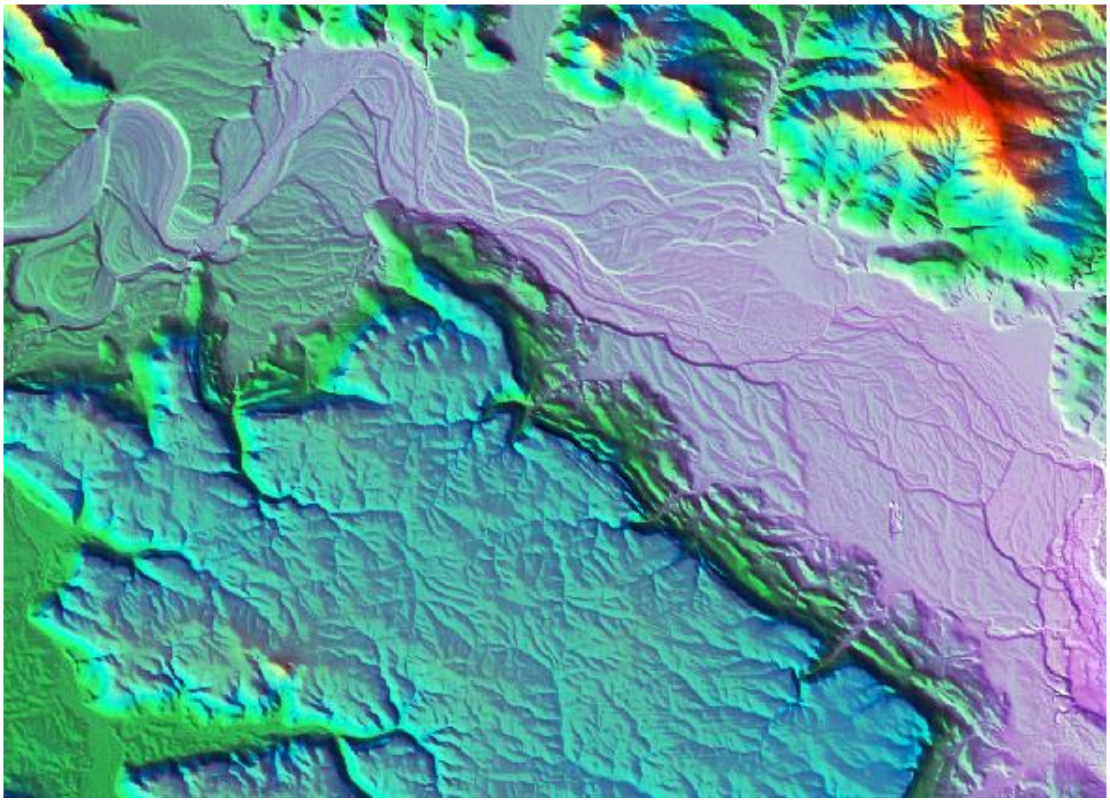
GeoTerra

INTERIM

LiDAR Technical Report
NE Washington LiDAR Production 2017



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Aerial Imagery | Mapping | LiDAR | GIS | Control Surveying
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Period of Performance:

1. Project Overview

GeoTerra, Inc. was selected by Washington Department of Natural Resources (DNR) to provide low density LiDAR remote sensing data including LAS files of the classified LiDAR points and derivative products for approximately 4,351 square mile area per the boundary provided. During the period of April through August 2016 – 3,109 square miles were acquired and processed. Airborne LiDAR mapping technology provides 3D information for the surface of the Earth which includes ground information, vegetation characteristics and man-made features.

LiDAR was acquired for the project in the following order:

- Zone 1– 7-April, 8-April and 1-May 2016 (*459 square miles*)
- Zone 2 – 1-May, 2-May, 3-May, 21-July, 29-July, 30-July, 31-July, 4-August, 5-August, 16-August, 17-August, 18-August 2016 (*2650 square miles*)
- Zone 3 – TBD (*1242 square miles*)

The Optech Galaxy LiDAR system was mounted in a Cessna 310 fixed-wing aircraft. This report describes the methods used and results of: flight plan design, survey control, Airborne GNSS and IMU post-processing, relative and absolute point cloud adjustment, control sources, point cloud classification and quality assurance and quality control (QA/QC).

Figure 1: Bare earth model colored by classification and intensity

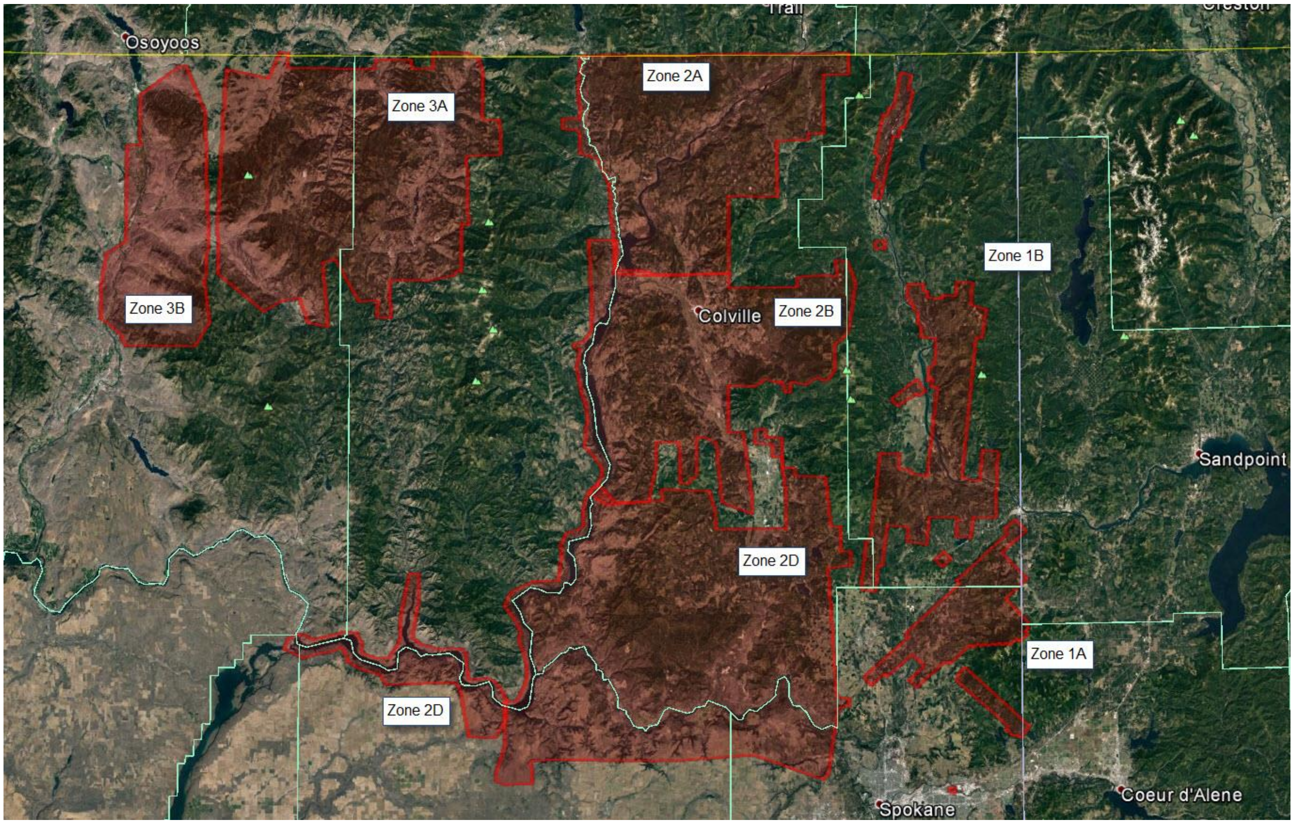


Figure 2: Acquisition zones

2. LiDAR Acquisition and Processing

2.1 Flight Planning and Sensor Specification

Flights were planned to acquire LiDAR data along 3 zones, totaling approximately 2,657 square miles. The flight plan was designed with a minimum of 50% overlap in swath footprint to minimize laser shadowing and gaps. Utilizing this flightplan in conjunction with flying opposing directions, GeoTerra can ensure final point density across the project. Flight planning was performed using Optech Flight Management System (FMS) software to calculate optimum parameters in order to meet project requirements and accommodate terrain variations. The Optech Galaxy sensor produces a pulse rate range of 35 – 550 kHz and can record up to 8 range measurements per laser pulse emitted. PulseTRAK and SwathTRAK technology were employed allowing the sensor to maintain regular point distribution and constant-width flight lines despite changes in terrain.

Flight planning specifications were developed for each block based on terrain fluctuations and point density requirements are listed in Tables 1 and 2 below. Zone 3 specifications will be reported once data has been collected and specifications are recorded.

