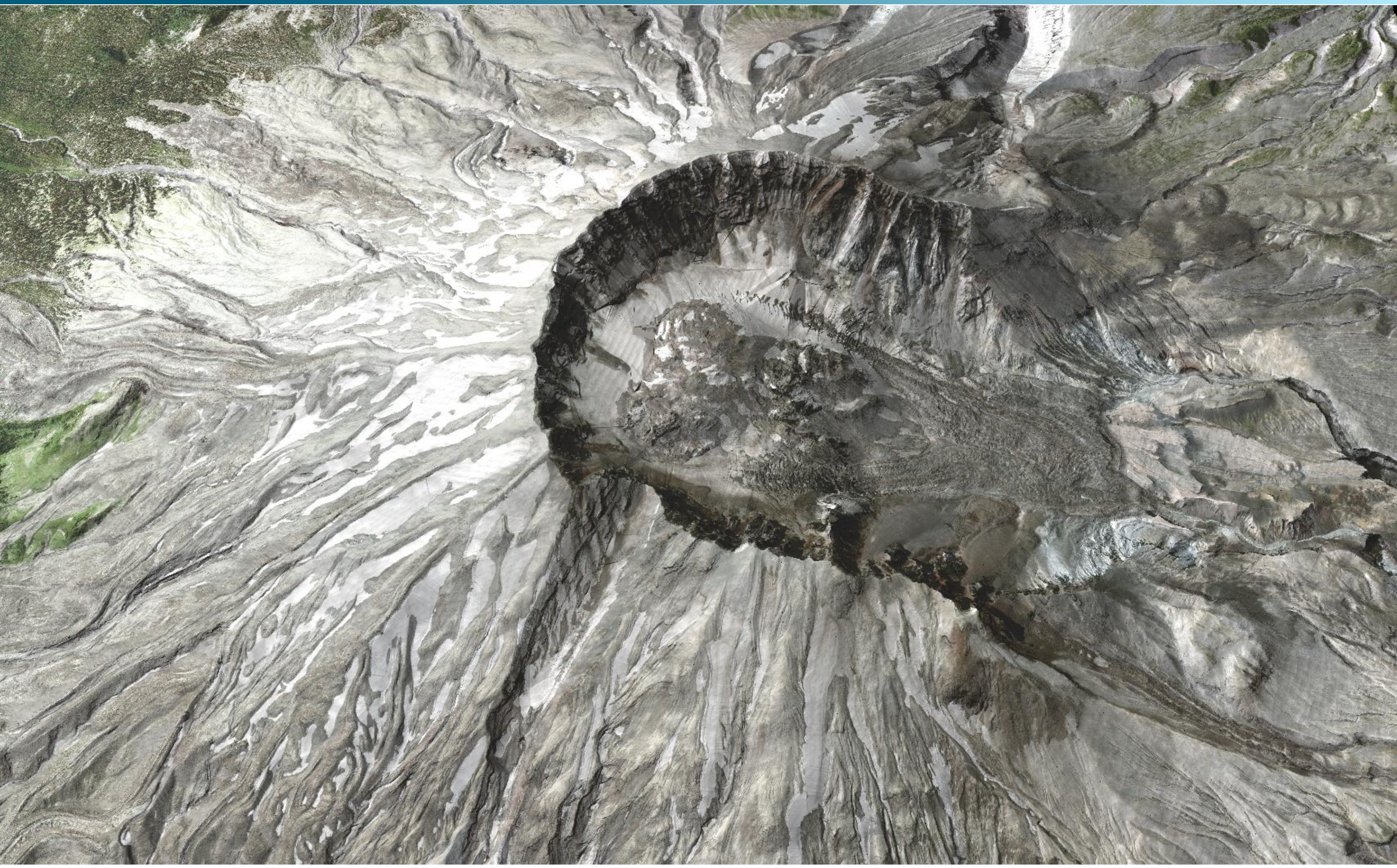
November 4, 2019



Washington FEMA 3DEP 2018 LiDAR Technical Data Report

Contract No. G16PC00016, Task Order No. 140G0218F00367

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Cover Photo: A view of the crater of Mt. St. Helens. This image was created from the bare earth gridded surface and colored with orthoimagery.

INTRODUCTION

This photo taken by QSI acquisition staff shows a view of GNSS equipment set up over monument FEMAWA_04 located to the northwest of Mt. Adams visible in this photo.

In July 2018, Quantum Spatial (QSI) was contracted by the United States Geological Survey (USGS), in collaboration with the Federal Emergency Management Agency (FEMA) and the Natural Resources Conservation Service (NRCS) to collect Light Detection and Ranging (LiDAR) data beginning in the summer of 2018 for the Washington FEMA 3DEP 2018 sites in Washington State. The Washington FEMA 3DEP 2018 LiDAR project area covers approximately 6,519 acres of Quality Level 1 data and 3,450,211 acres of Quality Level 2 data encompassing portions of 6 counties within the state of Washington: Whitman, Skamania, Cowlitz, Clark, Klickitat, and Pend Oreille. The data were collected to aid USGS in assessing the topographic and geophysical properties of the study area in support of USGS's 3D Elevation Program objective. Additionally, data will be utilized in support of FEMA's flood risk mapping, assessment, and planning program. Quality Level 1 data corresponding to the eastern Locke Dam will be provided to the NRCS for use in its natural resources conservation mission.

This project has been split into 4 separate deliveries (Figure 1). Block 1 included the QL1 LiDAR dataset near Lake Pend Oreille as well as the QL2 LiDAR dataset which covered the entirety of Whitman County. Block 2A covered an area of approximately 87,645 buffered acres, and encompasses portions of Skamania, Cowlitz, and Clark counties in central western Washington, including Mount Saint Helens. Block 2B covers the majority of Klickitat County and portions of the Columbia River, and Block 2C includes areas of Skamania and Clark Counties in southwest Washington.

This report details cumulative project information for all QL1 and QL2 LiDAR data deliveries. Documented herein are contract specifications, data acquisition procedures, processing methods, and analysis of the Washington FEMA 3DEP 2018 LiDAR dataset, including LiDAR accuracy and density. Acquisition dates and acreage are shown in Table 1, a complete list of contracted deliverables provided to USGS is shown in Table 2, and the project extent is shown in Figure 3.

Table 1: Acquisition dates, acreage, and data types collected on the Washington FEMA 3DEP 2018 LiDAR sites.

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
Washington FEMA HQ 2018 QL1	5,925	6,519	8/12/2018	QL1 NIR LiDAR
Washington FEMA HQ 2018 QL2	3,393,840	3,450,211	8/5/2018 – 5/6/2019	QL2 NIR LiDAR

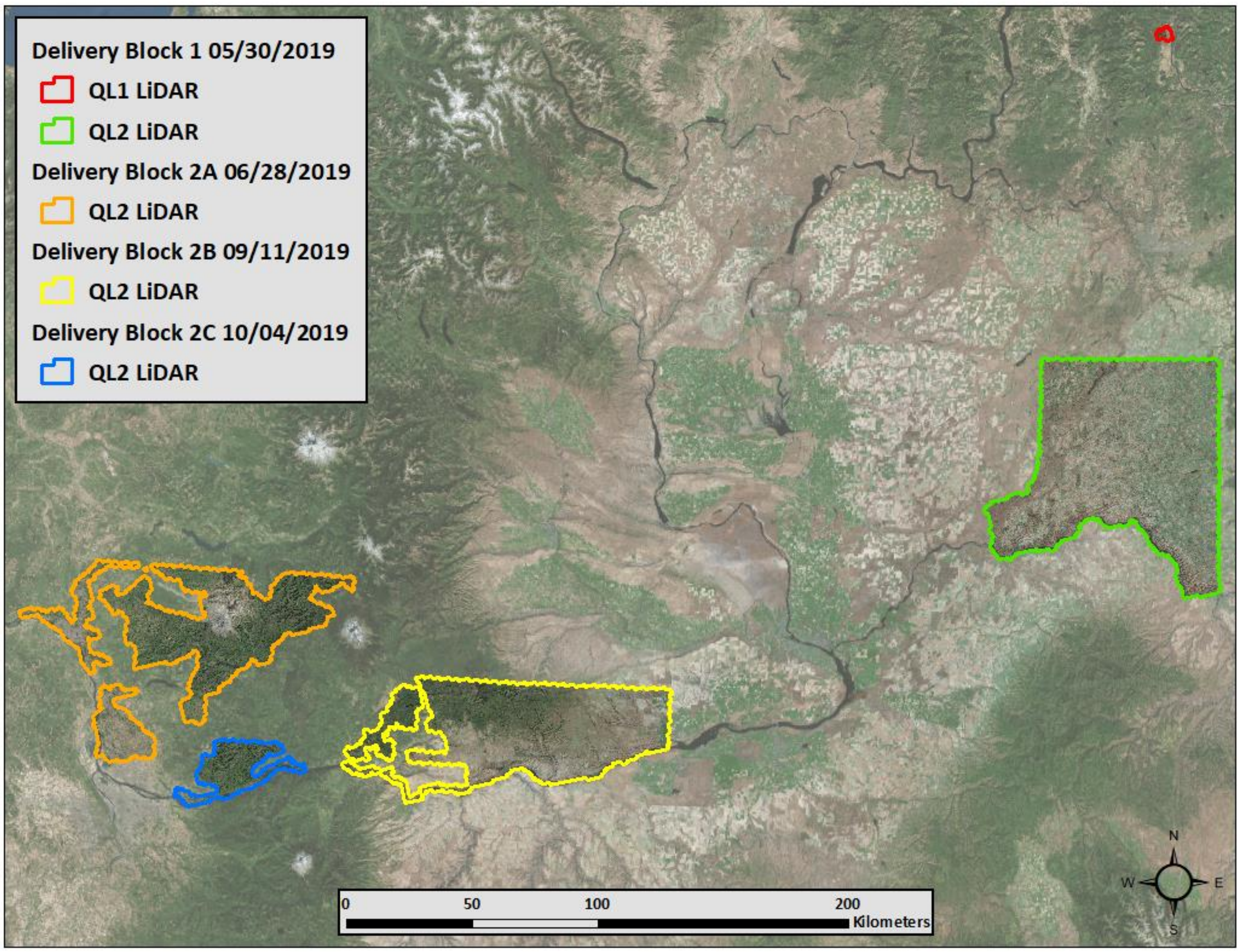

Figure 1: Washington FEMA 3DEP 2018 delivery map

Deliverable Products

Table 2: Products delivered to USGS for the Washington FEMA 3DEP 2018 LiDAR sites

<table>
<tr><th colspan="3">Washington FEMA 3DEP 2018 LiDAR Products
Projection: UTM Zones 10 & 11 North
Horizontal Datum: NAD83 (2011)
Vertical Datum: NAVD88 (GEOID12B)
Units: Meters</th></tr>
<tr><td>Points</td><td colspan="2">LAS v 1.4
All Classified Returns</td></tr>
<tr><td>Rasters</td><td>QL1 Dataset
0.5 Meter GeoTiffs
Hydroflattened Bare Earth Model (DEM) Tiled
Intensity Images Tiled
dZ Orthos Tiled</td><td>QL2 Dataset
1.0 Meter GeoTiffs
Hydroflattened Bare Earth Model (DEM) Tiled
Intensity Images Tiled
dZ Orthos Tiled</td></tr>
<tr><td>Vectors</td><td colspan="2">Shapefiles (*.shp)
Full Project Boundary
Block 1 Project Boundary
Block 2A Project Boundary
Block 2B Project Boundary
Block 2C Project Boundary
LiDAR Tile Index (1,000 x 1,000 meters)
Ground Survey Shapes
ESRI File Geodatabase (*.gdb)
Flightline Index
Flightline Swath Coverage Extents
Water’s Edge Breaklines
Bridge Breaklines
Ground Survey ASCIIs (*.xlsx)
Base Stations
Ground Control Points
Non-Vegetated Vertical Accuracy Check Points
Vegetated Vertical Accuracy Check Points</td></tr>
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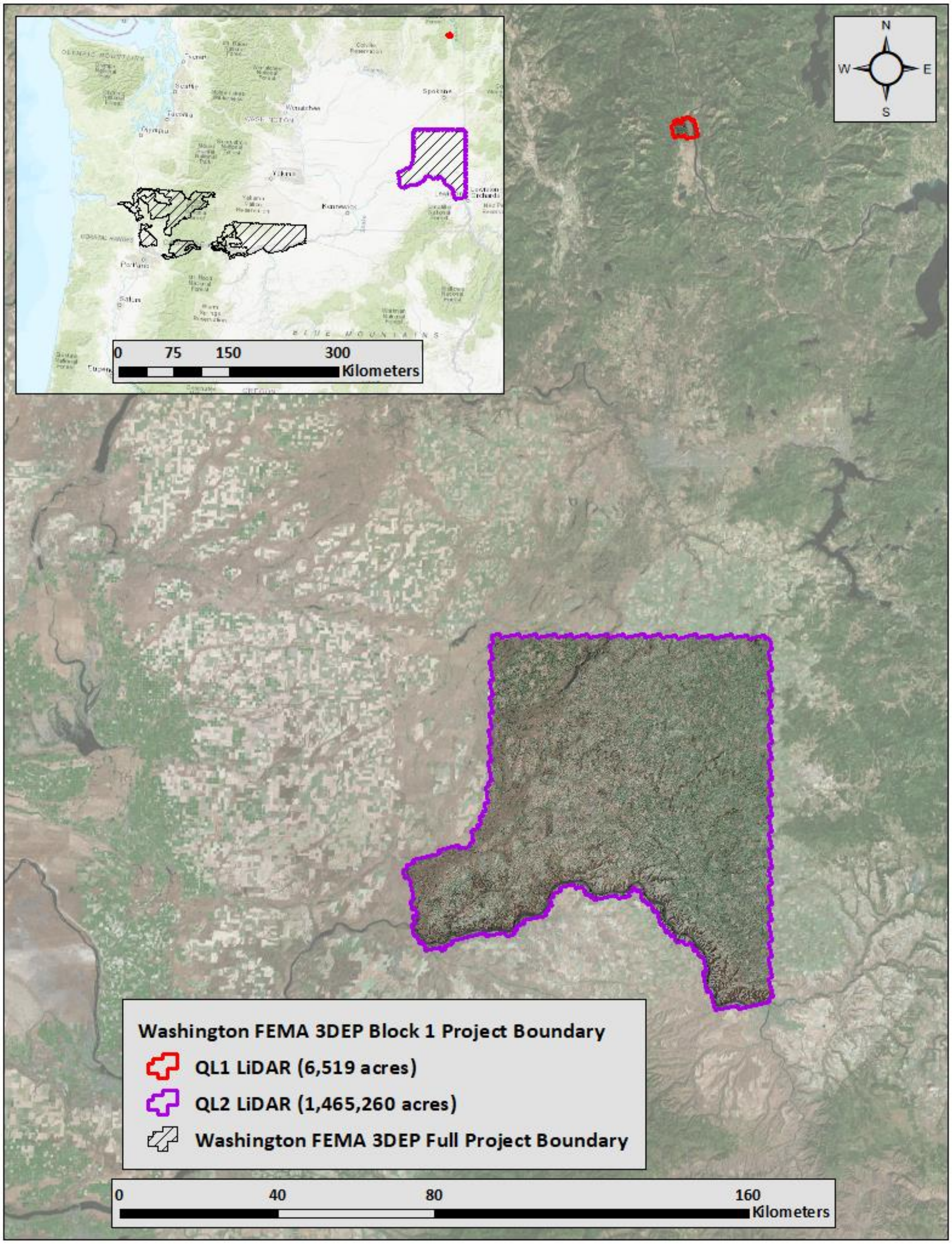


