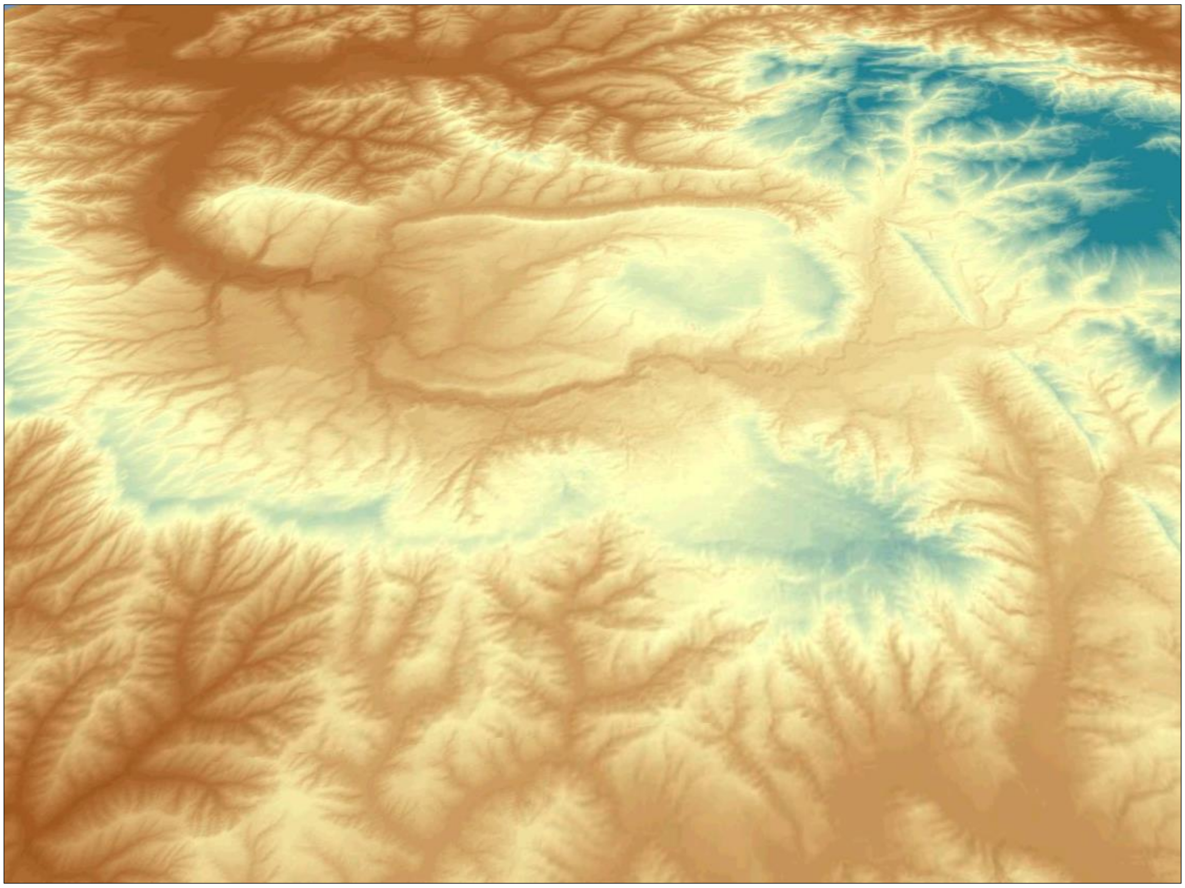
LiDAR Technical Report
Willapa AOI



Presented to:
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Submitted by:

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April 5th, 2017

Aerial Imagery | Mapping | LiDAR | GIS | Control Surveying
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Period of Performance: January 2017 – April 2017

1. Project Overview

GeoTerra, Inc. was selected by Washington Department of Natural Resources (DNR) to provide LiDAR remote sensing data including LAS files of the classified LiDAR points and derivative products, for approximately 117.9 square mile area per the boundary provided. Airborne LiDAR mapping technology provides 3D information for the surface of the Earth which includes ground information, vegetation characteristics and man-made features.