Table 1: Zone 1 acquisition specifications

Specification	Description
Pulse Repetition Frequency (PRF)	200 kHz (200,000 laser pulses per second)
Scan Rate	38 Hz (38 scan-lines per second)
Target Collection Density	≥ 1.12 pts/m² single swath
Field of View (FOV)	40°
Minimum Laser Sidelap	50% (to reduce laser shadowing and gaps)
Altitude	average 3000m Above Ground Level (AGL)
Ground Speed	140 knots

Table 2: Zone 2 acquisition specifications

Specification	Description
Pulse Repetition Frequency (PRF)	200 kHz (200,000 laser pulses per second)
Scan Rate	2A: 46 Hz (46 scan-lines per second) 2B: 46 Hz (46 scan-lines per second) 2C: 38 Hz (38 scan-lines per second) 2D: 42 Hz (42 scan-lines per second)
Target Collection Density	2A: ≥ 1.08 pts/m² single swath 2B: ≥ 1.08 pts/m² single swath 2C: ≥ 1.12 pts/m² single swath 2D: ≥ 1.10 pts/m² single swath
Field of View (FOV)	40°
Minimum Laser Sidelap	50% (to reduce laser shadowing and gaps)
Altitude	average 3000m Above Ground Level (AGL)
Ground Speed	140 knots

3. LiDAR Acquisition and Airborne GNSS (AGNSS) Survey

During the aerial LiDAR survey, Airborne GNSS (AGNSS) technique was utilized to obtain X,Y,Z coordinates of the laser during acquisition. The data collected during the flight was post-processed into a Smoothed Best Estimate of Trajectory (SBET) binary file of the laser trajectory (Figure 3). This SBET is the combination of processed data from both GNSS satellite and Inertial Motion Unit (IMU) data. Once it has been created it is used to geo-reference the laser point cloud during the mapping process.

The LiDAR data was acquired utilizing an Optech Galaxy sensor with integrated Applanix POS AV GNSS/IMU systems. During the flights the receiver on board the aircraft logged GNSS data at 1 Hz interval and IMU data at 200 Hz interval. After the flights, the GNSS and IMU data were post-processed using NovAtel's Waypoint Products Group software package, Inertial Explorer Versions 8.60.6323. The GNSS data was processed using a Precise Point Positioning (PPP) technique. PPP is an autonomous positioning method where data from only the onboard aircraft receiver is used. Inertial Explorer's PPP processor requires dual frequency data as well as precise orbit and clock files. The processed GNSS data are then combined with the IMU data using a loosely coupled technique.

Lever arm offsets between the IMU and the L1 phase center of the aircraft antenna were computed within Inertial Explorer for each flight mission and then combined with the fixed lever arm from the IMU to the mirror which were held at the internal Optech provided values of x=-0.051, y=0.153, z=0.003 m (x-right, y-fwd, z-up, IMU->Mirror). This resulted in a precise trajectory of the laser that was output as an NAD83(2011)(Epoch 2010.0) SBET file with data points each 1/200 of a second.

Below in Table 3 the coordinate system information for all processed and delivered products are specified. All data are delivered in this projection and it is referenced in all metadata.

Table 3: Project coordinate system and datum

Specification	Description
Coordinate System	Washington State Plane (SPCS), South Zone
Horizontal Datum	NAD83 (2011)(Epoch 2010.0) (labeled HARN for GIS purposes)
Vertical Datum	NAVD88
Geoid	12A (CONUS)
Units	US Survey Feet

Figure 3: Aircraft trajectories for Zone 1

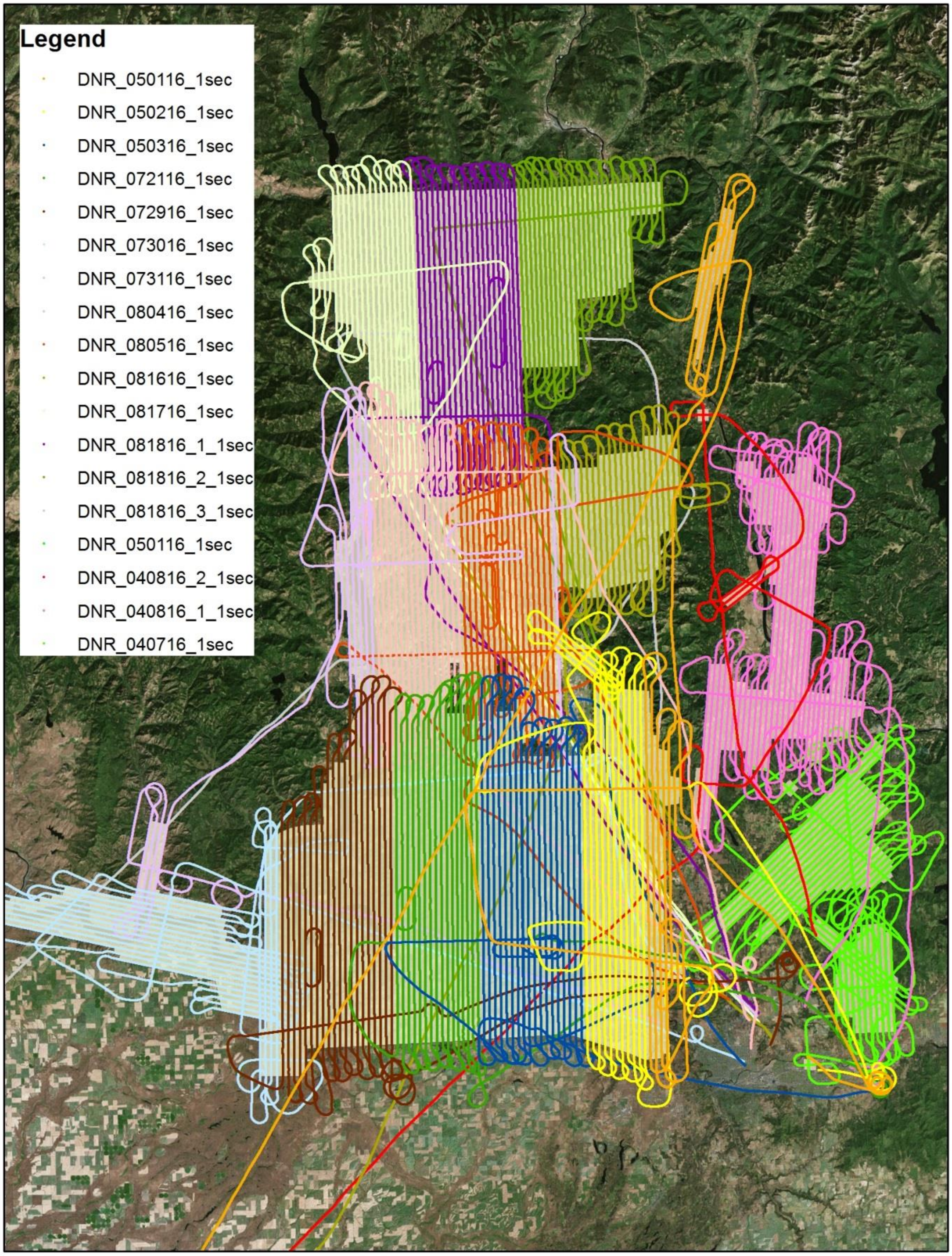


Figure 4: Aircraft trajectories for all flown zones

3.1 Laser Post-Processing

Raw range data from the sensor was decoded using Optech's LMS software. Instrument corrections were then applied to the laser ranges and scan angles. Afterwards, the range files were split into the separate flight lines. The laser point computation used the results of the decoding, description of the instrument, and locations of the aircraft (from the SBET files) as inputs and calculated the location of each point for every laser pulse emitted from the sensor.

3.2 Relative and Absolute Adjustment

Relative and absolute adjustment of all strips was accomplished using Optech's LMS and TerraMatch software. Optech's LMS software performed automated extraction of planar surfaces from the point cloud according to specified parameters in this project. Tie plane determinations established the correspondence between planes in overlapping flight lines. All plane centers of the lines that formed a block are organized into a gridded matrix. Planes from overlapping flight lines, co-located to within an acceptable tolerance are then tested for spatial accuracy.

A set of accurately calculated tie planes are selected for self-calibration. Selection criteria include variables such as: size and shape or the plane, the number of laser points, slope of plane, orientation of plane with respect to flight direction, location of plane within the flight line, and the fitting error. These criteria have an effect of the overall correction, as they determine the geometry of the adjustment. Self-calibration parameters are then calculated. After these parameters are determined, they are used to re-calculate the laser point locations (x,y,z). The planar surfaces are then re-calculated for a final adjustment. Figure 5 illustrates the correctional process.