Figure 2: Location map of the Washington FEMA 3DEP 2018 Block 1 sites

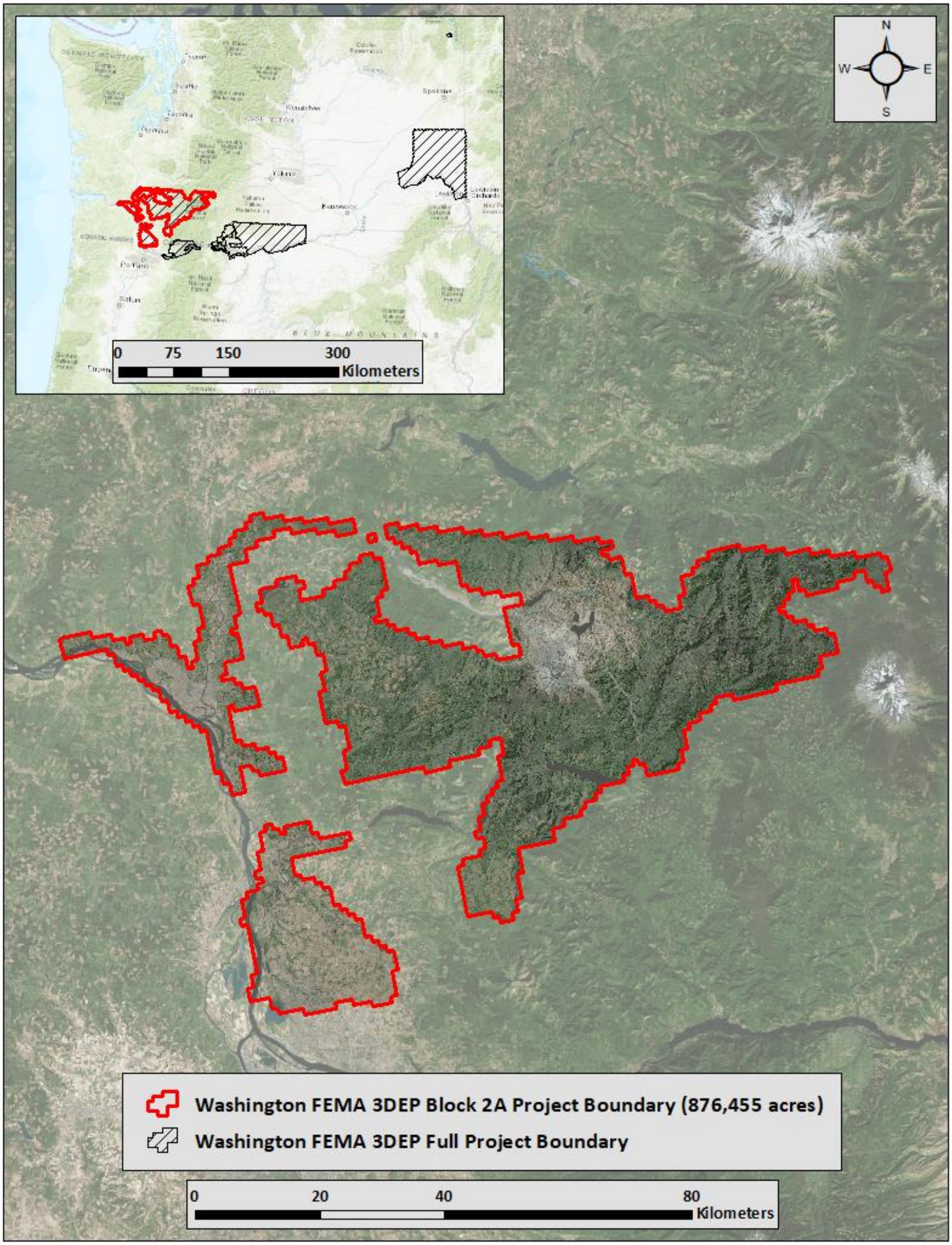


Figure 3: Location map of the Washington FEMA 3DEP 2018 Block 2A site

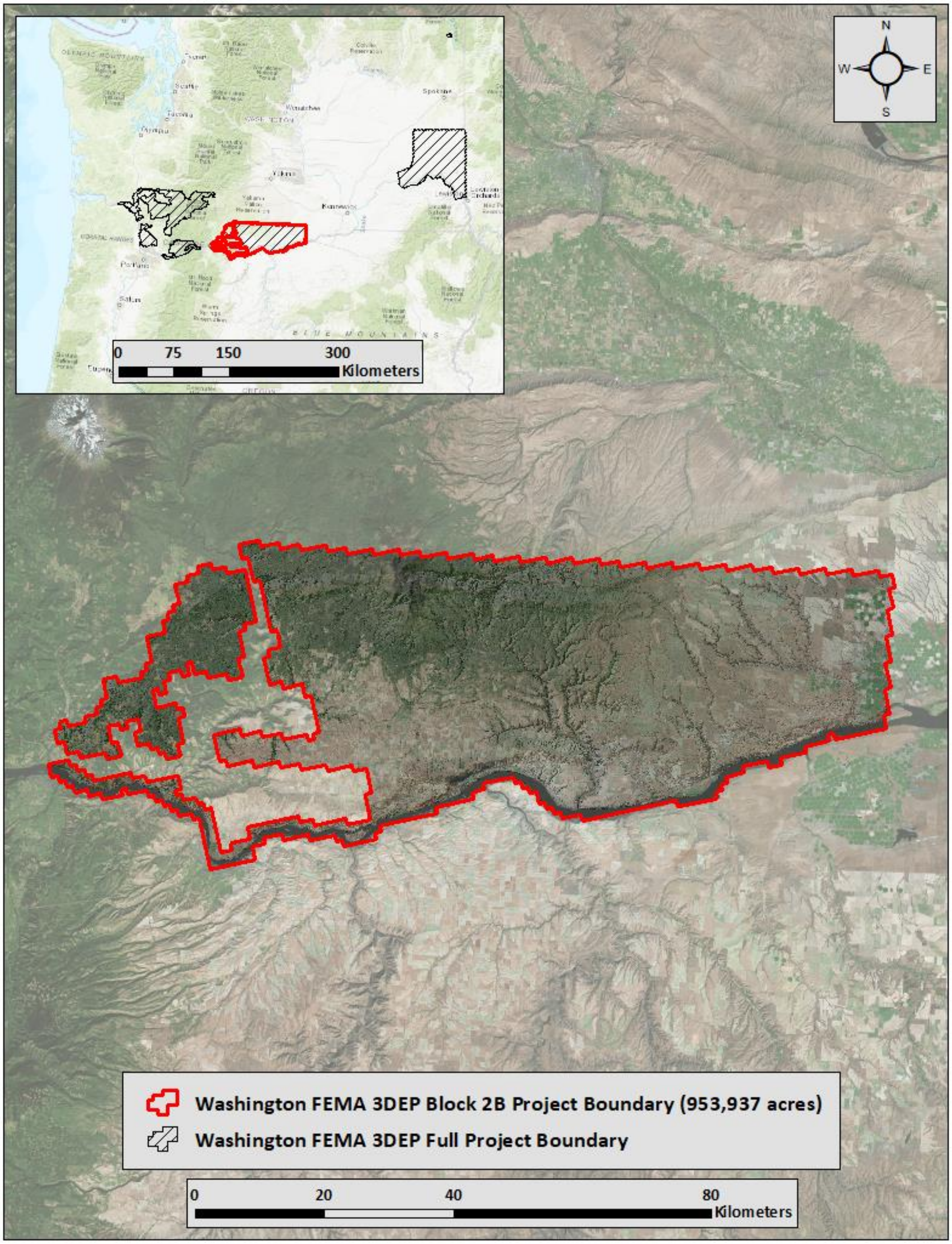


Figure 4: Location map of the Washington FEMA 3DEP Block 2B site

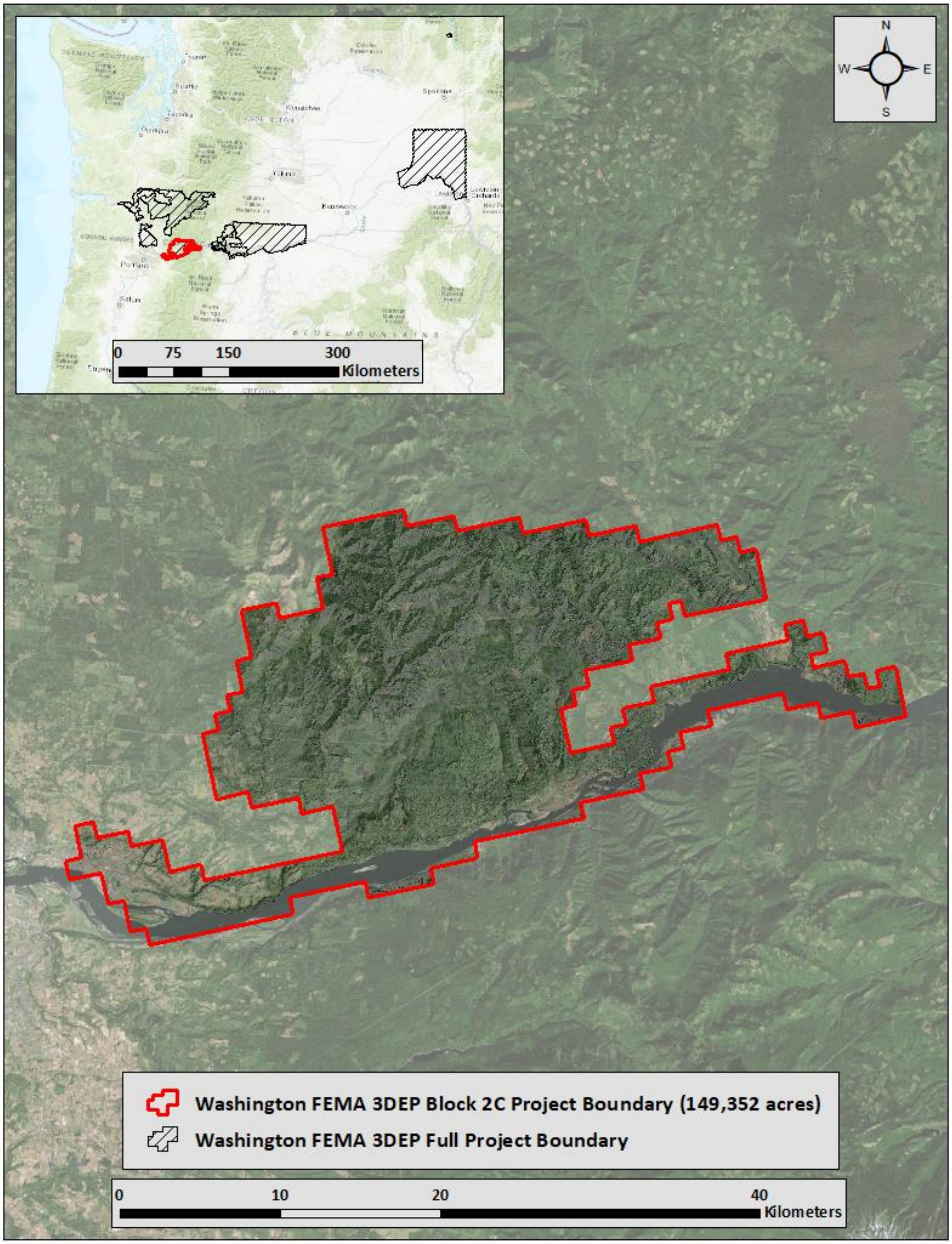


Figure 5: Location map of the Washington FEMA 3DEP Block 2C site

ACQUISITION

A photo taken by QSI acquisition staff showing a view of the Washington FEMA 3DEP study area

Planning

In preparation for data collection, QSI reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Washington FEMA 3DEP 2018 LiDAR study areas at the target point density of ≥8.0 points/m^2 to achieve QL1 specifications and ≥2.0 points/m^2 to achieve QL2 specifications. Acquisition parameters including orientation relative to terrain, flight altitude, pulse rate, scan angle, and ground speed were adapted to optimize flight paths and flight times while meeting all contract specifications.

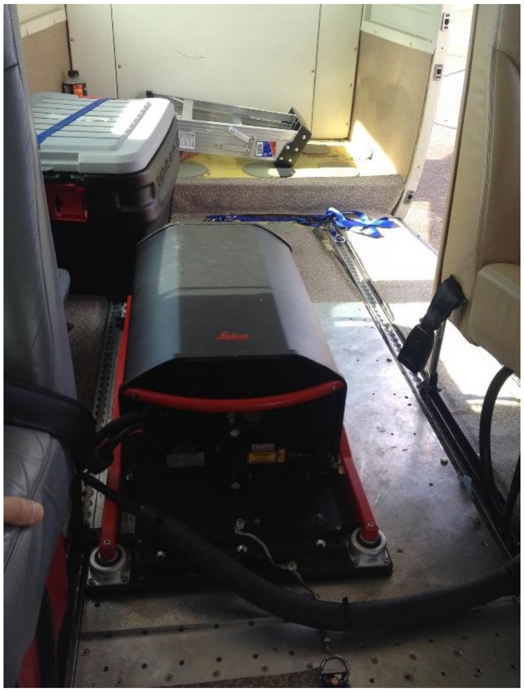
Factors such as satellite constellation availability and weather windows must be considered during the planning stage. Any weather hazards or conditions affecting the flights were continuously monitored due to their potential impact on the daily success of airborne and ground operations. In addition, logistical considerations including private property access and potential air space restrictions were reviewed.

Airborne LiDAR Survey

The LiDAR survey was accomplished using both a Leica ALS80 and a Riegl VQ-1560i sensor system mounted in Cessna Caravans. Table 3 summarizes the settings used to yield an average pulse density of ≥8 pulses/m^2 over QL1 project areas, and ≥2 pulses/m^2 over QL2 project areas. Both laser systems can record unlimited range measurements (returns) per pulse. It is not uncommon for some types of surfaces (e.g., dense vegetation or water) to return fewer pulses to the LiDAR sensor than the laser originally emitted. The discrepancy between first return and overall delivered density will vary depending on terrain, land cover, and the prevalence of water bodies. All discernible laser returns were processed for the output dataset.

All QL1 areas were surveyed with an opposing flight line side-lap of ≥50% (≥100% overlap) and all QL2 areas were surveyed with an opposing flight line side-lap of ≥25% (≥50% 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.

Riegl VQ-1560i LiDAR Sensor



Leica ALS80 LiDAR Sensor

Table 3: LiDAR specifications and survey settings

LiDAR Survey Settings & Specifications			
Quality Level	QL1	QL2	QL2
Acquisition Dates	8/12/2018	8/30/2018 – 3/26/2019	8/5/2018 – 5/6/2019
Aircraft Used	Cessna Caravan	Cessna Caravan	Cessna Caravan
Sensor	Leica	Leica	Riegl
Laser	ALS80	ALS80	VQ-1560i
Maximum Returns	Unlimited	Unlimited	Unlimited
Resolution/Density	Average 8 pulses/m^2	Average 2 pulses/m^2	Average 2 pulses/m^2
Aggregate Nominal Pulse Spacing	0.35 m	0.70 m	0.70 m
Survey Altitude (AGL)	1,800 m	2,300 m	2,392 m
Survey speed	110 knots	125 knots	130 knots
Field of View	30^o	30^o	58.5^o
Mirror Scan Rate	42 Hz	44 Hz	68.1 Hz
Target Pulse Rate	300 kHz	245 kHz	700 kHz (350/channel)
Pulse Length	2.5 ns	2.5 ns	3 ns
Laser Pulse Footprint Diameter	39.6 cm	50.6 cm	43.1 cm
Central Wavelength	1064 nm	1064 nm	1064 nm
Pulse Mode	Multi Pulse in Air (2PiA)	Multi Pulse in Air (2PiA)	Multiple Times Around (MTA)
Beam Divergence	0.22 mrad	0.22 mrad	0.18 mrad
Swath Width	965 m	1,233 m	1,145 m
Swath Overlap	67%	25%	20%
Intensity	8-bit, scaled to 16-bit	8-bit, scaled to 16-bit	16-bit
Accuracy	NVA (95% Confidence Level) ≤ 19.6 cm	NVA (95% Confidence Level) ≤ 19.6 cm	NVA (95% Confidence Level) ≤ 19.6 cm
	VVA (95th Percentile) ≤ 30 cm	VVA (95th Percentile) ≤ 30 cm	VVA (95th Percentile) ≤ 30 cm
	Relative < 8cm between swaths	Relative < 8cm between swaths	Relative < 8cm between swaths