LiDAR for this project was acquired on January 27th and January 28th 2017.

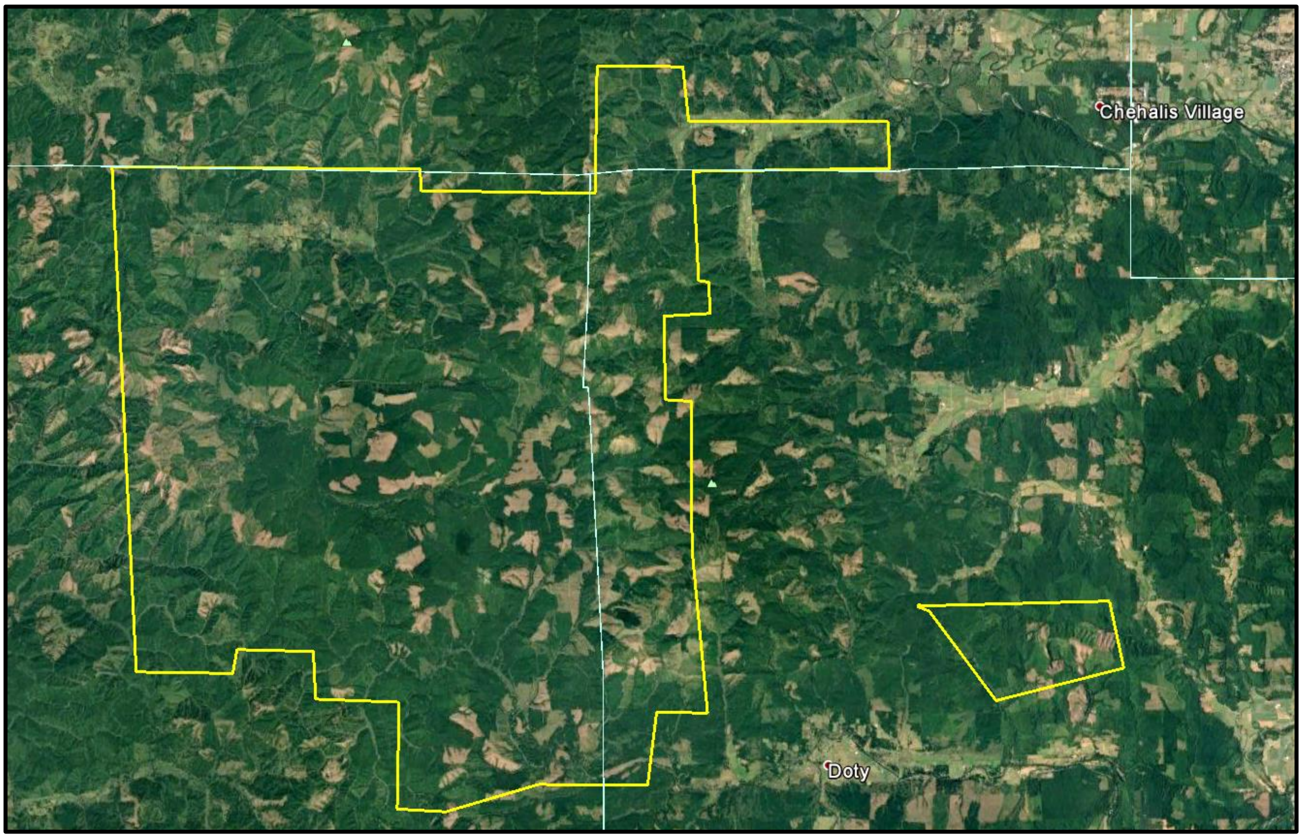


Figure 1: Acquisition zones

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).