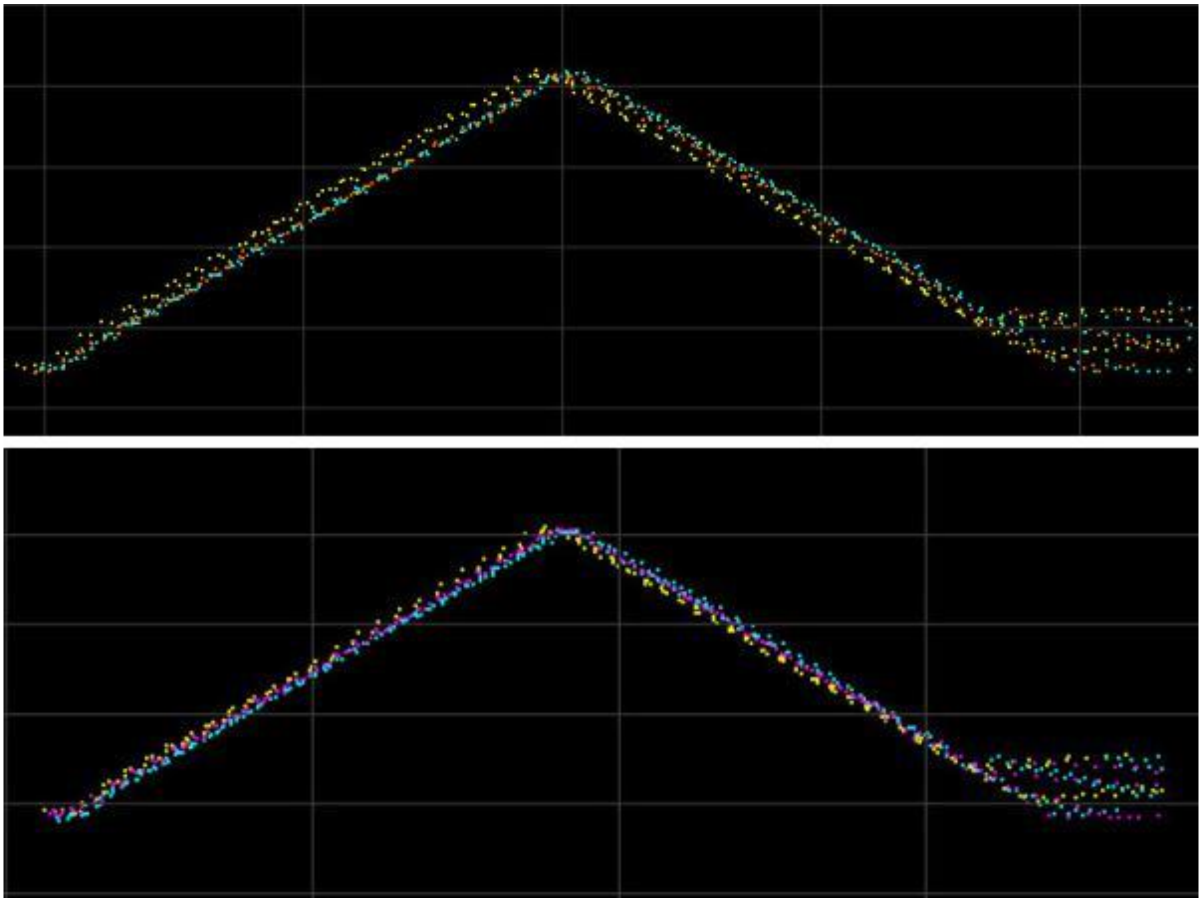


Figure 5: Planes in overlapping strips before and after adjustment

Afterward the planes were analyzed to assess the internal fit of the data block as a whole. For each tie plane, the mean values were computed for each flight line that overlapped the tie plane. Mean values of the point to plane distances were plotted over scan angle (Figure 6).

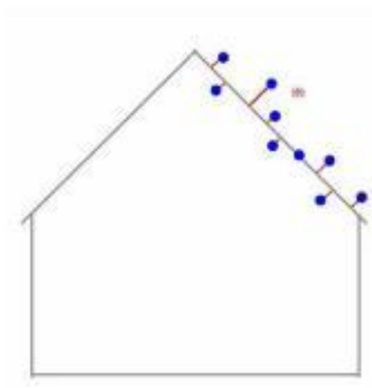


Figure 6: Point to plane distances

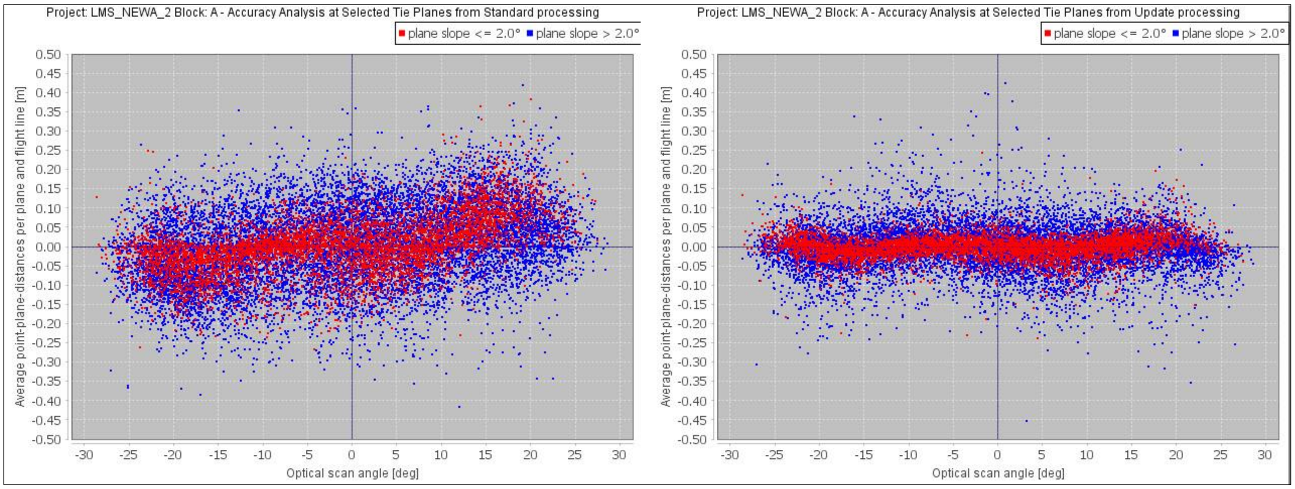


Figure 7: Example of Zone 2A – mean values if the point to plane distances plotted over scan angle

Additionally, flight mission were further reviewed and adjusted in TerraMatch using a tie line approach. This method allows adjustments in areas where planes aren't easily determined. The process began as the software measured the difference between lines (observations) in overlapping strips. These observed differences were translated into correction values for the system orientation – easting, northing, heading, roll, pitch and mirror scale.

Below are statistics for internal observations and relative fit of the data. Tile lines were detected per specified criteria of tie line length and density. The RMS value represents the relative fit of the data.

Table 4: 1A - 132,838 section lines

Error Type	X (ft.)	Y (ft.)	Z (ft.)
Average Magnitude	0	0	0
RMS	0	0	0.043
Maximum Values	0	0	0.540

Table 5: 1B - 236,384 section lines

Error Type	X (ft.)	Y (ft.)	Z (ft.)
Average Magnitude	0	0	0.037
RMS	0	0	0.049
Maximum Values	0	0	0.287

Table 6: 2AB - 546,705 section lines

Error Type	X (ft.)	Y (ft.)	Z (ft.)
Average Magnitude	0	0	0.061
RMS	0	0	0.080
Maximum Values	0	0	0.410

Table 7: 2CD - 498,196 section lines

Error Type	X (ft.)	Y (ft.)	Z (ft.)
Average Magnitude	0	0	0.570
RMS	0	0	0.075
Maximum Values	0	0	0.497

LiDAR QC points were obtained using post processed kinematic GNSS data from a moving vehicle along selected roads within the project area boundary (Figure 8). The rover (vehicle) was processed against one of 13 temporary base stations located throughout the survey sites. These stations were positioned by the National Geodetic Survey (NGS) Online Positioning User Service (OPUS) with output in NAD83(2011)(Epoch 2010.0). The post processed kinematic data relative to the temporary base stations were then filtered by the following criteria: fixed ambiguity positions only, 3D quality better than 0.2 feet and no two consecutive points spaced closer than 50 feet horizontally. This resulted in 61,392 usable points for all three phases of the project which were used to QC the vertical fit of the LiDAR data.