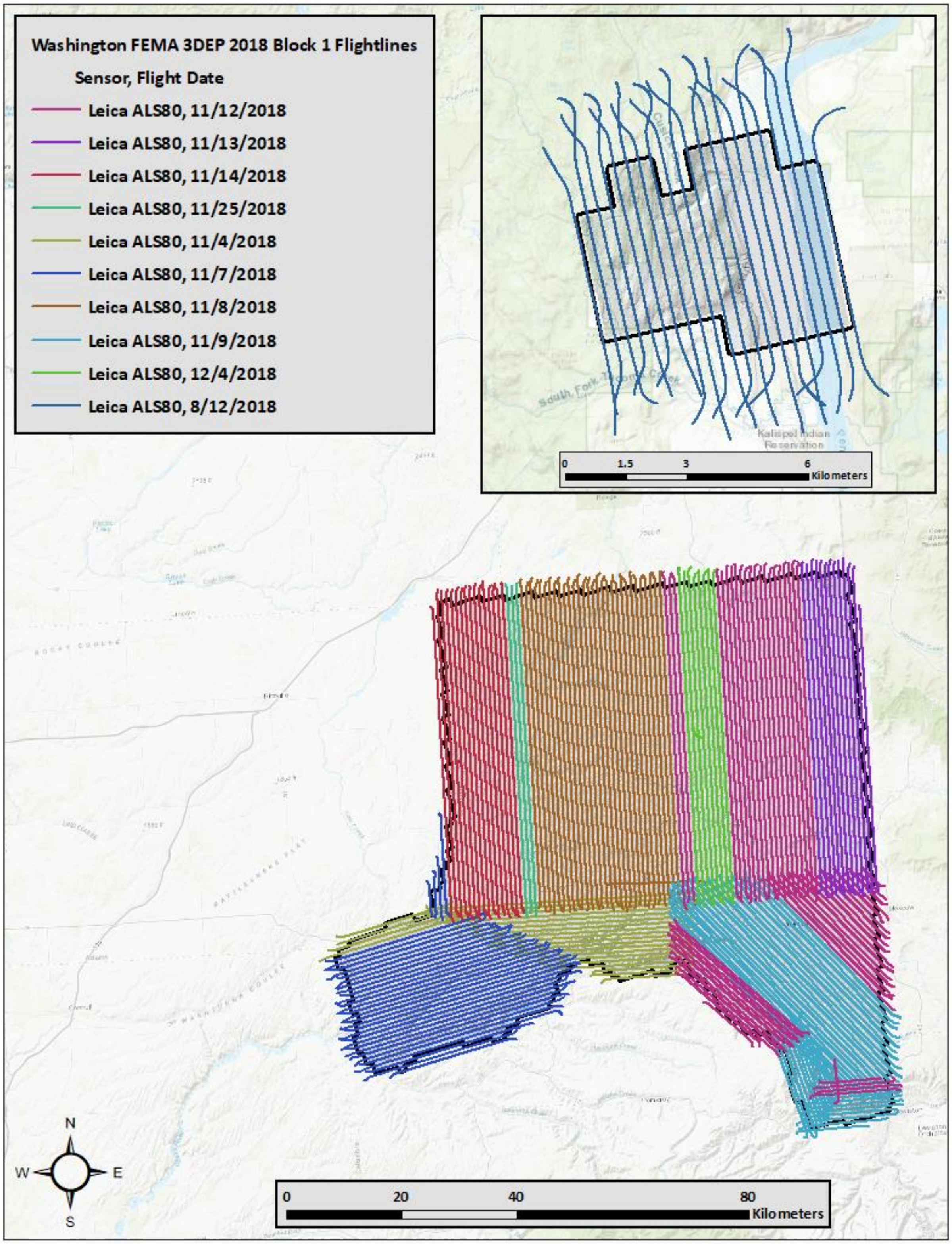


Figure 6: Washington FEMA 3DEP 2018 Block 1 LiDAR Flightline Map

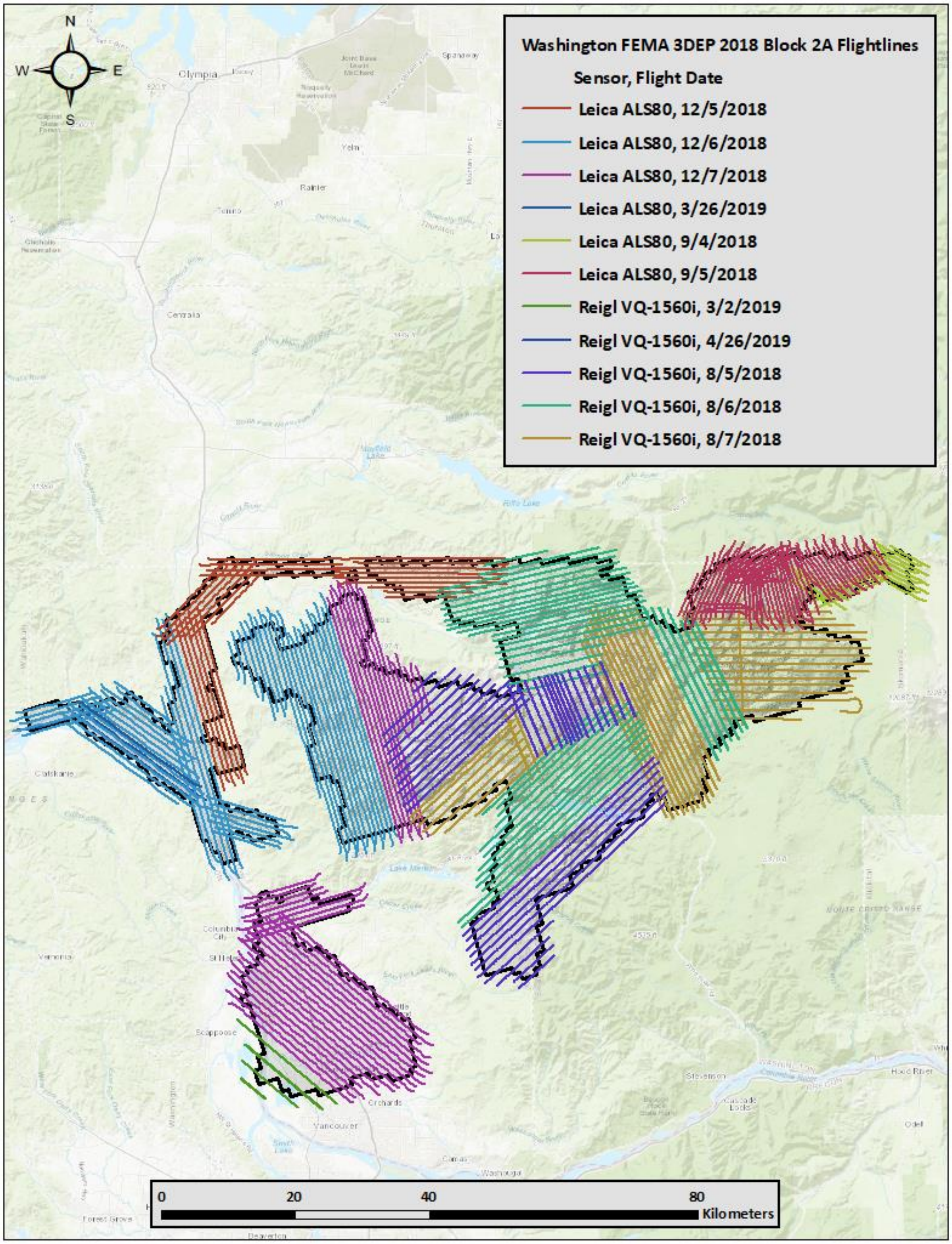


Figure 7: Washington FEMA 3DEP 2018 Block 2A LiDAR Flightline Map

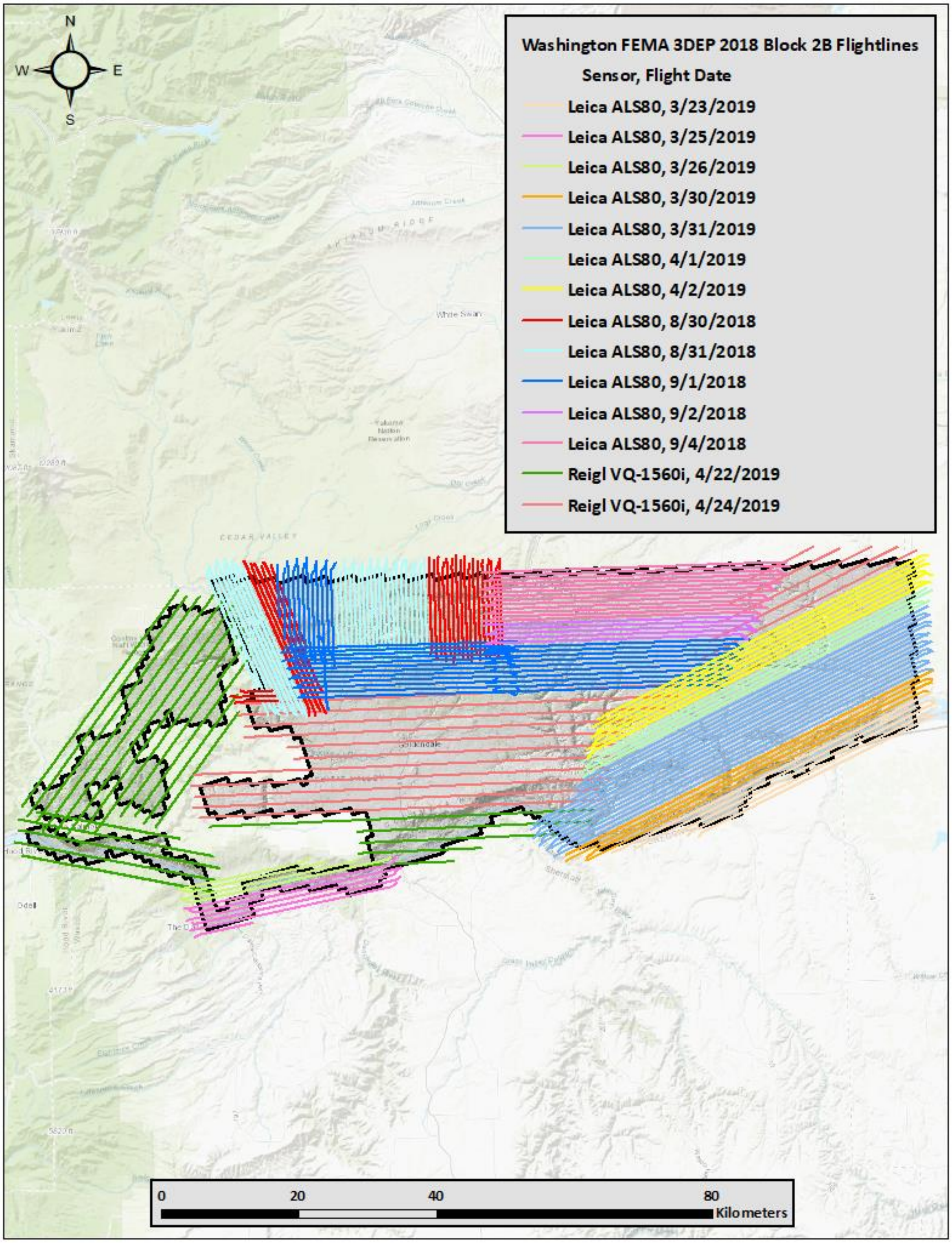


Figure 8: Washington FEMA 3DEP 2018 Block 2B LiDAR Flightline Map

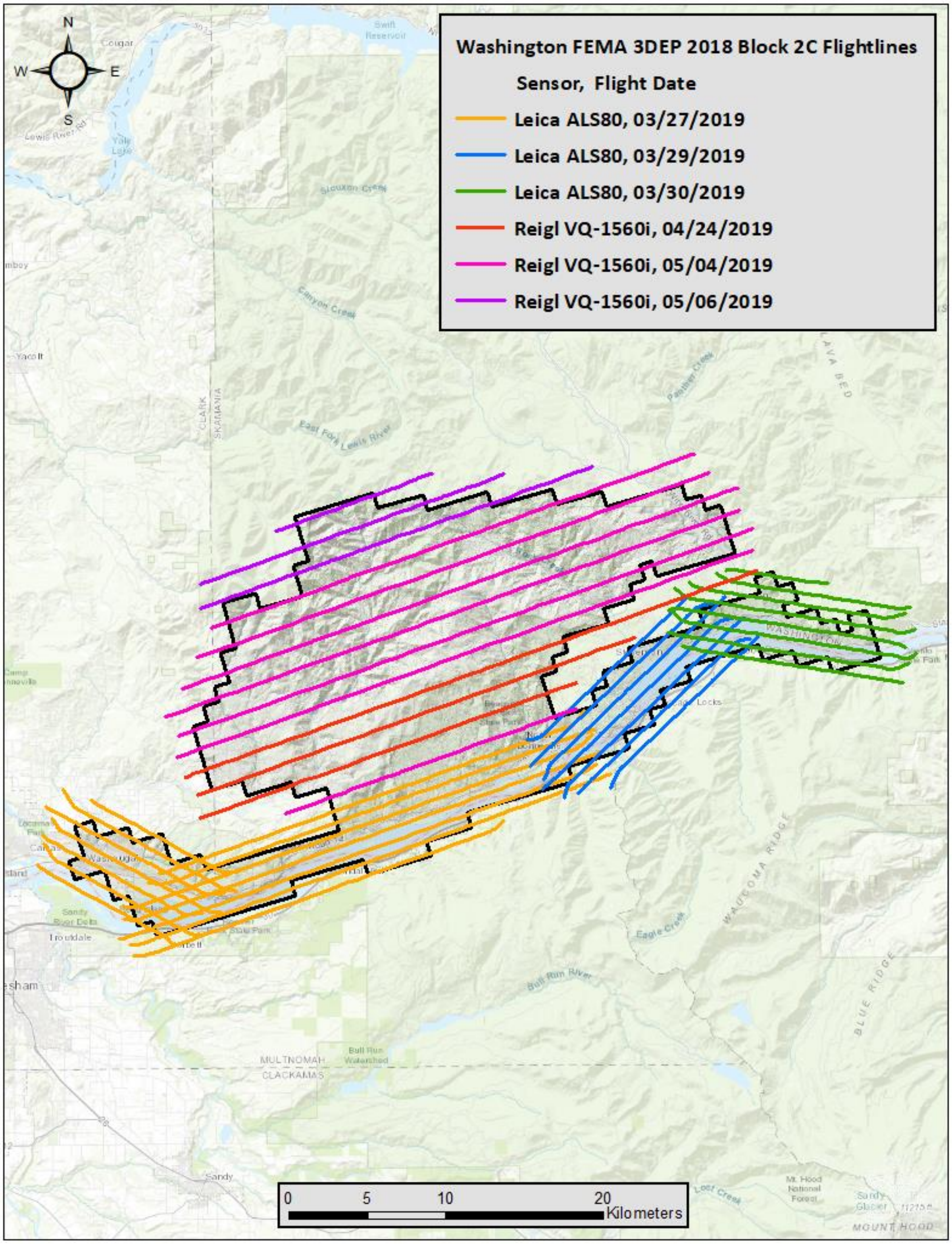


Figure 9 Washington FEMA 3DEP 2018 Block 2C LiDAR Flightline Map

Ground Survey

Ground control surveys, including monumentation and ground survey point (GSP) collection, were conducted by Quantum Spatial to support the airborne acquisition. Ground control data were used to geospatially correct the aircraft positional coordinate data and non-vegetated and vegetated check points were collected to perform quality assurance checks on final LiDAR data.

Base Stations

Base stations were utilized 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. QSI utilized 22 permanent Washington State Reference Network (WSRN) Real-Time Network (RTN) base stations, five permanent Leica SmartNet RTN base stations, one permanent Oregon Reference Network (ORGN) RTN base station, and seven newly-established RTK monuments for the Washington FEMA 3DEP 2018 LiDAR project (Table 4, Figure 10). New monumentation was set using a 6” mag nail. QSI’s professional land surveyor, Evon Silvia (WAPLS#53957) oversaw and certified the establishment of all monuments.