2. LiDAR Acquisition and Processing

2.1 Flight Planning and Sensor Specification

Flights were planned to acquire LiDAR data in the provided boundary, totaling approximately 118 square miles. The flight plan was designed with a minimum of 50% overlap in swath footprint to minimize laser shadowing and gaps. Utilizing this flight plan in conjunction with flying in 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 the area based on terrain fluctuations and point density requirements are listed in Tables 1.

Table 1: Zone 1 acquisition specifications

Specification	Description
Pulse Repetition Frequency (PRF)	500 kHz (500,000 laser pulses per second)
Scan Rate	76 Hz (76 scan-lines per second)
Target Collection Density	≥ 4.4 pts/m² single swath
Field of View (FOV)	34°
Minimum Laser Sidelap	50% (to reduce laser shadowing and gaps)
Altitude	average 1850m Above Ground Level (AGL)
Ground Speed	140 knots

3. LiDAR Acquisition and Airborne GNSS (AGNSS) Survey

During the aerial LiDAR survey, the Airborne GNSS (AGNSS) technique was utilized to obtain X,Y,Z coordinates of the laser during acquisition. The data collected during the two flights (27 & 28-Jan-2017) was post-processed into a Smoothed Best Estimate of Trajectory (SBET) binary file of the laser trajectory. Once the SBET had been created it was 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 flight the receiver on board the aircraft logged GNSS data at 1 Hz interval and IMU data at 200 Hz interval. After the flight, the GNSS and IMU data were post-processed using NovAtel's Waypoint Products Group software package, Inertial Explorer Version 8.70.3114.

Three Plate Boundary Observatory (PBO) Continuously Operating Reference Stations (CORS) (P415, P417 and P430) located within approximately 30 km of the project area were used for ground control stations during the flights and were held at their surveyed (NAD83)(2011)(epoch 2010.0) positions relative to the ground control points (GCP) previously established during the project. The CORS and their positions are as follows:

- P415: 46 39 21.55257, -123 43 47.45466, -15.121 m (ellipsoidal height)
- P417: 46 34 29.04177, -123 17 52.48619, 102.786 m (ellipsoidal height)
- P430: 47 00 13.82430, -123 26 10.33804, -4.108 m (ellipsoidal height)

For the 27-Jan-2017 flight all three CORS were used and for the 28-Jan-2017 flight, P417 and P430 were used.

Lever arm offsets between the IMU and the L1 phase center of the aircraft antenna were computed within Inertial Explorer for the 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 meters from the IMU to the Mirror (where positive x = right, positive y = fwd, positive z = up). 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 , the coordinate system information for all processed and delivered products is specified. All data is delivered in this projection and it is referenced in all metadata.