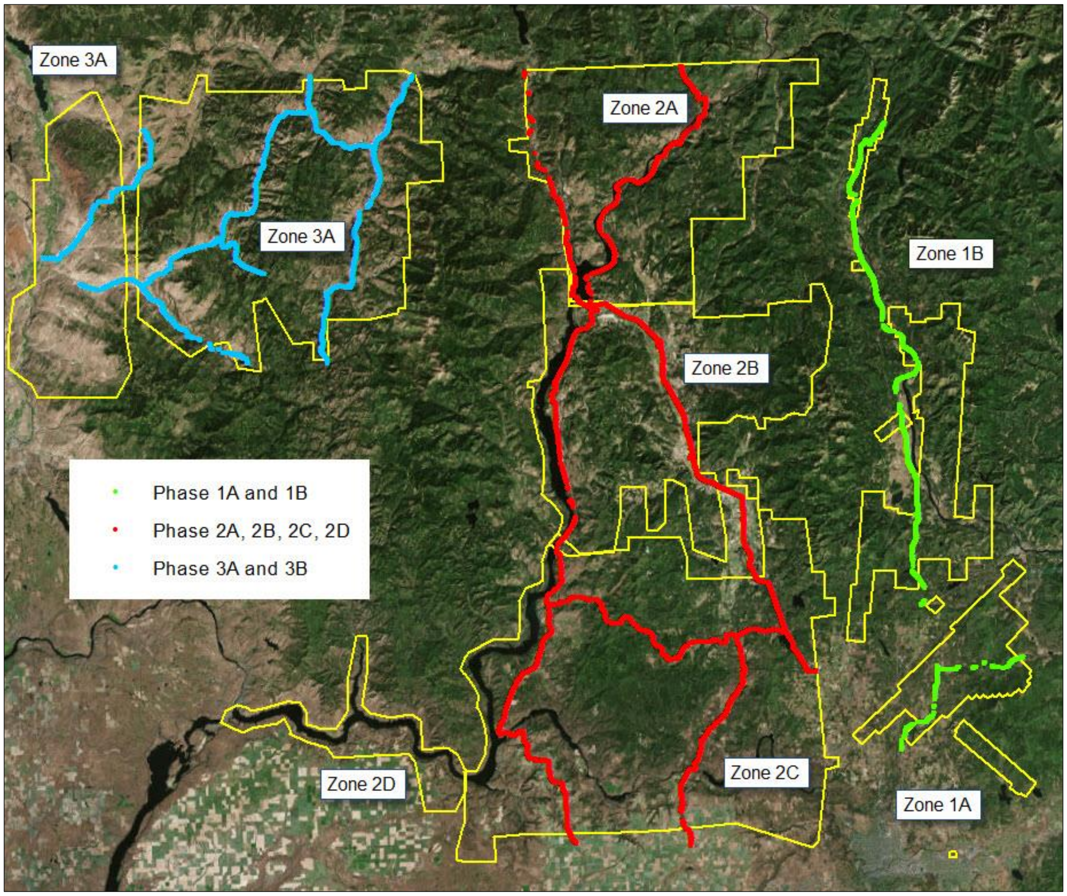


Figure 8: RTK point distribution

Table 8: Zone 1A RTK assessment

Error Type	Accuracy [ft]
Vertical Error Mean	0
Vertical Error Range	[-0.490,0.594]
Vertical Skew	0.049
Vertical RMSE	0.139
Vertical NMAS/VMAS Accuracy (90% CI)	±0.228
Vertical ASPRS/NSSDA Accuracy (95% CI)	±0.271
Vertical Accuracy Class	0.14
Vertical Min Contour Interval	0.42

Table 9: Zone 1B RTK assessment

Error Type	Accuracy [ft]
Vertical Error Mean	0
Vertical Error Range	[-1.237,0.954]
Vertical Skew	-0.686
Vertical RMSE	0.171
Vertical NMAS/VMAS Accuracy (90% CI)	±0.281
Vertical ASPRS/NSSDA Accuracy (95% CI)	±0.334
Vertical Accuracy Class	0.18
Vertical Min Contour Interval	0.54

Table 10: Zone 2A RTK assessment

Error Type	Accuracy [ft]
Vertical Error Mean	-0.121
Vertical Error Range	[-1.990,0.985]
Vertical Skew	-0.143
Vertical RMSE	0.225
Vertical NMAS/VMAS Accuracy (90% CI)	±0.370
Vertical ASPRS/NSSDA Accuracy (95% CI)	±0.441
Vertical Accuracy Class	0.23
Vertical Min Contour Interval	0.69

Table 11: Zone 2B RTK assessment

Error Type	Accuracy [ft]
Vertical Error Mean	-0.194
Vertical Error Range	[-0.756,0.855]
Vertical Skew	0.259
Vertical RMSE	0.253
Vertical NMAS/VMAS Accuracy (90% CI)	±0.416
Vertical ASPRS/NSSDA Accuracy (95% CI)	±0.495
Vertical Accuracy Class	0.26
Vertical Min Contour Interval	0.78

Table 12: Zone 2CD RTK assessment

Error Type	Accuracy [ft]
Vertical Error Mean	-0.097
Vertical Error Range	[-0.777,0.792]
Vertical Skew	-0.09
Vertical RMSE	0.207
Vertical NMAS/VMAS Accuracy (90% CI)	±0.341
Vertical ASPRS/NSSDA Accuracy (95% CI)	±0.406
Vertical Accuracy Class	0.21
Vertical Min Contour Interval	0.63

3.3 Point Density

The final point density of all combined LiDAR strips within the project boundary was calculated for first return using LP360. Point density is based upon acquisition at a 50% sidelap with a planned average of 1 points per square meter for each strip and meeting a final overall acquired density of 2 points per square meter. Results per zones are found in Table 13. First return density maps can be found below (Figure 9 and Figure 10). In addition, statistical point density distribution histograms are below (Figure 11 and Figure 12).

Table 13: First return point density

Zone	Δ first return point density
1A	2.822 pts/m^2
1B	2.526 pts/m^2
2A	3.085 pts/m^2
2B	2.693 pts/m^2
2CD	2.817 pts/m^2