Table 4: Monument positions for the Washington FEMA 3DEP 2018 acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Base Station ID	Type	Latitude	Longitude	Ellipsoid (meters)
ARLN	WSRN	45° 42' 29.52492"	-120° 10' 59.71120"	120.839
CATH	WSRN	46° 11' 50.27590"	-123° 22' 02.11280"	56.668
CCPW	WSRN	46° 19' 16.31812"	-117° 58' 42.88324"	497.798
CROK	WSRN	46° 16' 28.54486"	-122° 54' 45.09329"	1.473
DMND	WSRN	48° 08' 12.36032"	-117° 09' 49.10455"	718.552
FEMAWA_01	Monument	46° 11' 03.56429"	-121° 59' 36.38843"	990.792
FEMAWA_02	Monument	46° 16' 38.33284"	-122° 13' 48.63739"	1180.886
FEMAWA_03	Monument	46° 08' 29.70611"	-122° 20' 04.05642"	650.156
FEMAWA_04	Monument	46° 21' 39.11467"	-121° 41' 06.52976"	1248.636
GLWD	WSRN	46° 01' 11.36774"	-121° 17' 18.92602"	561.399
GOLY	WSRN	45° 49' 43.29713"	-120° 48' 08.78673"	500.616
GRCK	WSRN	48° 08' 36.89091"	-117° 39' 52.38897"	670.155
KLTS	WSRN	46° 38' 35.52937"	-118° 33' 29.34766"	257.666
LCRS	WSRN	46° 49' 10.46563"	-117° 52' 42.92742"	441.603
LWST	WSRN	46° 22' 23.42488"	-117° 00' 08.24688"	427.599
ORGR	Leica Smart Net	45° 29' 51.50135"	-122° 24' 57.24160"	98.042
ORWA	Leica Smart Net	45° 35' 11.07357"	-120° 41' 11.66085"	389.699

Base Station ID	Type	Latitude	Longitude	Ellipsoid (meters)
P414	WSRN	45° 50' 05.51211"	-122° 41' 34.15479"	64.212
P429	WSRN	45° 40' 34.04468"	-121° 52' 38.43679"	25.942
PKDL	ORGN	45° 31' 05.87695"	-121° 33' 49.18807"	512.142
PLMN	WSRN	46° 44' 02.13454"	-117° 11' 35.11470"	743.434
POME	WSRN	46° 28' 47.78598"	-117° 37' 54.08907"	551.491
PTSN	WSRN	45° 56' 20.95558"	-119° 36' 35.05790"	119.017
SPKN	WSRN	47° 37' 39.57240"	-117° 30' 09.22493"	695.026
SPRG	WSRN	47° 18' 35.46381"	-117° 58' 31.13705"	600.951
TDLS	ORGN	45° 36' 27.74414"	-121° 07' 46.16432"	26.935
VCWA	WSRN	45° 37' 03.44337"	-122° 30' 57.79896"	77.397
VRNT	WSRN	46° 38' 12.67324"	-119° 43' 55.25553"	116.288
WACX	Leica Smart Net	46° 57' 16.17413"	-117° 19' 56.67976"	677.288
WAFEMA_RTK_01	Monument	45° 59' 51.73769"	-120° 17' 29.52286"	894.64
WAFEMA_RTK_02	Monument	47° 07' 16.27277"	-117° 46' 20.52667"	543.455
WAFEMA_RTK_03	Monument	45° 49' 21.53958"	-120° 20' 48.49178"	721.53
WAKL	Leica Smart Net	46° 06' 48.54165"	-122° 53' 22.02789"	-10.381
WARZ	Leica Smart Net	47° 07' 16.10611"	-118° 22' 59.50459"	538.253
WEBG	WSRN	45° 46' 46.46143"	-122° 33' 46.11592"	67.657

To correct the continuously recorded onboard measurements of the aircraft position, QSI concurrently conducted multiple static Global Navigation Satellite System (GNSS) ground surveys (1 Hz recording frequency) at each base station location. During post-processing, the static GPS data were triangulated with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS1) for precise positioning. Multiple independent sessions over the same monument were processed to confirm antenna height measurements and to refine position accuracy.

Monuments were established according to the national standard for geodetic control networks, as specified in the Federal Geographic Data Committee (FGDC) Geospatial Positioning Accuracy Standards for geodetic networks.[1] This standard provides guidelines for classification of monument quality at the 95% confidence interval as a basis for comparing the quality of one control network to another. The monument rating for this project is shown in Table 5.

[1] Federal Geographic Data Committee, Geospatial Positioning Accuracy Standards (FGDC-STD-007.2-1998). Part 2: Standards for Geodetic Networks, Table 2.1, page 2-3. http://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part2/chapter2

Table 5: Federal Geographic Data Committee monument rating for network accuracy

Direction	Rating
1.96 * St Dev $_{NE}$:	0.050 m
1.96 * St Dev $_{z}$:	0.050 m

For the Washington FEMA 3DEP 2018 LiDAR project, the monument coordinates contributed no more than 5.7 cm of positional error to the geolocation of the final ground survey points and LiDAR, with 95% confidence.

Ground Survey Points (GSPs)

Ground survey points were collected using real time kinematic (RTK), post-processed kinematic (PPK), fast-static (FS), and total station (TS) 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 6 for Trimble unit specifications.

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 10).

Table 6: ground survey equipment identification

Receiver Model/Antenna	OPUS Antenna ID	Use
Trimble R8/Integrated Antenna	TRM_R8_GNSS	Rover
Trimble R7 GNSS/ Zephyr GNSS Geodetic Model 2 RoHS	TRM57971.00	Static
NIKON Total Station	n/a	Forested VVA Check Points
Trimble M3 Total Station	n/a	Forested VVA Check Points

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 7, see LiDAR Accuracy Assessments, page 35).

Table 7: Land Cover Types and Descriptions

Land cover type	Land cover code	Example	Description	Accuracy Assessment Type
Shrubs	SH		Areas dominated by herbaceous shrubland	VVA
Tall Grass	TG		Herbaceous grasslands in advanced stages of growth	VVA
Forest	FR		Forested areas dominated by coniferous and deciduous species	VVA
Bare Earth	BE		Areas of bare earth surface	NVA
Urban	UA		Areas dominated by urban development, including parks	NVA