Table 2: 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

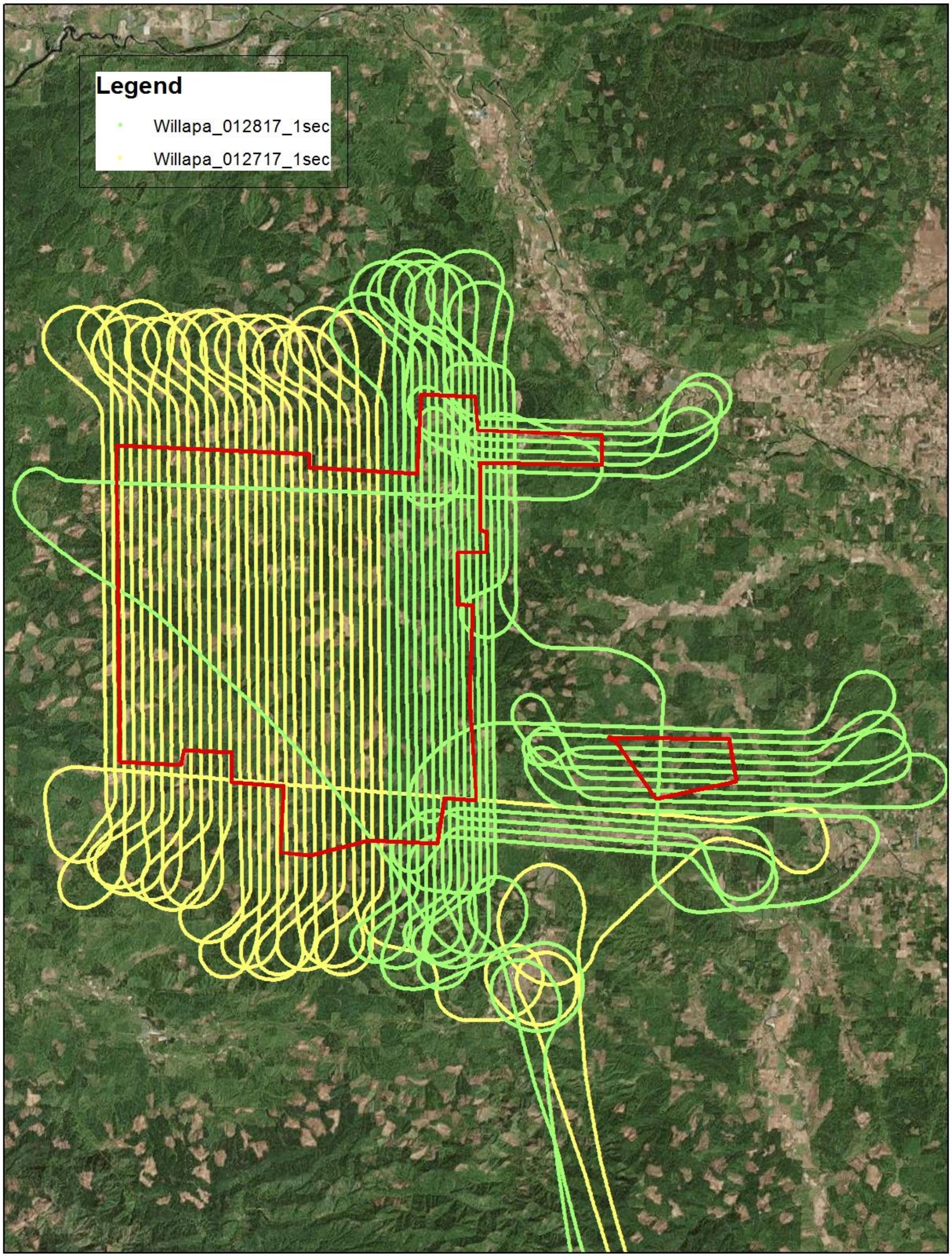


Figure 2: Aircraft trajectories

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 of 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 on 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 illustrates the correctional process.