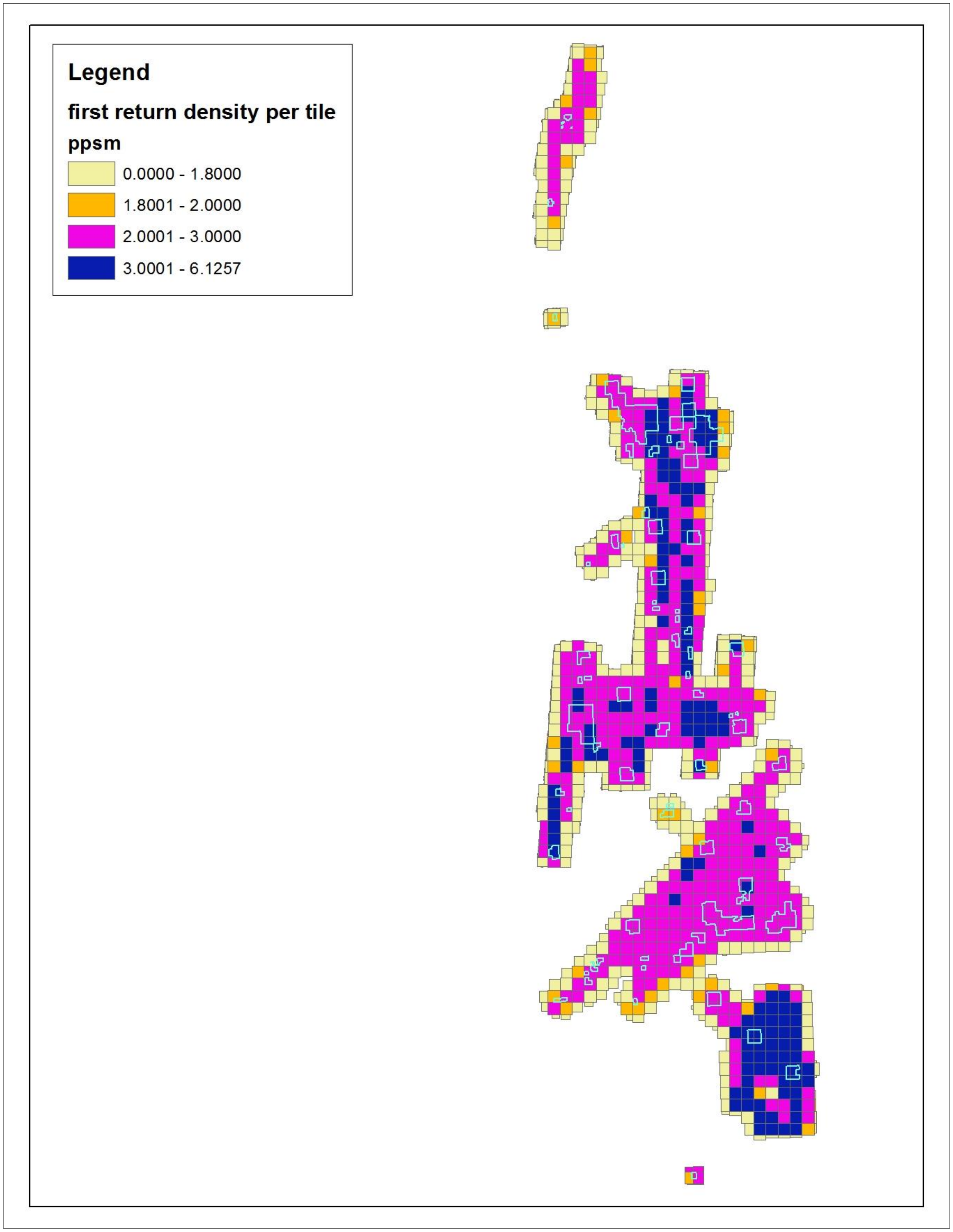


Figure 9: Point density per tile – Zone 1

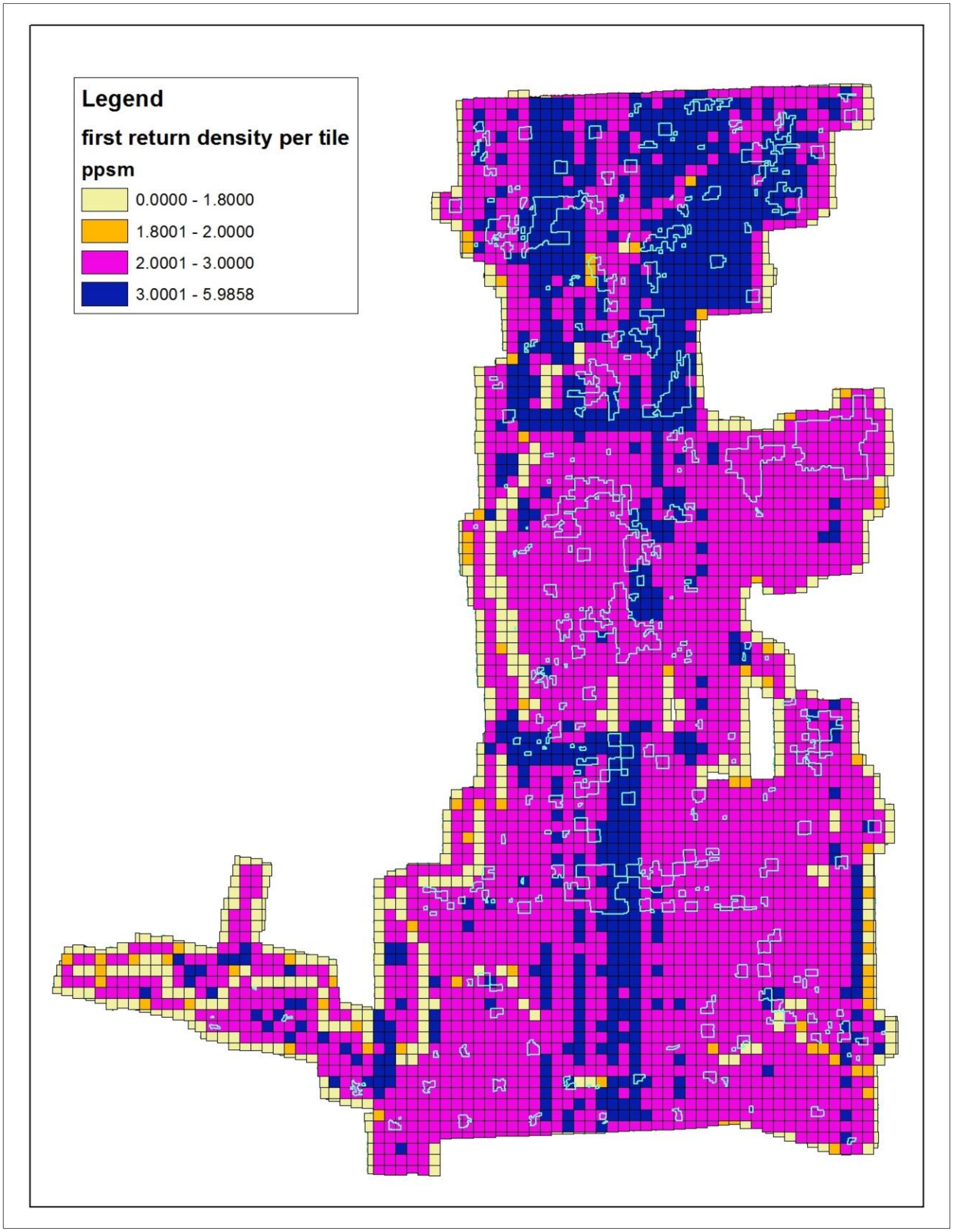


Figure 10: Point density per tile – Zone 2

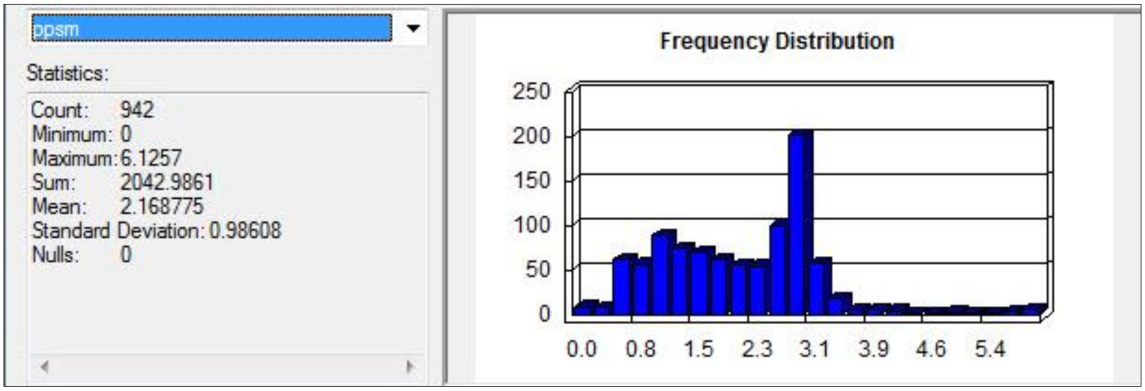


Figure 11: Statistical point density distribution – Zone 1

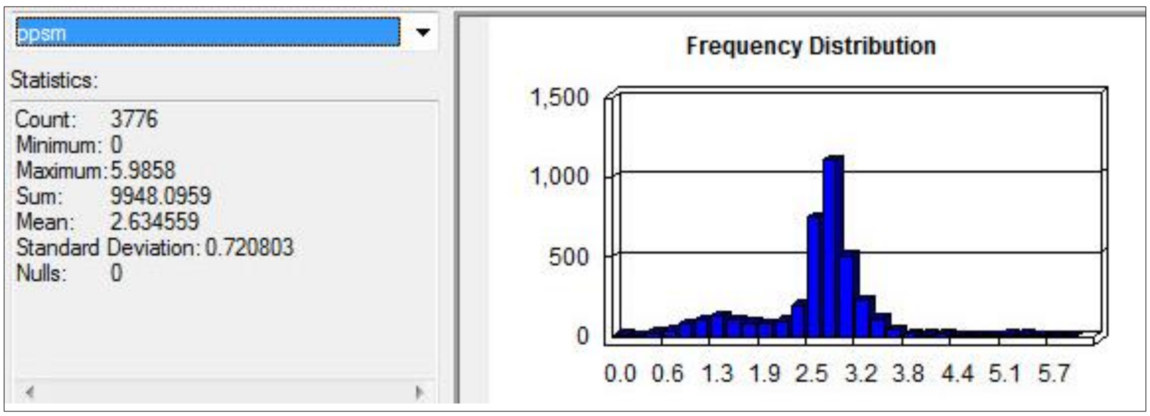


Figure 12: Statistical point density distribution – Zone 2

3.4 Point Cloud Classification

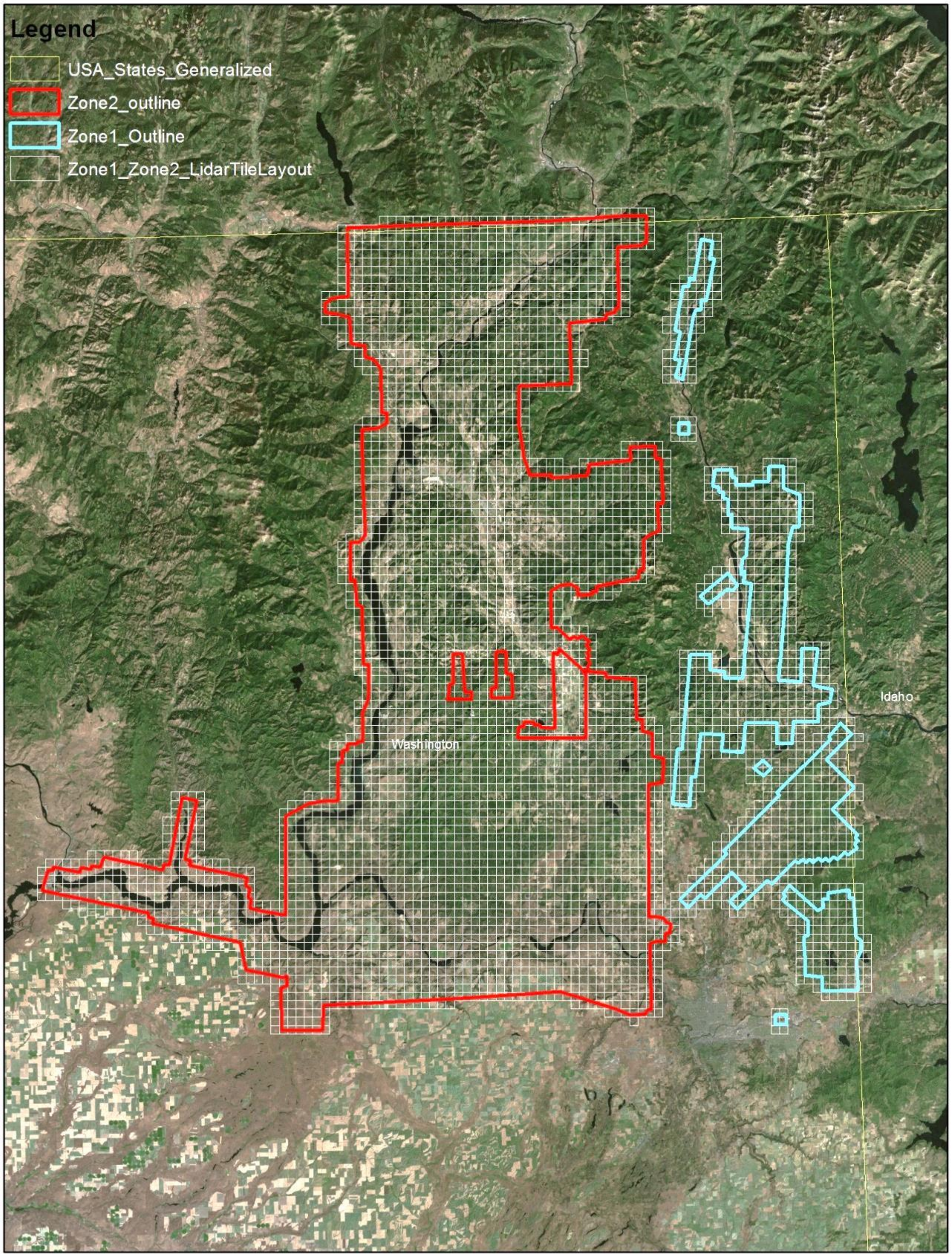
Once the point cloud adjustment was achieved with desired relative and absolute accuracy, all strips in LAS format were brought into a classification software. Rigorous selection algorithms built within TerraScan were used to automatically classify the data. To ensure accurate ground classification, various parameters were defined to ensure proper ground classification.

Data from the edges of the strips were omitted during the initial ground classification to increase quality and grounding was initiated at low seed points and increased from the bottom up. A tailored approach was formulated for each project area. Various specifications were used to determine how 'aggressive' the automated ground classification algorithm should have been. In relatively flat or urban areas, a more 'tempered' approach was used as to not include small buildings and urban features. In the more rural areas, a more 'aggressive' grounding approach was used to better capture steep slopes and sharp natural features that might otherwise be ignored as a ground feature.

Once the ground surface was established, points above the ground were extracted into separate classes including: vegetation, structures and water. Significant buildings and structures were auto-extracted by searching above ground classes for planar features. QC procedures were implemented in LP360 and TerraScan to manually check and correct any remaining misclassifications. Area within Zone outlines was processed and reviewed.

Several routines were implemented to determine 'bird strikes' and other 'high noise' points as well as Overlap points. Routines that were employed are below.

- Isolated points – Points that have few neighbors within a determined 3d search radius were classified as class18_high noise points.
- Height filter – After ground surface was created a height above ground was determined to delete points beyond that threshold.