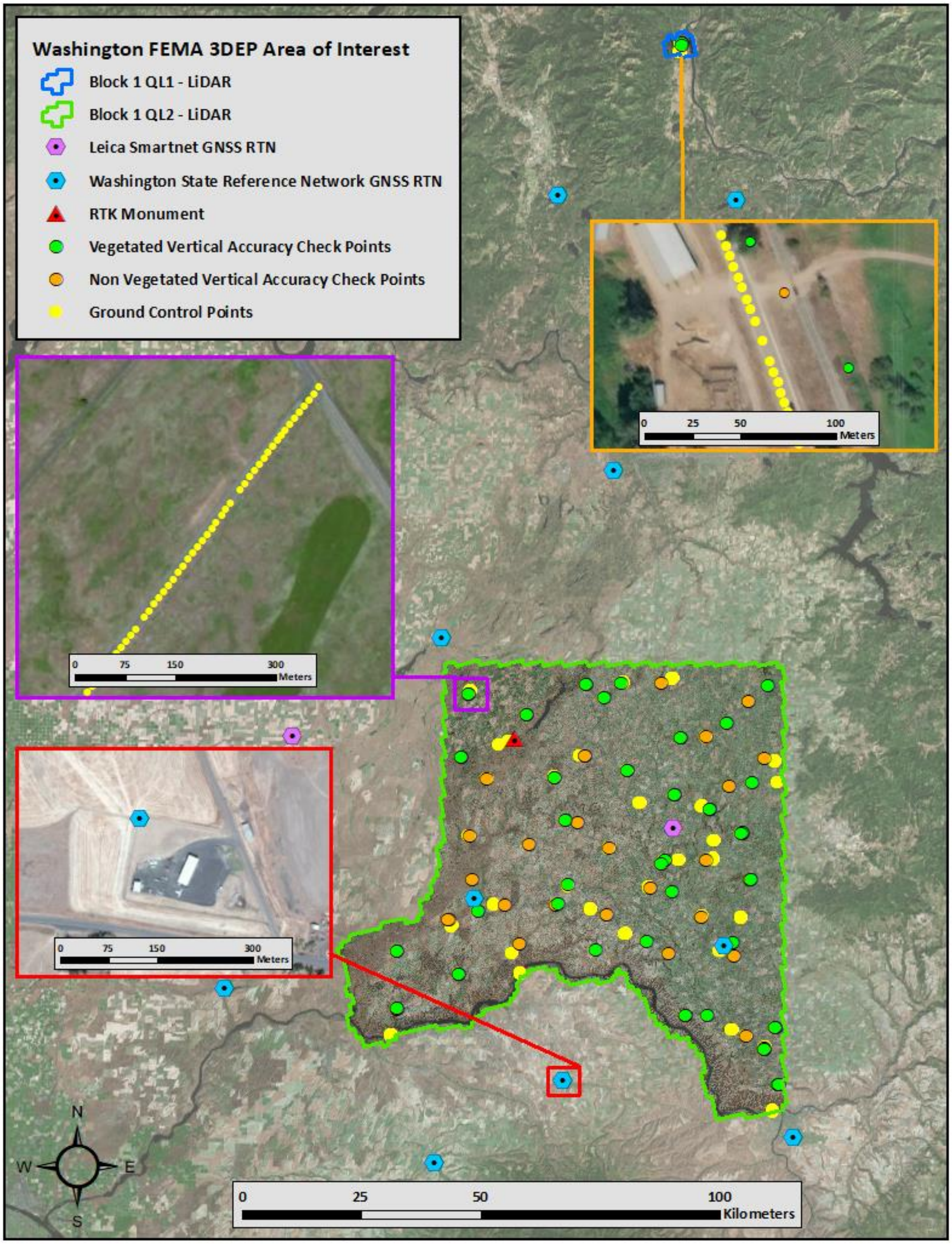


Figure 10: USGS Washington FEMA Block 1 ground survey location map

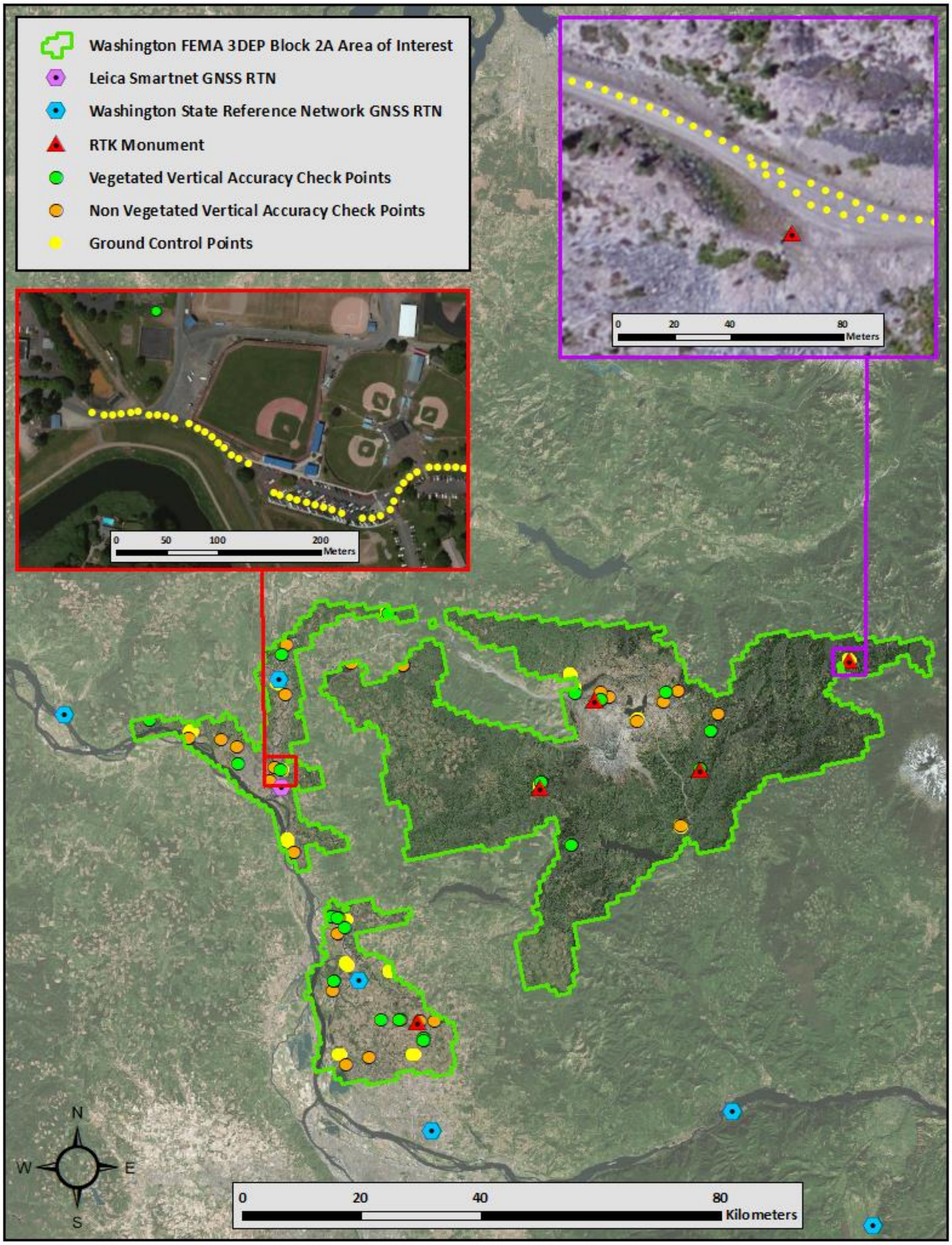


Figure 11: USGS Washington FEMA Block 2A ground survey location map

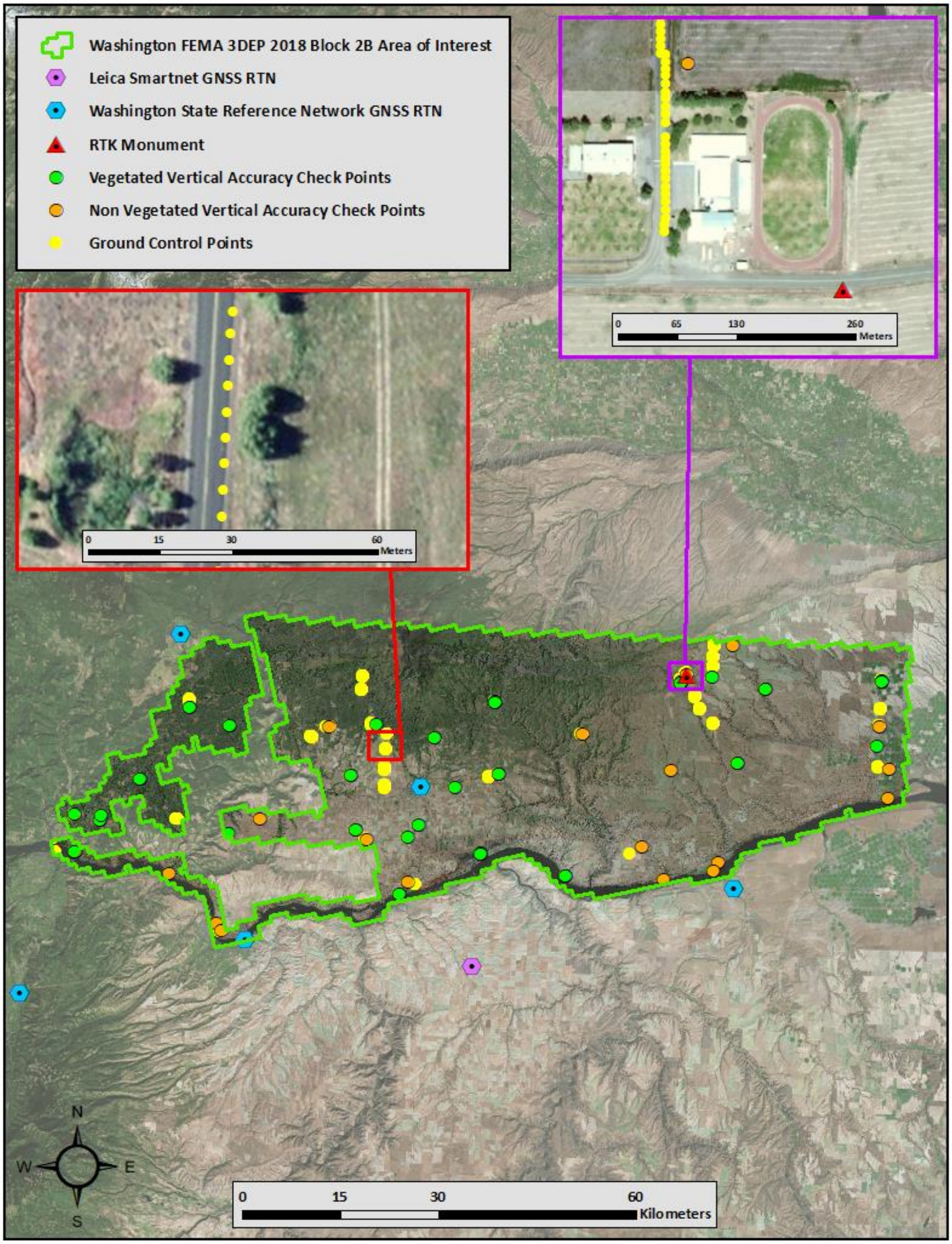


Figure 12: USGS Washington FEMA Block 2B ground survey location map

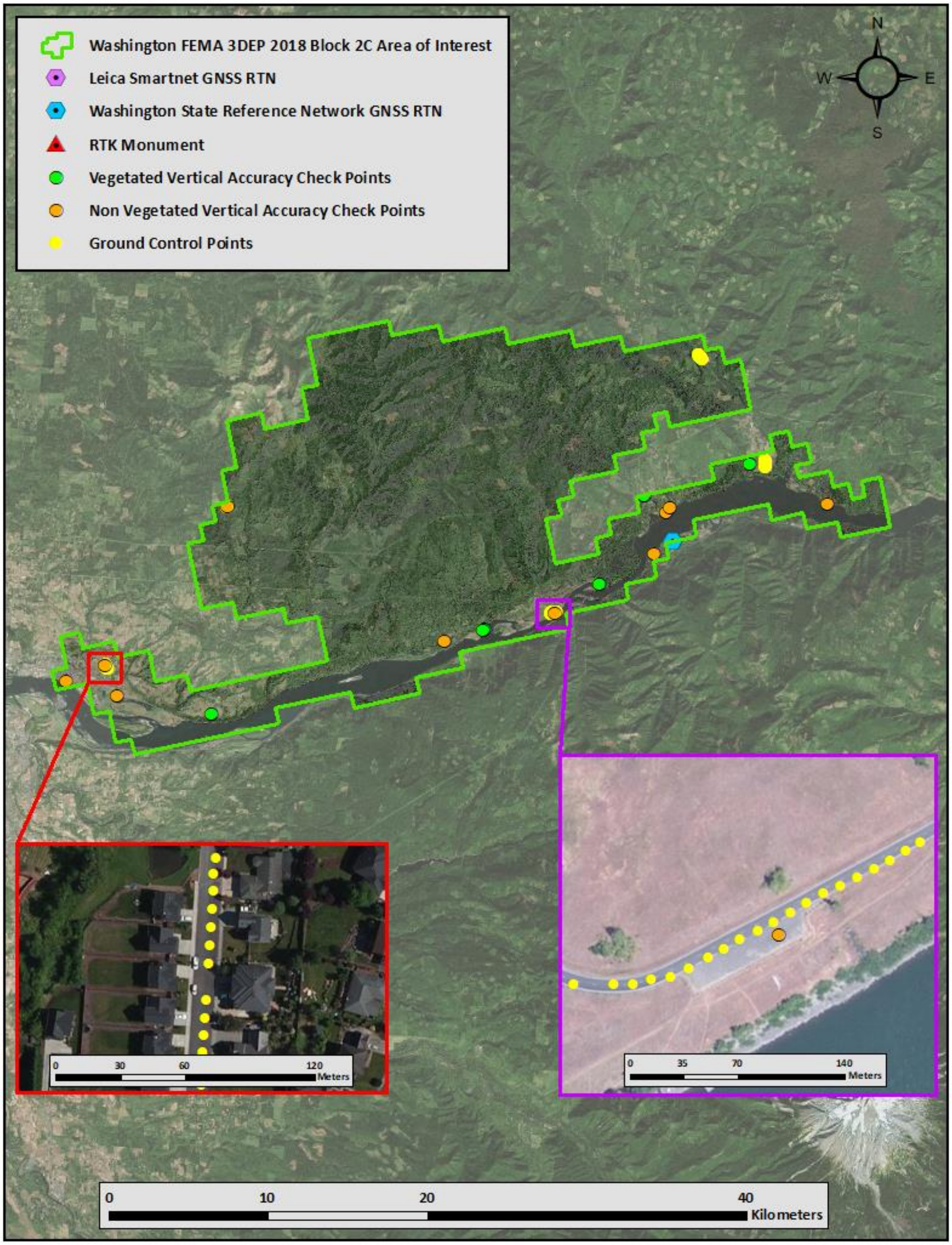
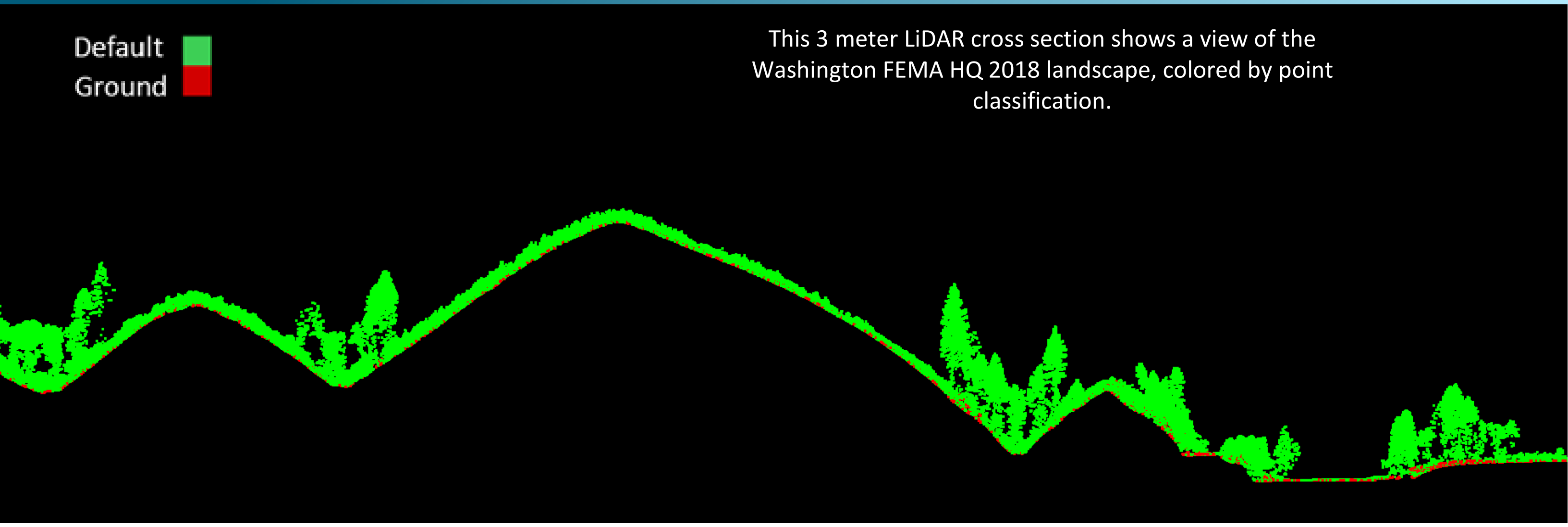


Figure 13: USGS Washington FEMA Block 2C ground survey location map



LiDAR Data

Upon completion of data acquisition, QSI processing staff initiated a suite of automated and manual techniques to process the data into the requested deliverables. Processing tasks included GPS control computations, smoothed best estimate trajectory (SBET) calculations, kinematic corrections, calculation of laser point position, sensor and data calibration for optimal relative and absolute accuracy, and LiDAR point classification (Table 8). Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 9.

Table 8: ASPRS LAS classification standards applied to the Washington FEMA 3DEP 2018 dataset

Classification Number	Classification Name	Classification Description
1	Default/Unclassified	Laser returns that are not included in the ground class, composed of vegetation and anthropogenic features
1-O	Overlap/Edge Clip	Flightline edge clip, identified using the overlap flag
2	Ground	Laser returns that are determined to be ground using automated and manual cleaning algorithms
7	Noise	Laser returns that are often associated with birds, scattering from reflective surfaces, or artificial points below the ground surface
9	Water	Laser returns that are determined to be water using automated and manual cleaning algorithms
17	Bridge	Bridge decks
20	Ignored Ground	Ground points proximate to water's edge breaklines; ignored for correct model creation

Table 9: LiDAR processing workflow

LiDAR Processing Step	Software Used
Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data. Develop a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with sensor head position and attitude recorded throughout the survey.	Waypoint Inertial Explorer v.8.7
Calculate laser point position by associating SBET position to each laser point return time, scan angle, intensity, etc. Create raw laser point cloud data for the entire survey in *.las (ASPRS v. 1.4) format. Convert data to orthometric elevations by applying a geoid correction.	Waypoint Inertial Explorer v.8.7 Leica Cloudpro v. 1.2.4
Import raw laser points into manageable blocks to perform manual relative accuracy calibration and filter erroneous points. Classify ground points for individual flight lines.	TerraScan v.19
Using ground classified points per each flight line, test the relative accuracy. Perform automated line-to-line calibrations for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calculate calibrations on ground classified points from paired flight lines and apply results to all points in a flight line. Use every flight line for relative accuracy calibration.	TerraMatch v.19
Classify resulting data to ground and other client designated ASPRS classifications (Table 8). 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 and export in Geotiff format at a half meter pixel resolution for QL1 areas and a 1-meter pixel resolution for QL2 areas.	LAS Product Creator 3.0 (QSI proprietary) ArcMap v. 10.3.1
Export intensity images as GeoTIFFs at a half meter pixel resolution for QL1 areas and a 1-meter pixel resolution for QL2 areas.	Las Monkey 2.4 (QSI proprietary) LAS Product Creator 3.0 (QSI proprietary) ArcMap v. 10.3.1

Feature Extraction

Hydroflattening and Water's Edge Breaklines

Hydroflattening was performed on rivers and lakes within the Washington FEMA 3DEP 2018 project areas in accordance with USGS LBS 1.3 specifications. Bodies of water that were flattened include lakes and other closed water bodies with a surface area greater than 2 acres, all streams and rivers that are nominally wider than 30 meters including portions of the Columbia, Washougal, Wind, Palouse, and Snake Rivers, and select smaller bodies of water as feasible. The hydroflattening process eliminates artifacts in the digital terrain model caused by both increased variability in ranges or dropouts in laser returns due to the low reflectivity of water.

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

Once polygons were developed the initial ground classified points falling within water polygons were reclassified as water points to omit them from the final ground model. Elevations were then obtained from the filtered LiDAR returns to create the final breaklines. Lakes were assigned a consistent elevation for an entire polygon while rivers were assigned consistent elevations on opposing banks and smoothed to ensure downstream flow through the entire river channel.

Water boundary breaklines were then incorporated into the hydroflattened DEM by enforcing triangle edges (adjacent to the breakline) to the elevation values of the breakline. This implementation corrected interpolation along the hard edge in the final flattened models (Figure 14).

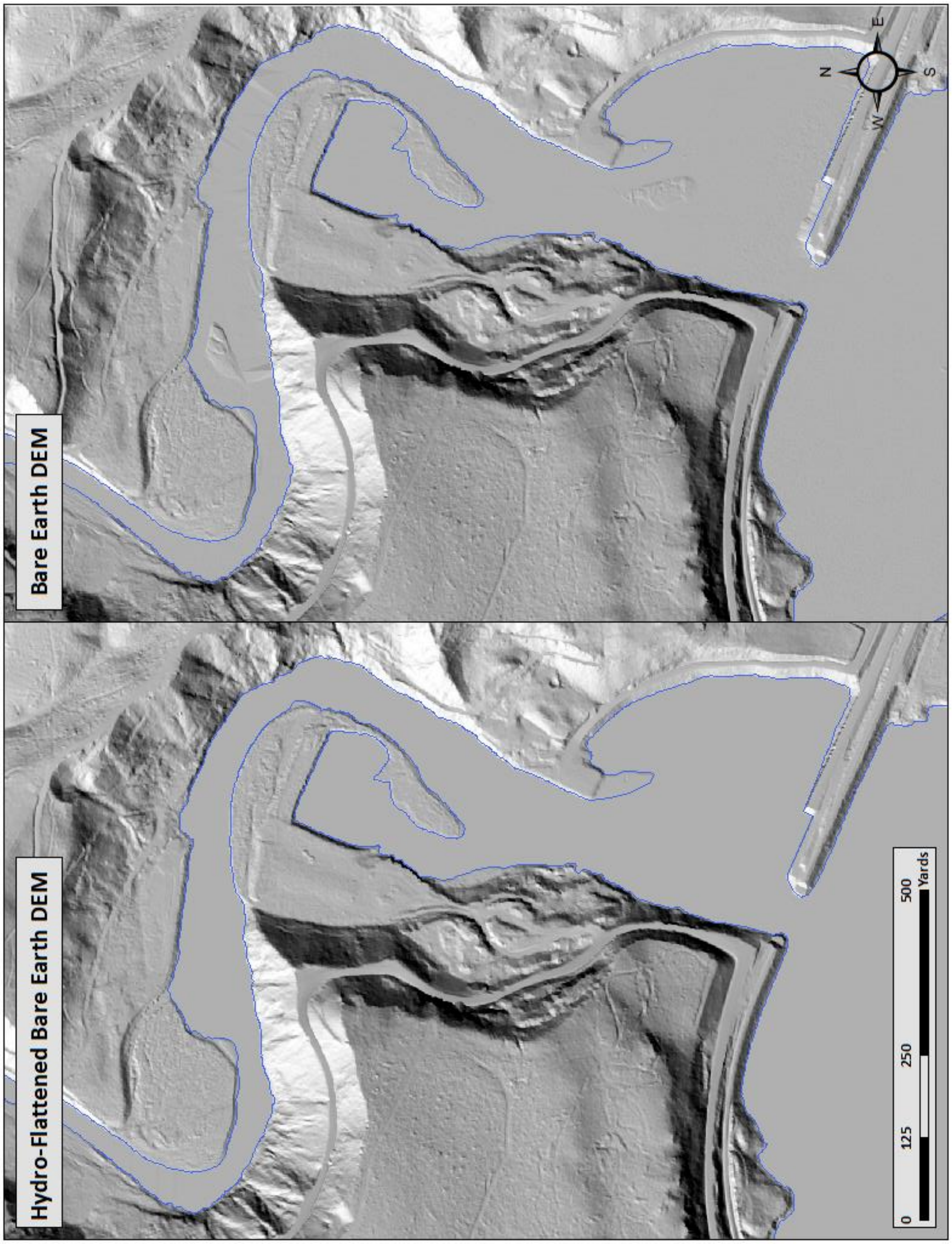
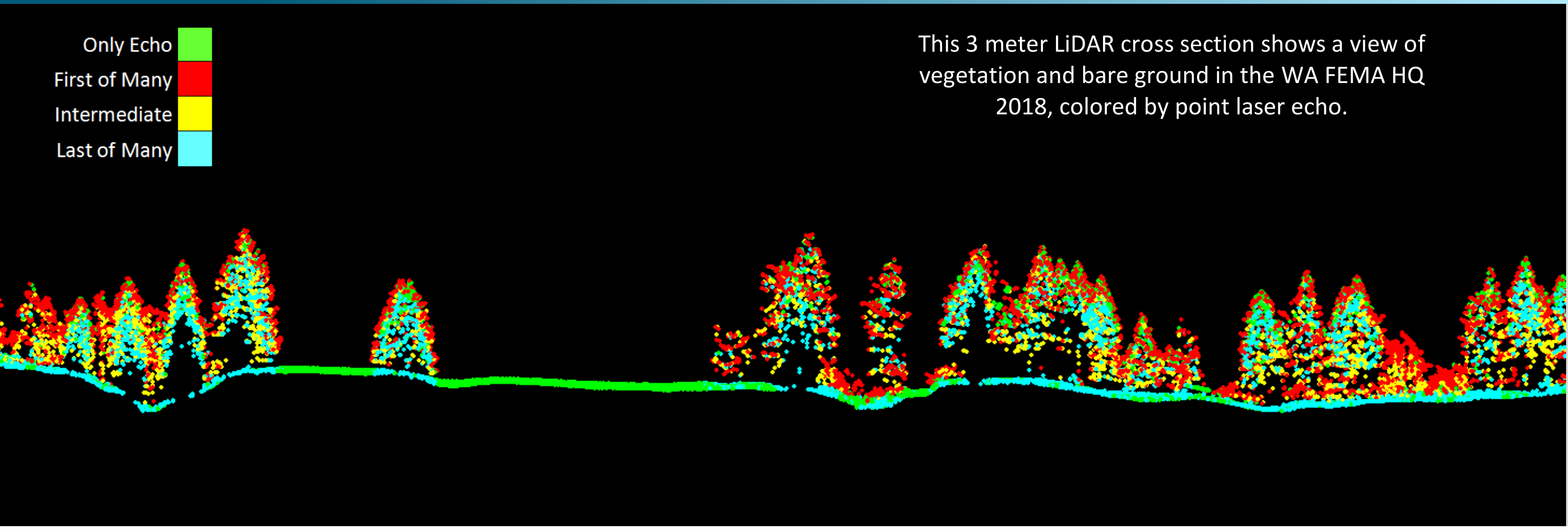


Figure 14: Example of hydroflattening in the Washington FEMA 3DEP 2018 LiDAR dataset



LiDAR Density

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

The density of ground-classified LiDAR returns was also analyzed for this project. Terrain character, land cover, and ground surface reflectivity all influenced the density of ground surface returns. In vegetated areas, fewer pulses may penetrate the canopy, resulting in lower ground density.