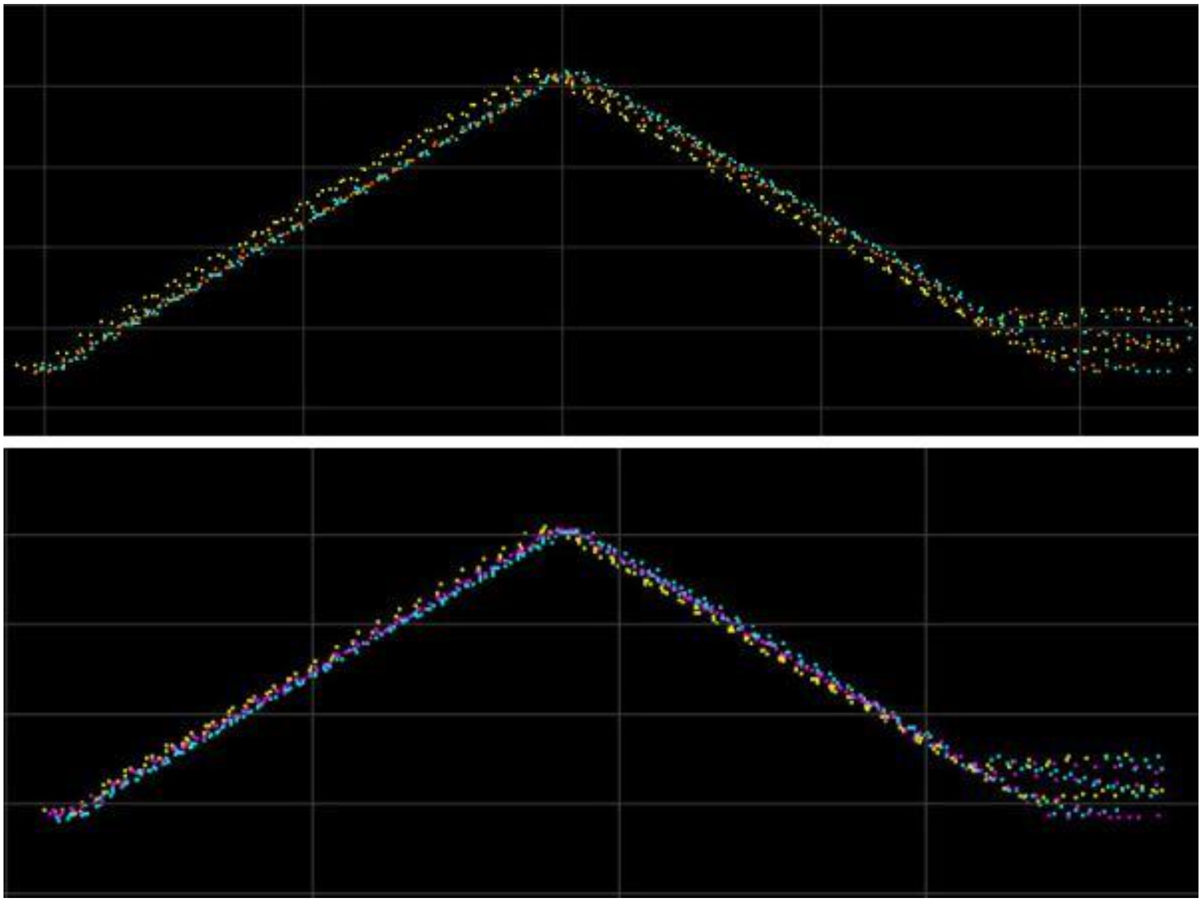


Figure 3: Planes in overlapping strips before and after adjustment

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).