- Manual checks using automatic and semi-automatic methods (subtracting ground from first return raster results in areas to check visually for any outstanding points); low points and noisy ground points were also found using several similar routines.
- Classifying points which are lower than others in their immediate neighborhood.
- Excluding points from ground surface that in the process of building ground triangles don't meet triangle edge length criteria – it ensures that some noisy points are excluded from ground surface.



Area processed and reviewed

Additionally, in the effort to maintain the highest quality ground representation, the data went through a process of identifying and excluding data on the outer edge of flight swaths that did not meet GeoTerra's quality standard. Due to the nature of an oscillating mirror scanner, the data farthest from nadir is somewhat disrupting resulting in less accurate point returns. This data is not utilized in the representation of the terrain surface.

The least accurate data from the outer edge was extracted to class 12-Overlap. All the remaining data went through GeoTerra's standard classification process of defining ground, and above ground features.
Once ground points were identified and classified in the middle part of the flight line, a quality base from neighboring flight lines was created that could be used to compare the class 12-Overlap data against the quality ground returns from the nadir collection. If data from class 12-Overlap was within a tight range of height above and below the nadir ground plane, it was reclassified from 12-Overlap to 02-Ground. If the data was outside of that range, it was not considered to have met the standard of quality needed to be used in the ground surface and will be left on 12-Overlap class (Figure 13). This data can be left in the dataset to later be used as supplemental reference information, however should not be considered as quality information from which to take measurements or conduct analysis on.

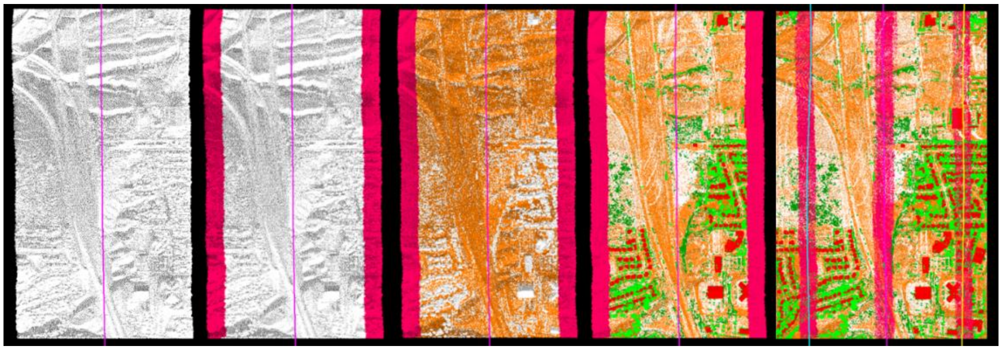


Figure 13: Process of determining 12-Overlap class

Below are image examples of some of the method employed by GeoTerra staff while classifying the 3D LiDAR point cloud. Figures X-X show the versatility in the tools utilized to classify ground, above ground features, and noise.

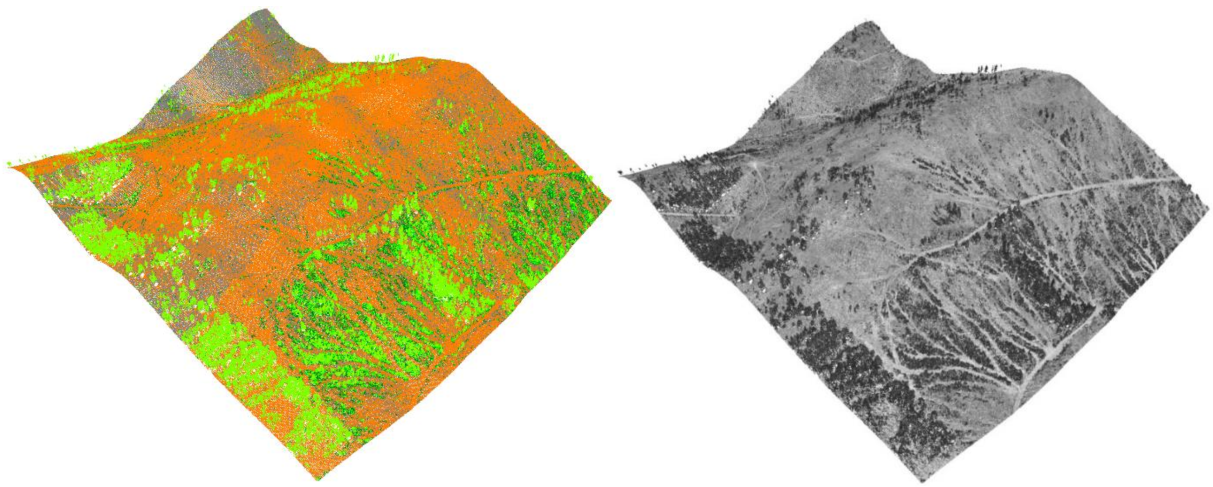


Figure 14: elected boxes of rotating 3D point clouds, viewed with toggled color-coded classification points