The average first-return density of LiDAR data for the Washington FEMA 3DEP 2018 QL1 data was 12.45 points/m^2 while the average ground classified density was 2.60 points/m^2. The average first-return density of LiDAR data for the Washington FEMA 3DEP 2018 QL2 areas was 4.79 points/m^2 while the average ground classified density was 1.87 points/m^2 (Table 10).

The statistical and spatial distributions of first return densities and classified ground return densities per 100 m x 100 m cell are portrayed in Figure 15 through Figure 23.

Table 10: Average LiDAR point densities

Classification	QL1 Point Density	QL2 Point Density
First-Return	12.45 points/m^2	4.79 points/m^2
Ground Classified	2.60 points/m^2	1.87 points/m^2

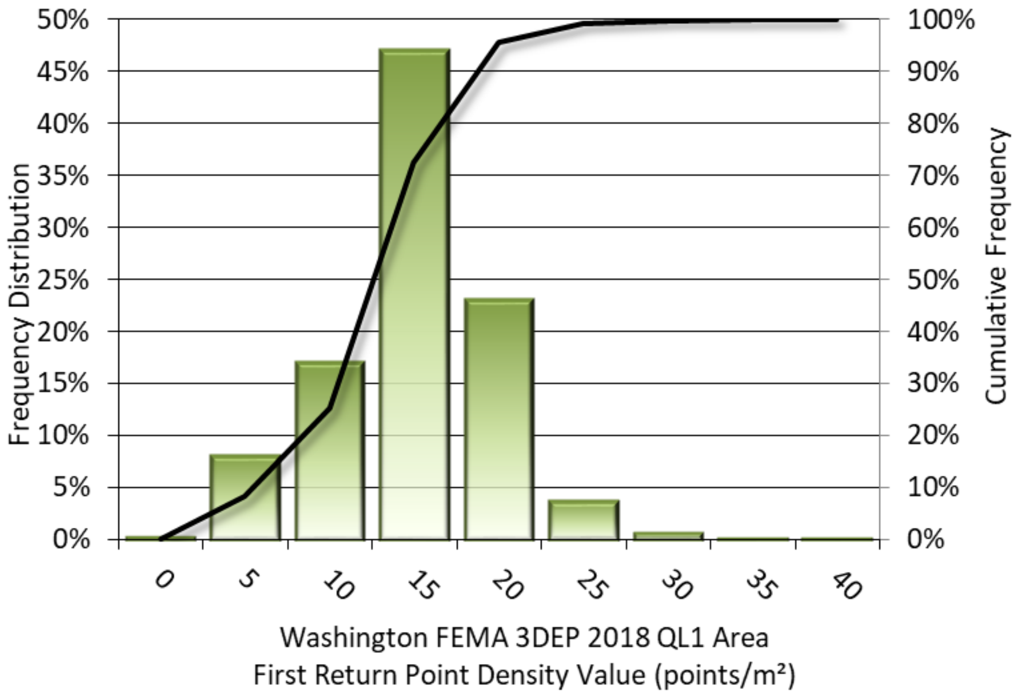


Figure 15: Frequency distribution of QL1 first return point density values per 100 x 100 m cell

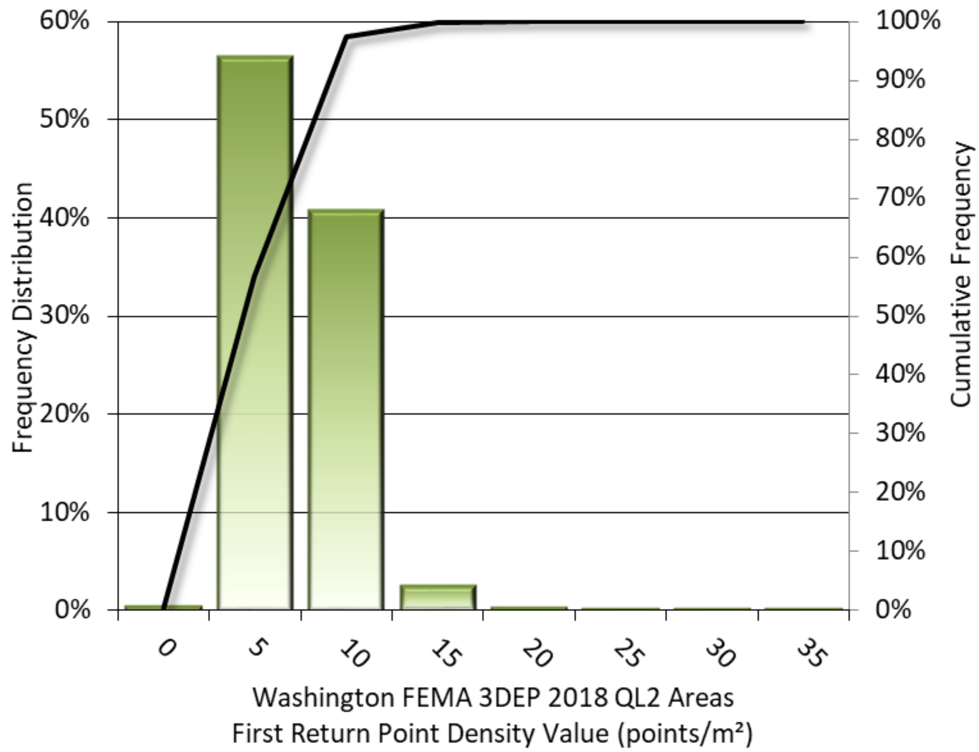


Figure 16: Frequency distribution of QL2 first return point density values per 100 x 100 m cell

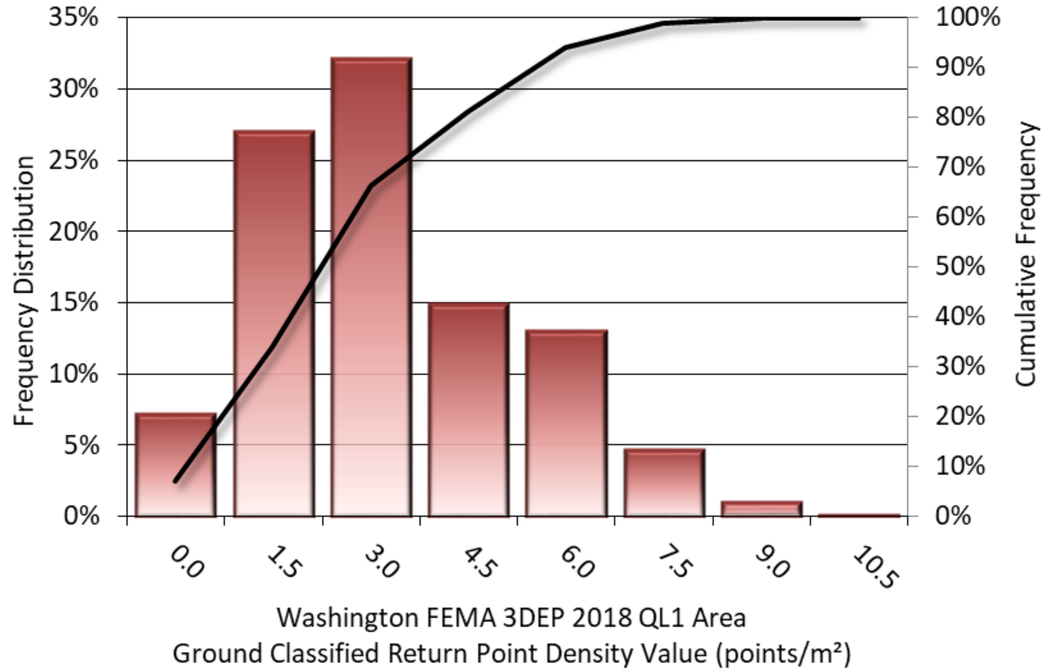


Figure 17: Frequency distribution of QL1 area ground-classified return point density values per 100 x 100 m cell

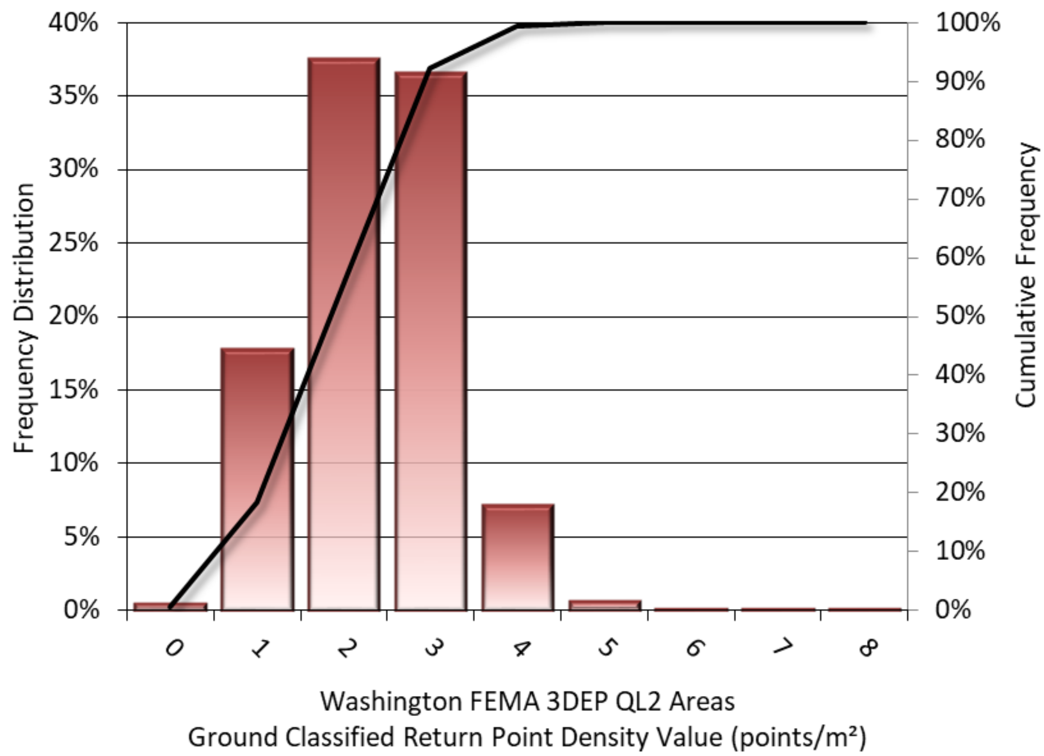


Figure 18: Frequency distribution of QL2 areas ground-classified return point density values per 100 x 100 m cell

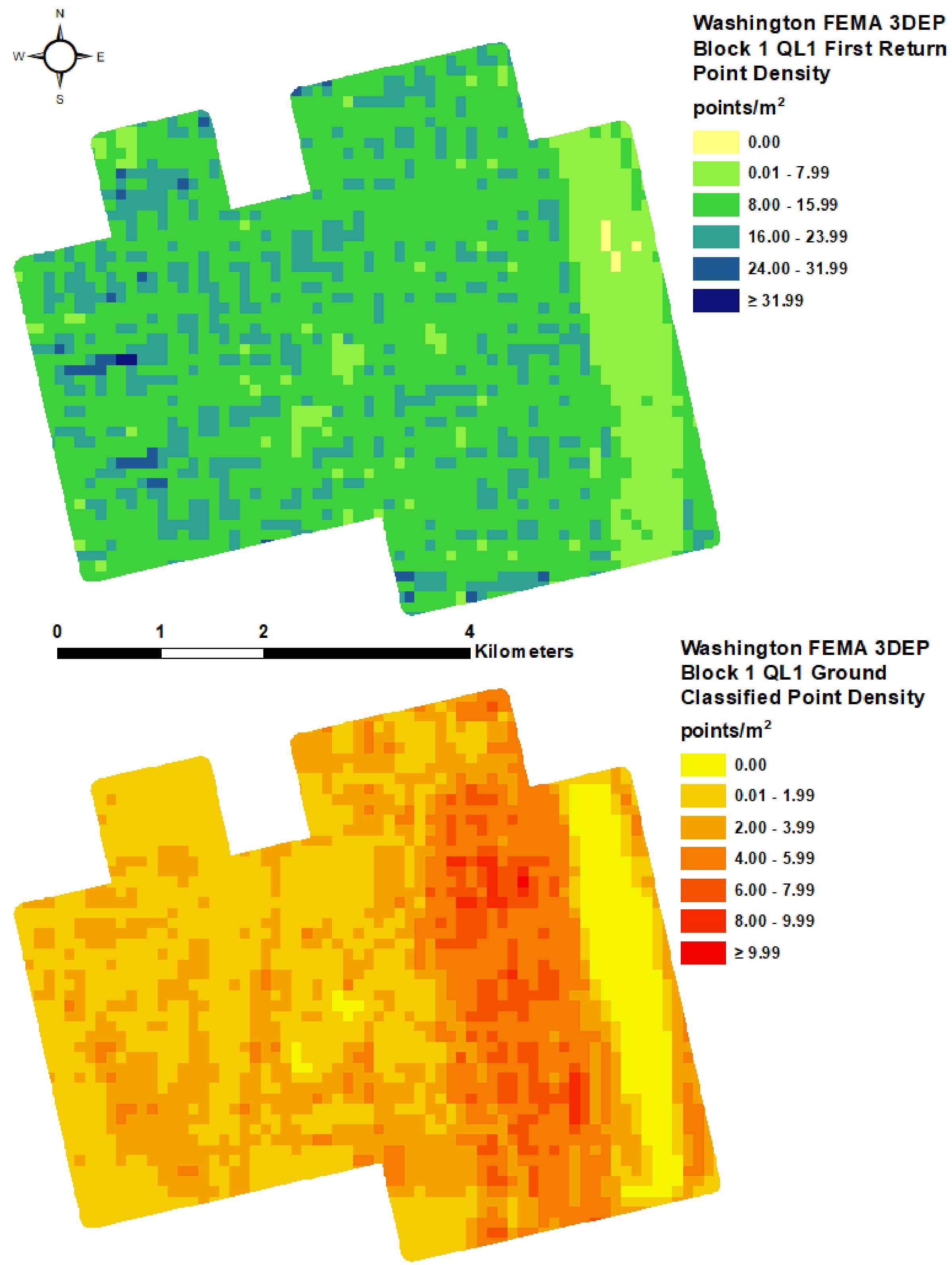


Figure 19: First return and ground-classified point density map for the Washington FEMA 3DEP 2018 Block 1 QL1 site (100 m x 100 m cells)