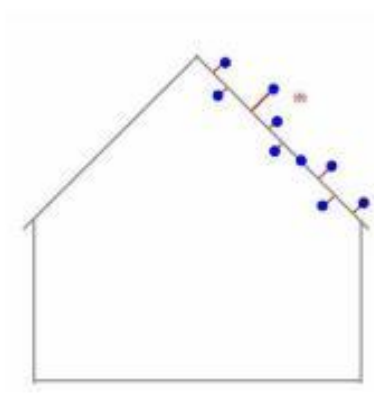


Figure 4: Point to plane distances

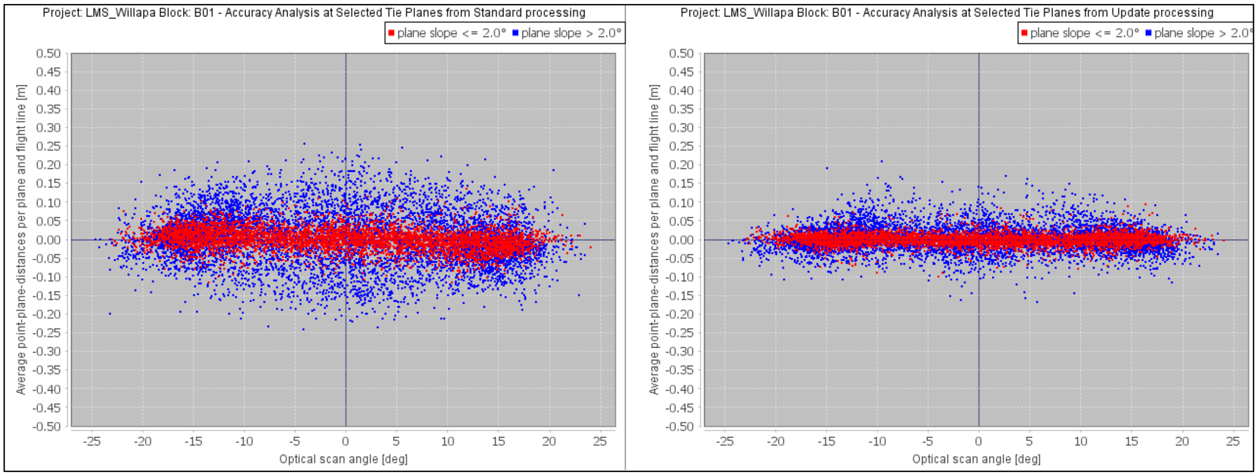


Figure 5: Mean values if the point to plane distances plotted over scan angle

Additionally, flight mission was 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, elevation, heading, roll, pitch and mirror scale.

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

Table 3: 1A – 42,524 section lines

Error Type	X (ft.)	Y (ft.)	Z (ft.)
Average Magnitude	0	0	0
RMS	0	0	0.017
Maximum Values	0	0	0.216

After a tight relative fit was achieved, an absolute vertical offset was calculated using surveyed control points. The algorithm computes an average value for the height difference for all control points by comparison to the laser points within specified radius around the control point. Below is the layout of surveyed control points and final statistics. Full report of ground control is attached.