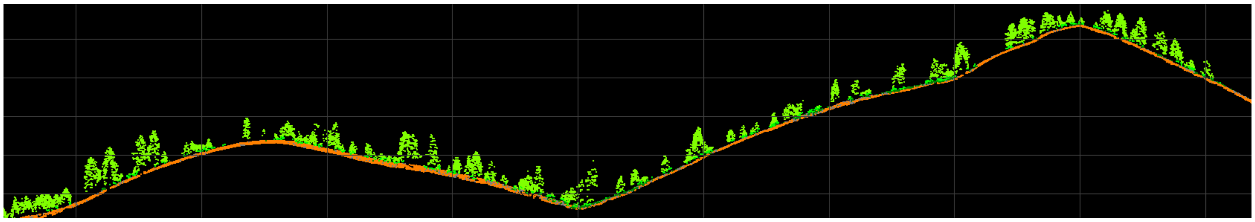


Figure 15: Point clouds viewed in profile view

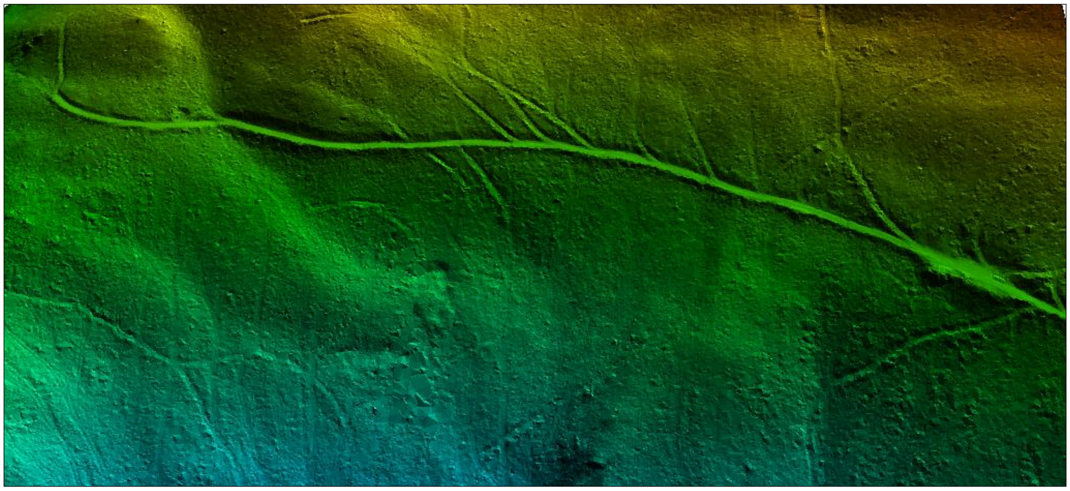


Figure 16: Temporary creation of TIN over ground points to assist in identifying points incorrectly classified as ground.

Below in Table 14 are the classifications that were utilized when defining the 3D LiDAR point cloud. All points will be found within one of the classifications listed.

Table 14: Point cloud classification scheme

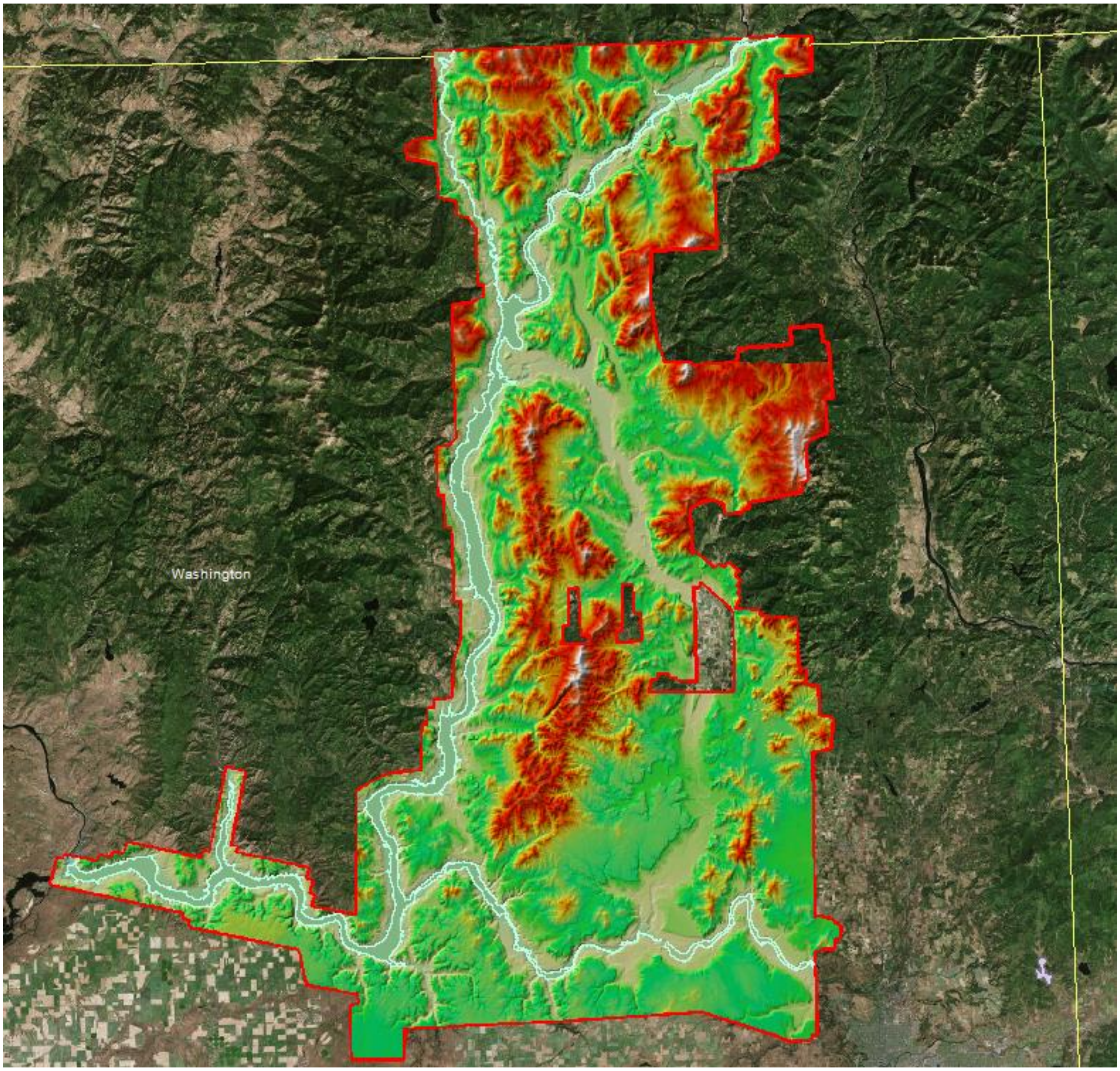
Classification	Definition
00_cross strip	Points from cross flightlines used in calibration
01_Unclassified	Other classes not fitting into other categories
02_Ground	Ground classified returns
03_Low Vegetation	Vegetation level that falls within 1.5’-5’ from the ground
04_Medium Vegetation	Vegetation level that falls within 5’– 10’ from the ground
05_High Vegetation	Vegetation level that falls within 10’ and above ground
06_Buildings and Associated Structures	Major structures
07_Low Noise	Noise below ground surface
09_Water	Points reflected off water bodies
12_Overlap	Points determined to be withheld from the edge of the strip
17_Bridge	Bridge classified points
18_High Noise	High noise points/bird strikes

3.5 Tiling Scheme

The final dataset was cut into delivery tiles of 5000ft by 5000ft as shown below. Data within the 100ft buffered outline for each Zone were reviewed for classification. Cross strips were left in the dataset as class 00 and were not used other classification determinations or any LiDAR derivative products.

4. Hydro-enforcement

Hydro-enforcement pertains only to the creation of derived DEM rasters. No geometric changes are made to the original LiDAR point cloud. Breaklines representing lake edges, standing marshland water, river edges and streams were developed and used to create a hydro-enforced DEM. These breaklines ensured that water surfaces were a constant elevation. In addition, triangulation near rivers and streams were enforced to ensure downstream elevations (Figure 17).