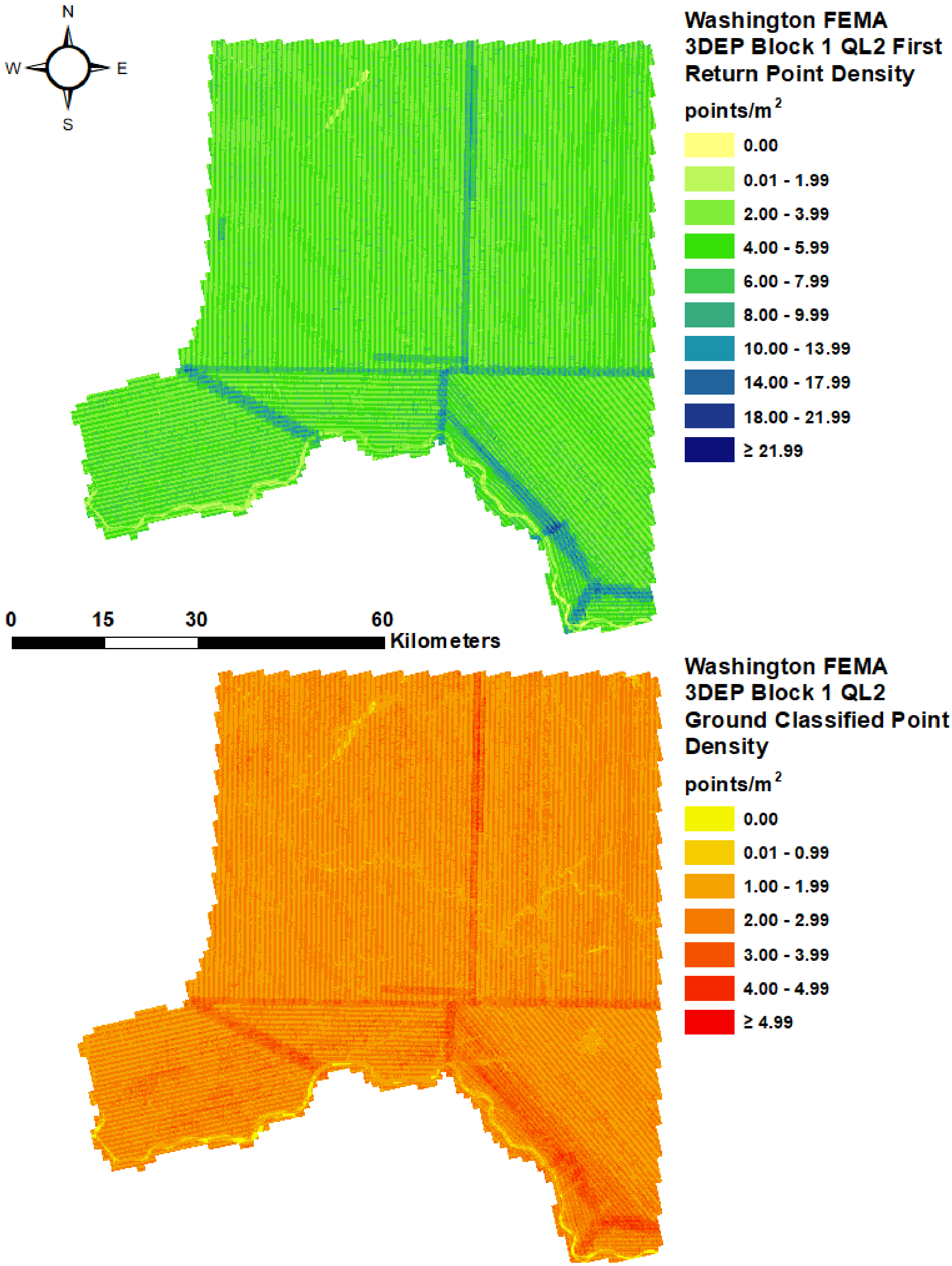


Figure 20: First return and ground-classified point density map for the Washington FEMA 3DEP 2018 Block 1 QL2 site (100 m x 100 m cells)

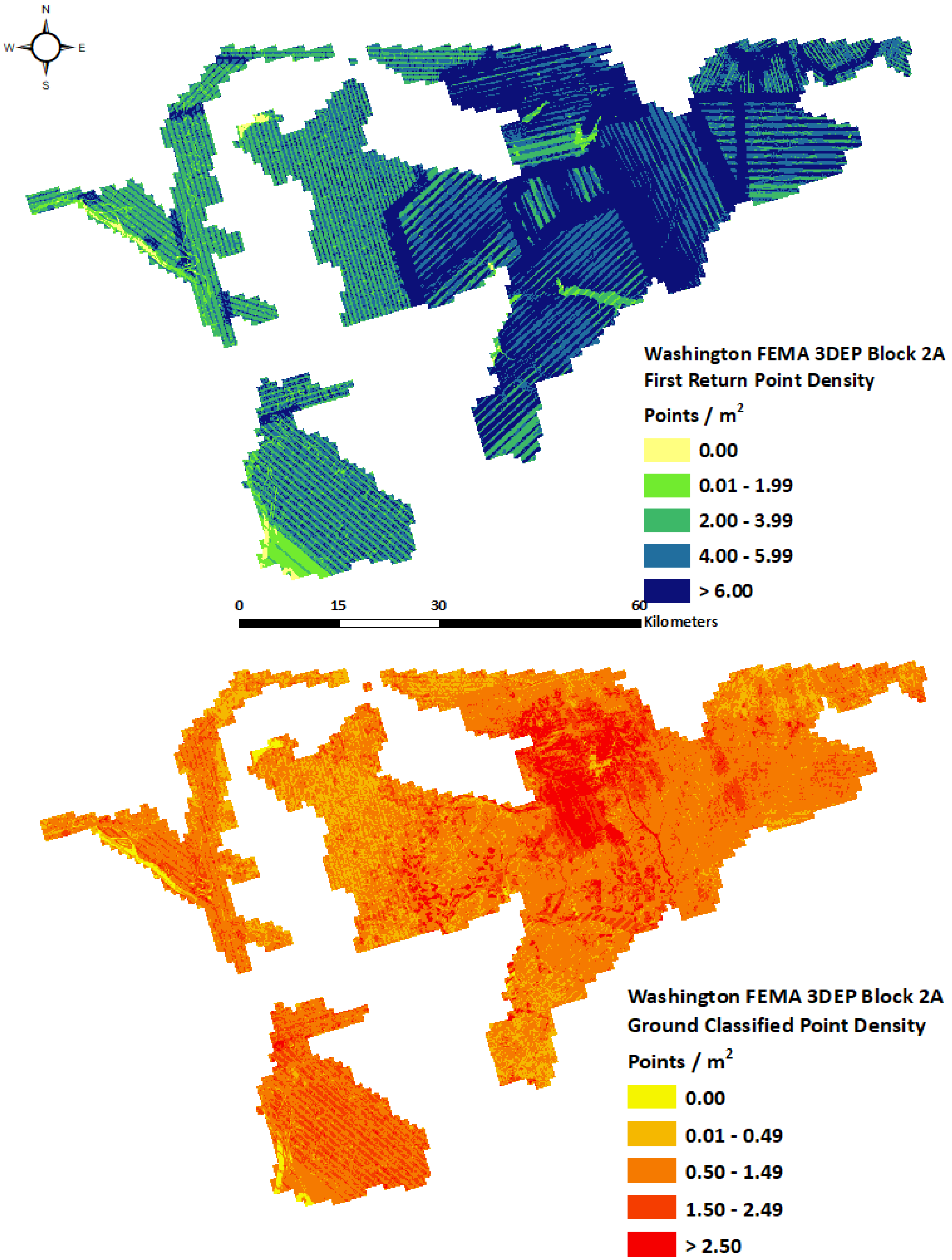


Figure 21: First return and ground-classified point density map for the Washington FEMA 3DEP 2018 Block 2A QL2 site (100 m x 100 m cells)

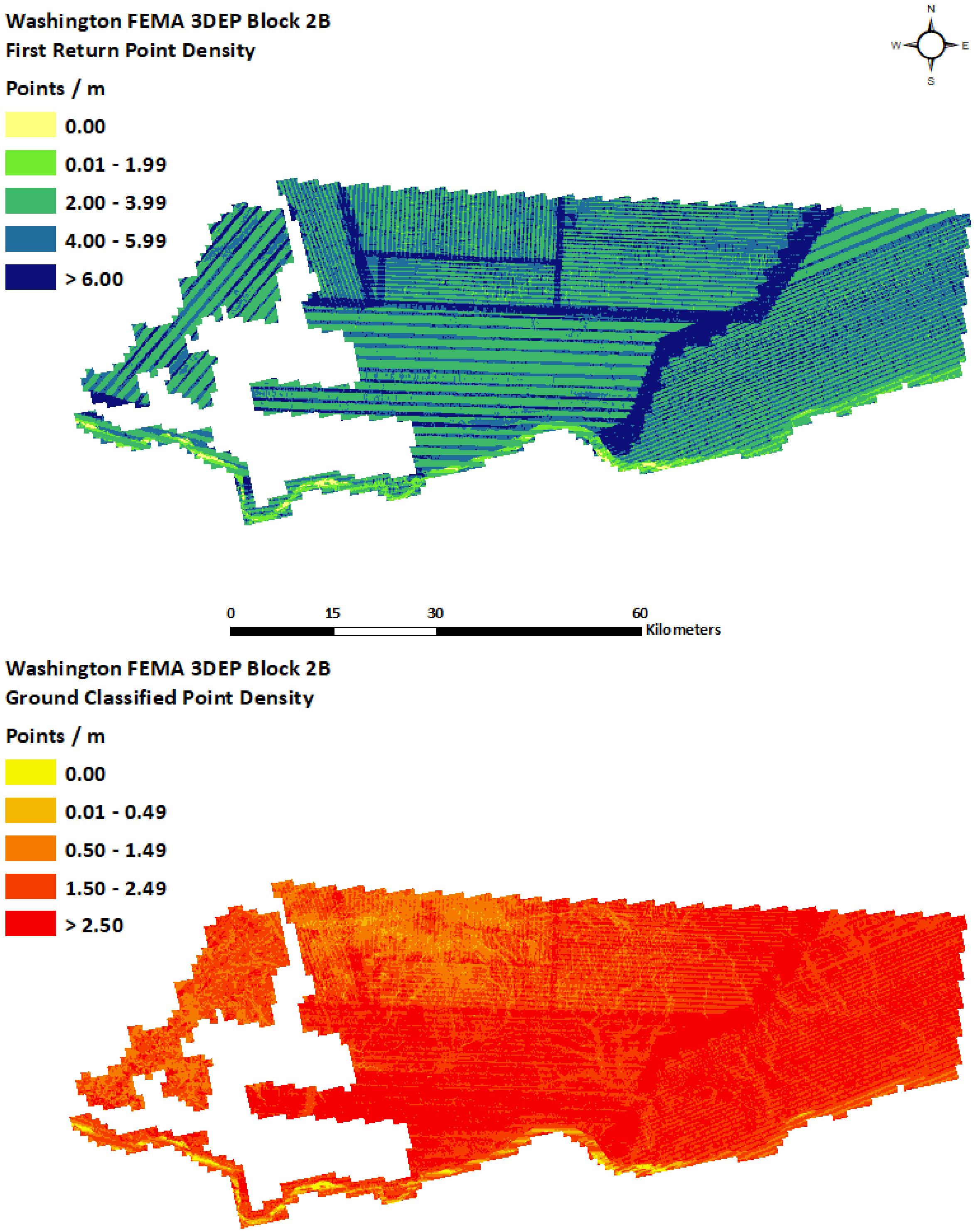


Figure 22: First return and ground-classified point density map for the Washington FEMA 3DEP 2018 Block 2B QL2 site (100 m x 100 m cells)

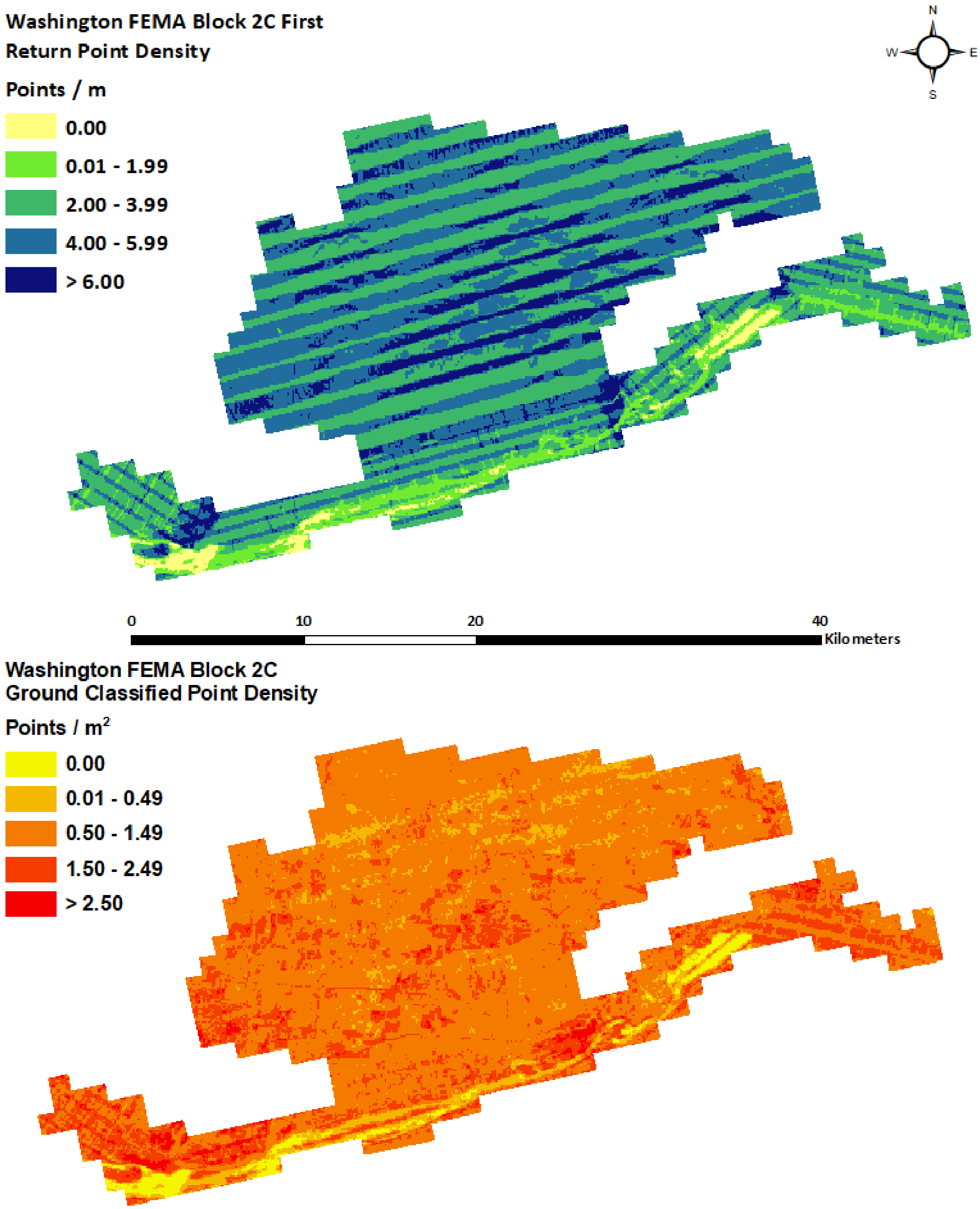


Figure 23: First return and ground-classified point density map for the Washington FEMA 3DEP 2018 Block 2C QL2 site (100 m x 100 m cells)

LiDAR Accuracy Assessments

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

LiDAR Non-Vegetated Vertical Accuracy

Absolute accuracy was assessed using Non-Vegetated Vertical Accuracy (NVA) reporting designed to meet guidelines presented in the FGDC National Standard for Spatial Data Accuracy[2]. NVA compares known ground check point data that were withheld from the calibration and post-processing of the LiDAR point cloud to the triangulated surface generated by the unclassified LiDAR point cloud as well as the derived gridded bare earth DEM. NVA is a measure of the accuracy of LiDAR point data in open areas where the LiDAR system has a high probability of measuring the ground surface and is evaluated at the 95% confidence interval (1.96 * RMSE), as shown in Table 11.

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 Washington FEMA 3DEP 2018 survey, 128 ground check points were withheld from the calibration and post processing of the LiDAR point cloud, with resulting non-vegetated vertical accuracy of 0.119 meters as compared to unclassified LAS, and 0.119 meters as compared to the bare earth DEM, with 95% confidence (Figure 24, Figure 25).

QSI also assessed absolute accuracy using 4,387 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 11 and Figure 26.

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[2] Federal Geographic Data Committee, ASPRS POSITIONAL ACCURACY STANDARDS FOR DIGITAL GEOSPATIAL DATA EDITION 1, Version 1.0, NOVEMBER 2014. http://www.asprs.org/PAD-Division/ASPRS-POSITIONAL-ACCURACY-STANDARDS-FOR-DIGITAL-GEOSPATIAL-DATA.html.

Table 11: Absolute accuracy results

Absolute Vertical Accuracy			
	NVA, as compared to unclassified LAS	NVA, as compared to bare earth DEM	Ground Control Points
Sample	128 points	128 points	4,387 points
95% Confidence (1.96*RMSE)	0.119 m	0.119 m	0.059 m
Average	0.016 m	0.003 m	- 0.002 m
Median	0.017 m	0.010 m	- 0.001 m
RMSE	0.061 m	0.061 m	0.030 m
Standard Deviation (1σ)	0.059 m	0.061 m	0.030 m

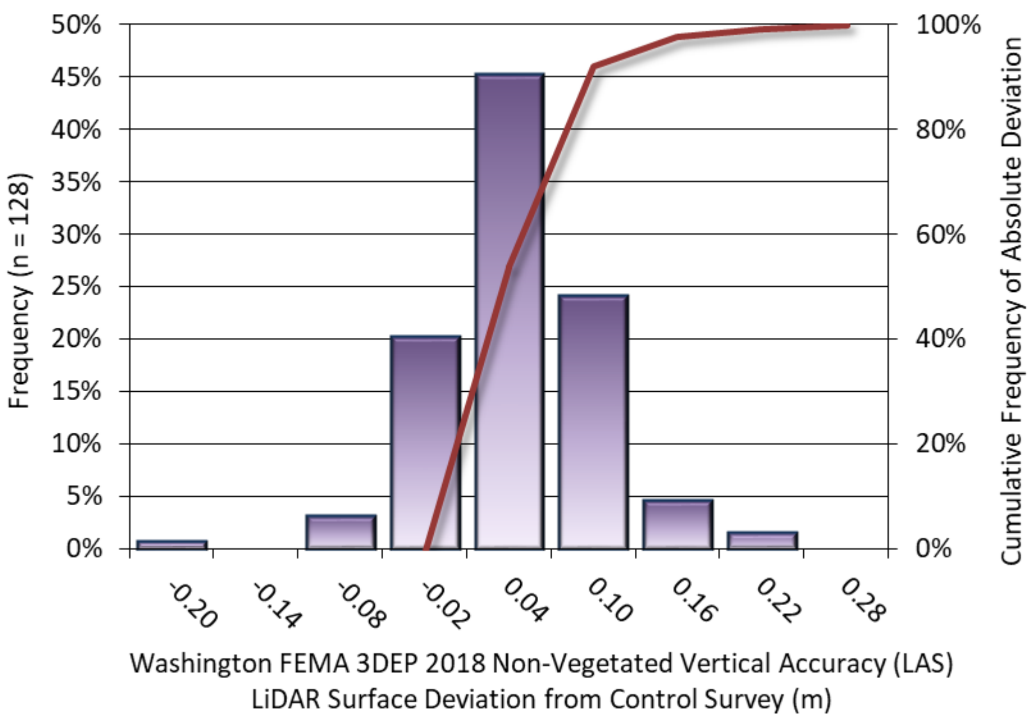

Figure 24: Frequency histogram for LiDAR unclassified LAS deviation from ground check point values (NVA)

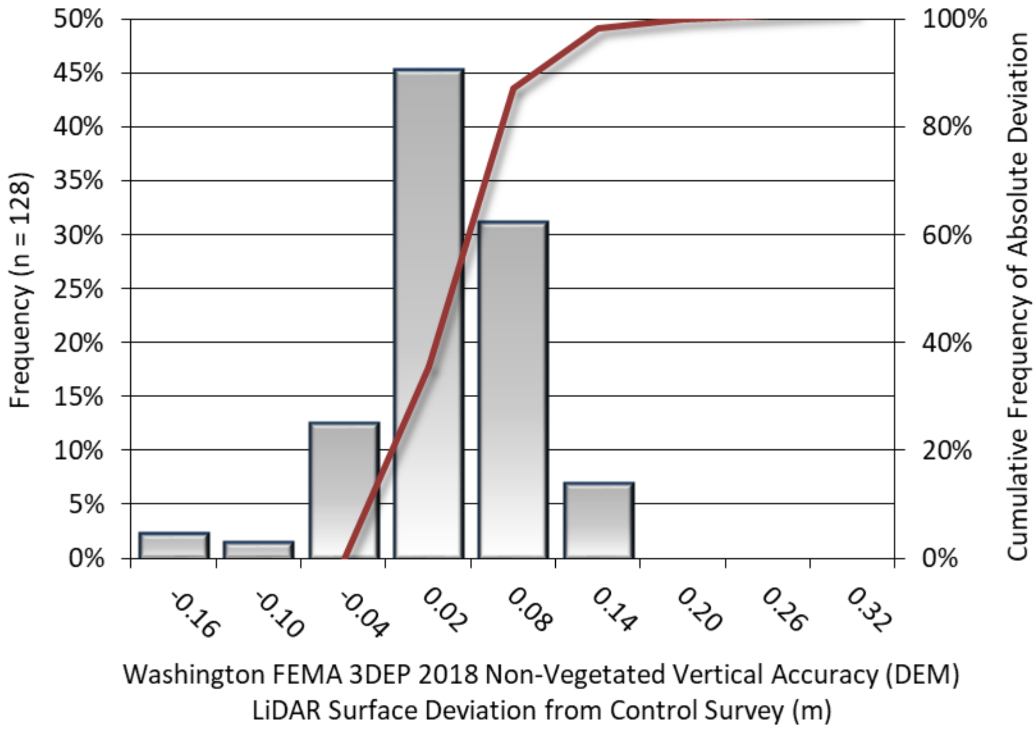

Figure 25: Frequency histogram for LiDAR bare earth DEM surface deviation from ground check point values (NVA)

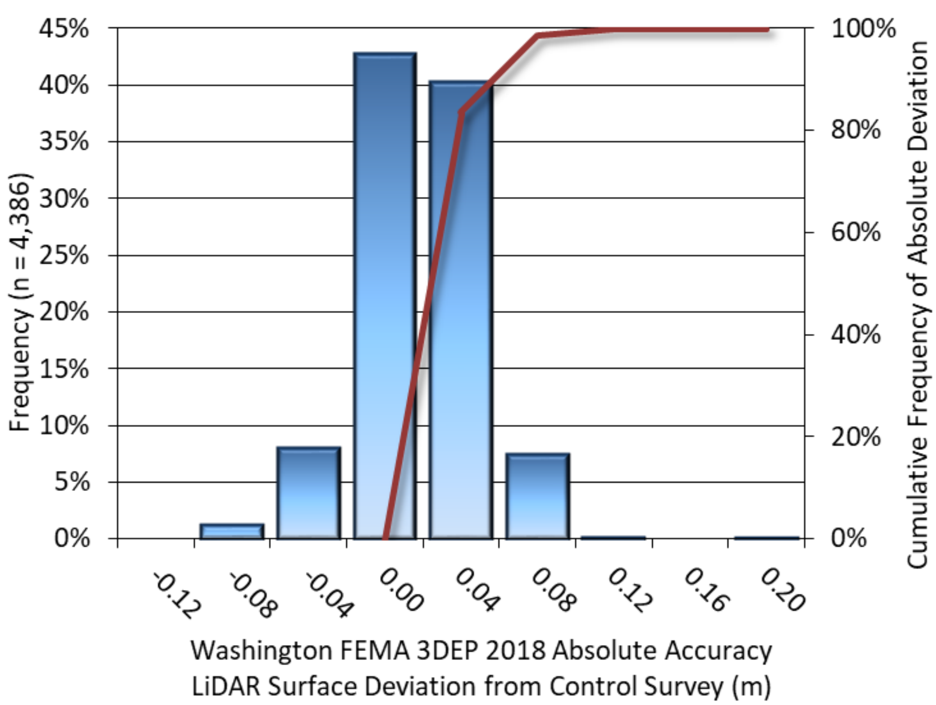

Figure 26: Frequency histogram for LiDAR surface deviation from ground control point values

LiDAR Vegetated Vertical Accuracies

QSI also assessed vertical accuracy using Vegetated Vertical Accuracy (VVA) reporting. VVA compares known ground check point data collected over vegetated surfaces using land class descriptions to the digital elevation model generated by the ground classified LiDAR points. For the Washington FEMA 3DEP 2018 survey, 98 vegetated check points were collected, with resulting vegetated vertical accuracy of 0.251 meters as compared to the bare earth DEM, evaluated at the 95th percentile (Table 12, Figure 27).

Table 12: Vegetated vertical accuracy results

Vegetated Vertical Accuracy	
Sample	98 points
95th Percentile	0.251 m
Average	0.049 m
Median	0.041 m
RMSE	0.129 m
Standard Deviation (1σ)	0.119 m

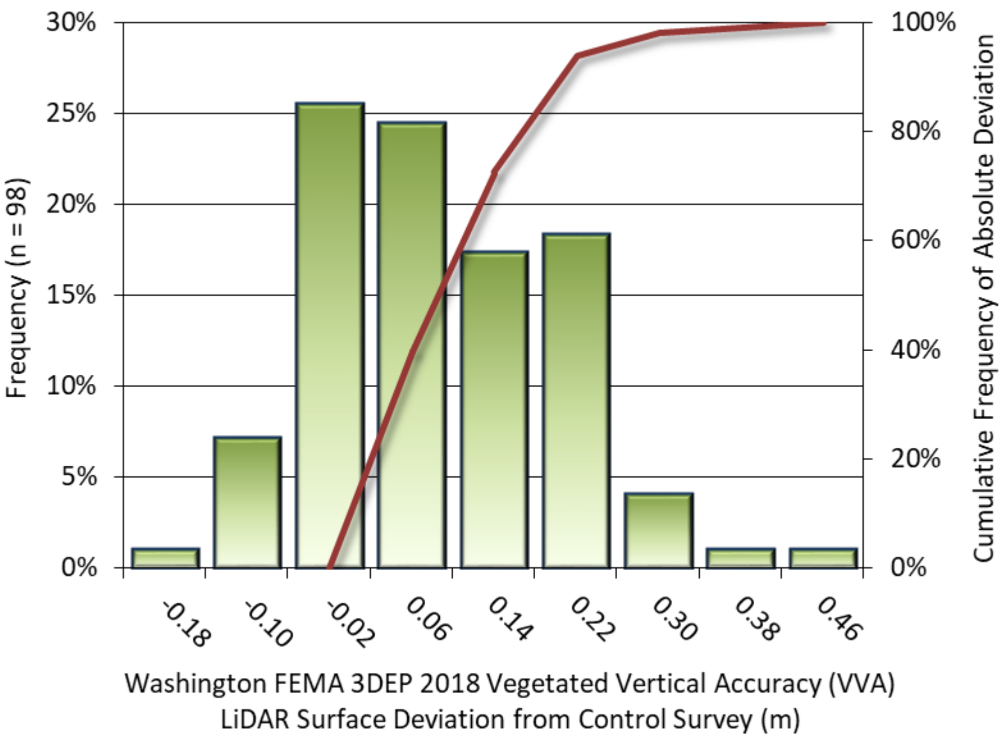

Figure 27: Frequency histogram for LiDAR surface deviation from vegetated check point values (VVA)

LiDAR Relative Vertical Accuracy

Relative vertical accuracy refers to the internal consistency of the data set as a whole: the ability to place an object in the same location given multiple flight lines, GPS conditions, and aircraft attitudes. When the LiDAR system is well calibrated, the swath-to-swath vertical divergence is low (<0.10 meters). The relative vertical accuracy was computed by comparing the ground surface model of each individual flight line with its neighbors in overlapping regions. The average (mean) line to line relative vertical accuracy for the Washington FEMA 3DEP 2018 LiDAR project was 0.036 meters (Table 13, Figure 28).

Table 13: Relative accuracy results

Relative Accuracy	
Sample	809 surfaces
Average	0.036 m
Median	0.040 m
RMSE	0.045 m
Standard Deviation (1σ)	0.014 m
1.96σ	0.028 m

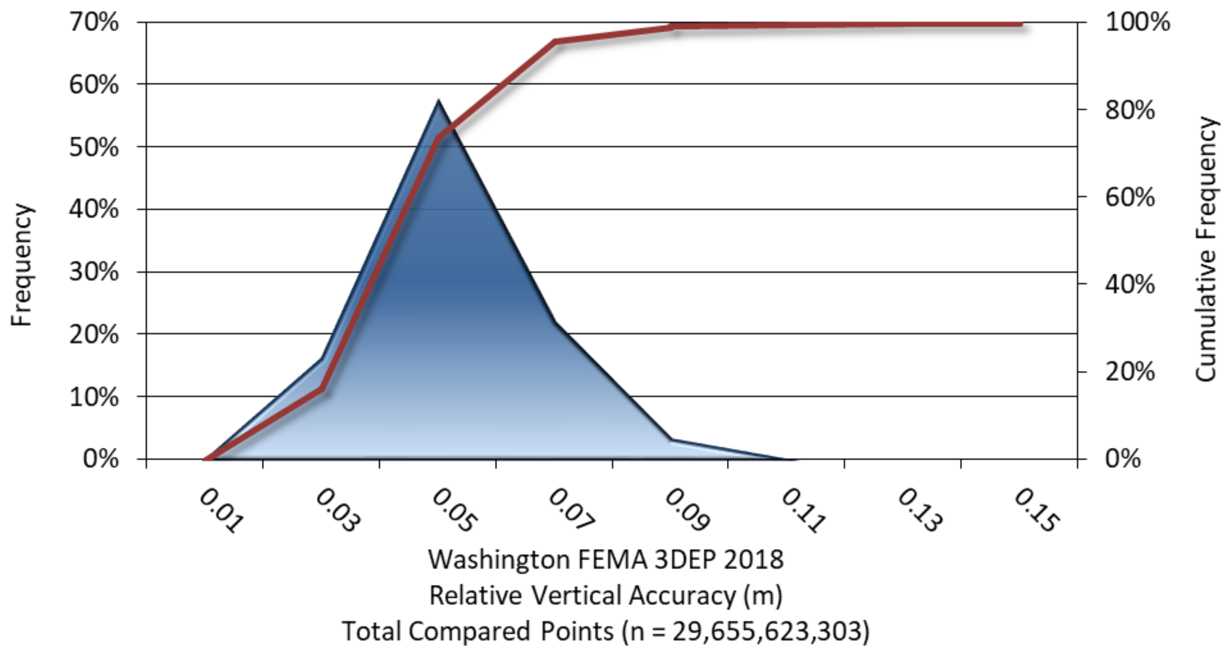

Figure 28: Frequency plot for relative vertical accuracy between flight lines

CERTIFICATIONS

Quantum Spatial, Inc. provided LiDAR services for the Washington FEMA 3DEP 2018 project as described in this report.

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

Tucker Selko
Tucker Selko (Nov 4, 2019) Nov 4, 2019

Tucker Selko
Project Manager
Quantum Spatial, Inc.

I, Evon P. Silvia, PLS, being duly registered as a Professional Land Surveyor in and by the state of Washington, hereby certify that the methodologies, static GNSS occupations used during airborne flights, and ground survey point collection were performed using commonly accepted Standard Practices. Field work conducted for this report was conducted between August 5, 2018 and May 6, 2019.

Accuracy statistics shown in the Accuracy Section of this Report have been reviewed by me and found to meet the "National Standard for Spatial Data Accuracy".

Evon P. Silvia Nov 4, 2019

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

GLOSSARY

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

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

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

> **Absolute Accuracy:** The vertical accuracy of LiDAR data is described as the mean and standard deviation (sigma σ) of divergence of LiDAR point coordinates from ground survey point coordinates. To provide a sense of the model predictive power of the dataset, the root mean square error (RMSE) for vertical accuracy is also provided. These statistics assume the error distributions for x, y and z are normally distributed, and thus we also consider the skew and kurtosis of distributions when evaluating error statistics.

> **Relative Accuracy:** Relative accuracy refers to the internal consistency of the data set; i.e., the ability to place a laser point in the same location over multiple flight lines, GPS conditions and aircraft attitudes. Affected by system attitude offsets, scale and GPS/IMU drift, internal consistency is measured as the divergence between points from different flight lines within an overlapping area. Divergence is most apparent when flight lines are opposing. When the LiDAR system is well calibrated, the line-to-line divergence is low (<10 cm).

> **Root Mean Square Error (RMSE):** A statistic used to approximate the difference between real-world points and the LiDAR points. It is calculated by squaring all the values, then taking the average of the squares and taking the square root of the average.

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

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

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

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

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

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

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

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

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

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

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

Relative Accuracy Calibration Methodology:

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

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

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

LiDAR accuracy error sources and solutions:

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

Operational measures taken to improve relative accuracy:

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

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

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