Example of hydro enforcement of Zone 2

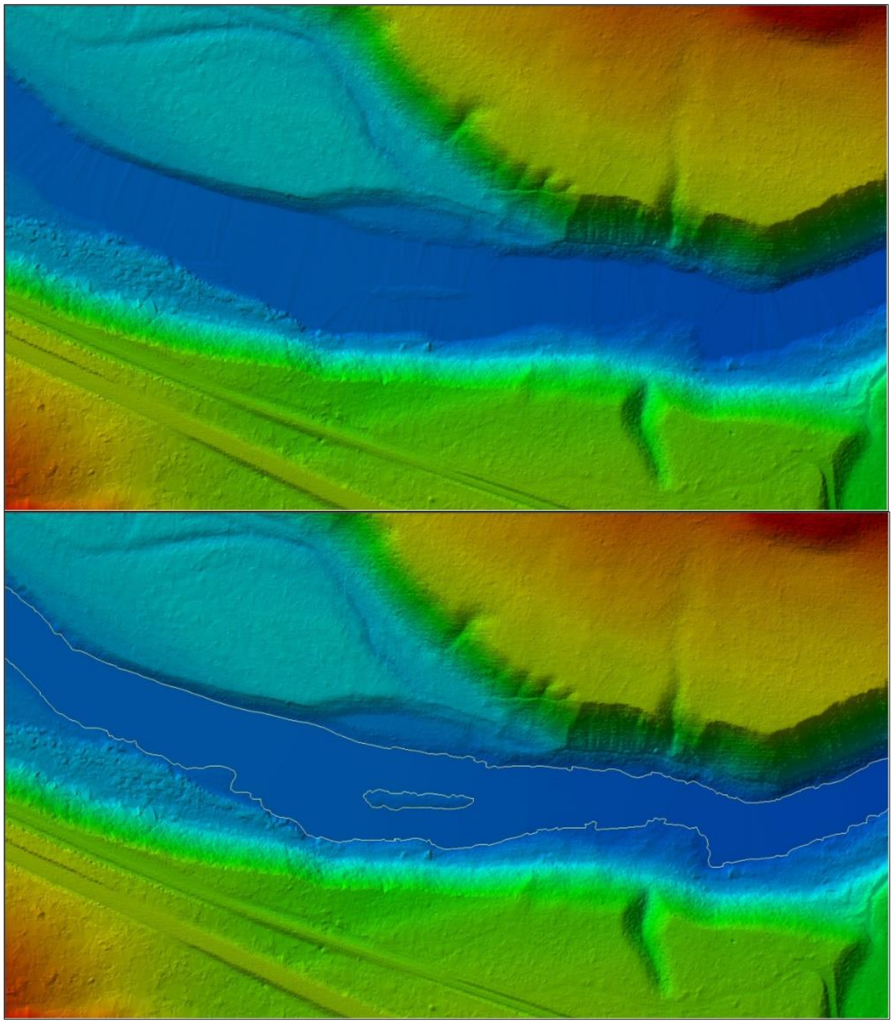


Figure 17: TIN Surface before implementing hydro breaklines enforcement and afterwards

5. Raster DEM Generation

5.1 Bare Earth

Classified ground returns were used to create a LAS Dataset layer in ArcGIS (Figure 18). Hydro-flattening ensured the most accurate surface near water bodies: still-standing water bodies were outlined with a single elevation line, and flowing rivers were outlined maintaining downstream flow. The LAS Dataset layer was converted into an ESRI floating grid with a 3ft-cell size using triangulation type and linear method of interpolation. Cell alignment of the raster product corresponded to an origin point of x=200,000, y=-200,000 (WA State Plane South, NAD83(HARN))

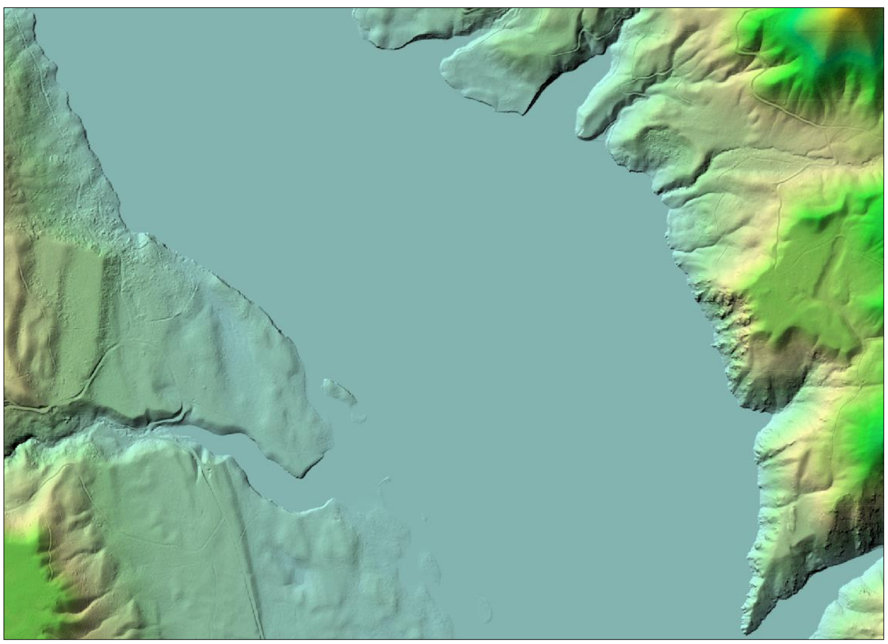


Figure 18: Example of Bare Earth DEM colored by height with hydro enforcement

5.2 Highest Hit

A highest hit model (Figure 19) was created using all LiDAR returns. The layer was converted to a 3-foot ESRI floating point grid using maximum value for the cell and linear interpolation for void filling Noise layers were excluded from creation of this raster to accurately represent digital surface model.

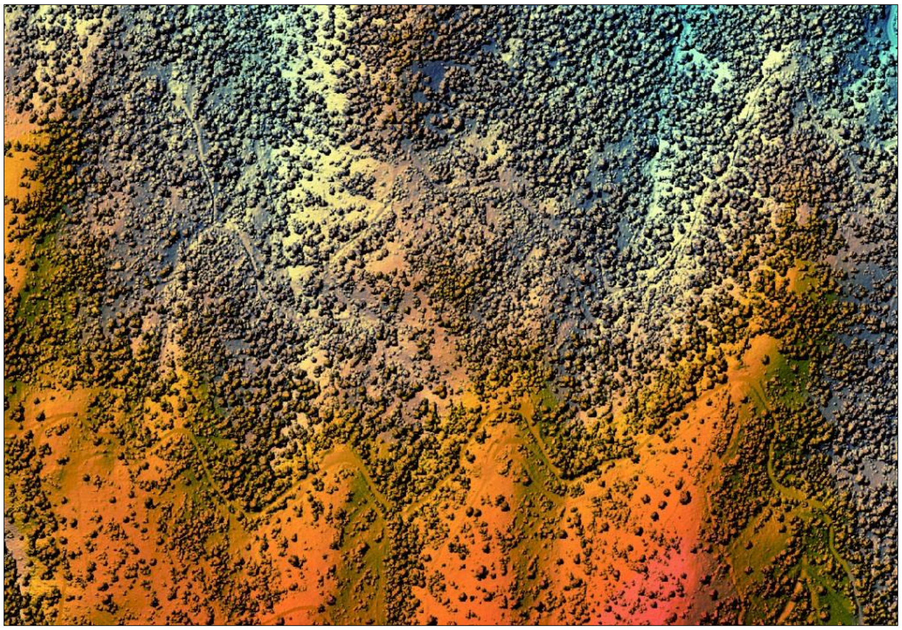


Figure 19: Hillshade representation of highest hit raster colored by height

5.3 QA/QC of the raster products

Bare earth and highest hit 3ft rasters were generated in ArcGIS and snapped to a specified origin. They have been checked for alignment and footprint. Number of passes and first return density were generated using LP360 which does not allow specification of the origin point but arbitrarily snaps to 0,0. GeoTerra has requested that capability from the software manufacturer in a next update.

6. Final Deliverables

Final deliverables are listed below in Table 15.

Table 15: Deliverables

Deliverable	Format
Classified LiDAR	LAS 1.2 format
3ft Highest Hit Model	ArcGIS format
3ft Bare Earth Model	ArcGIS format
3ft Number of Passes Grid	ArcGIS format
100ft Raster Grid of first or only return density	ArcGIS raster format
Tile Index	Shapefile format
LiDAR Technical Report	PDF
Formal FGDC compliant metadata	.XML