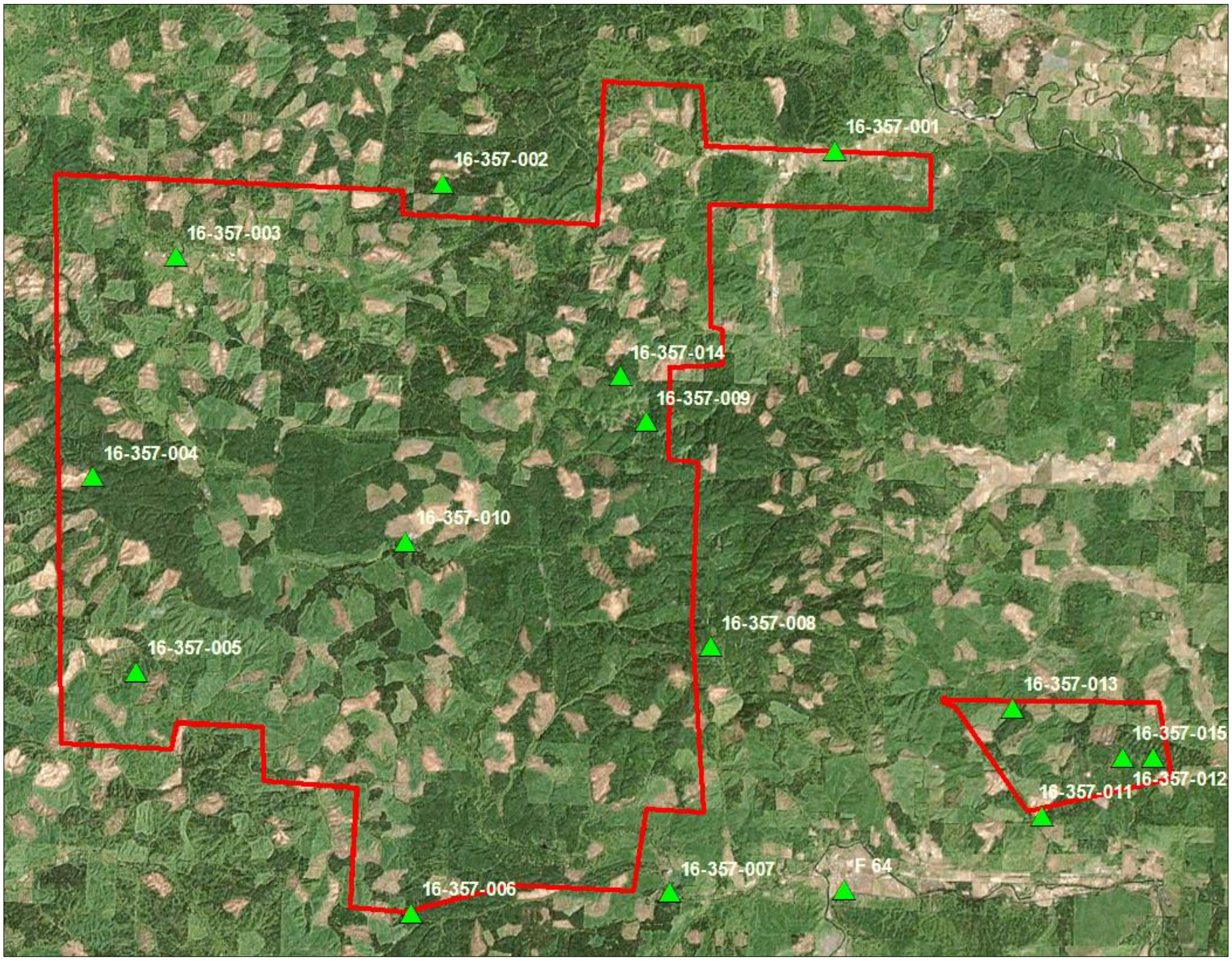


Figure 6: Layout of surveyed control points

During absolute adjustment, data was shifted by the following value: *+0.201ft*

Point 16-357-007 was withheld from statistics due to it being collected on top of concrete block, but was used to visually asses the horizontal fit.

	ID	X	Y	Z	Surface Z	Dz
	16-357-001	942480.39	549565.20	122.66	122.70	-0.04
	16-357-002	908521.38	546731.24	648.78	648.73	0.05
	16-357-003	885476.51	540412.47	192.98	193.02	-0.04
	16-357-004	878225.91	521329.13	1198.27	1198.26	0.01
	16-357-005	882025.93	504438.17	587.60	587.48	0.12
	16-357-006	905814.38	483561.40	937.25	937.31	-0.06
Turned OFF	16-357-007	928184.37	485323.10	389.18	387.30	1.88
	16-357-008	931787.24	506653.63	2157.61	2157.53	0.08
	16-357-009	926154.56	526106.38	1955.74	1955.69	0.05
	16-357-010	905293.32	515714.44	818.92	819.03	-0.11
	16-357-011	960472.30	491972.34	374.83	374.83	0.00
	16-357-012	970134.27	497031.13	771.38	771.32	0.06
	16-357-013	957958.85	501318.06	701.90	701.81	0.09
	16-357-014	923922.31	530037.78	2078.14	2078.12	0.02
	16-357-015	967438.54	497053.45	738.15	738.08	0.07

Error Type	Accuracy [ft]
Vertical Error Mean :	0.022
Vertical Error Range:	[-0.107,0.120]
Vertical Skew:	-0.425
Vertical RMSE:	**0.067**
Vertical NMAS/VMAS Accuracy (90% CI):	±0.110
Vertical ASPRS/NSSDA Accuracy (95% CI):	±0.131
Vertical Accuracy Class:	0.07
Vertical Min Contour Interval:	0.21

LiDAR QC points were obtained using post processed kinematic GNSS data from a moving vehicle along selected roads within the project area boundary (**Error! Reference source not found.**). The rover (vehicle) as 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.

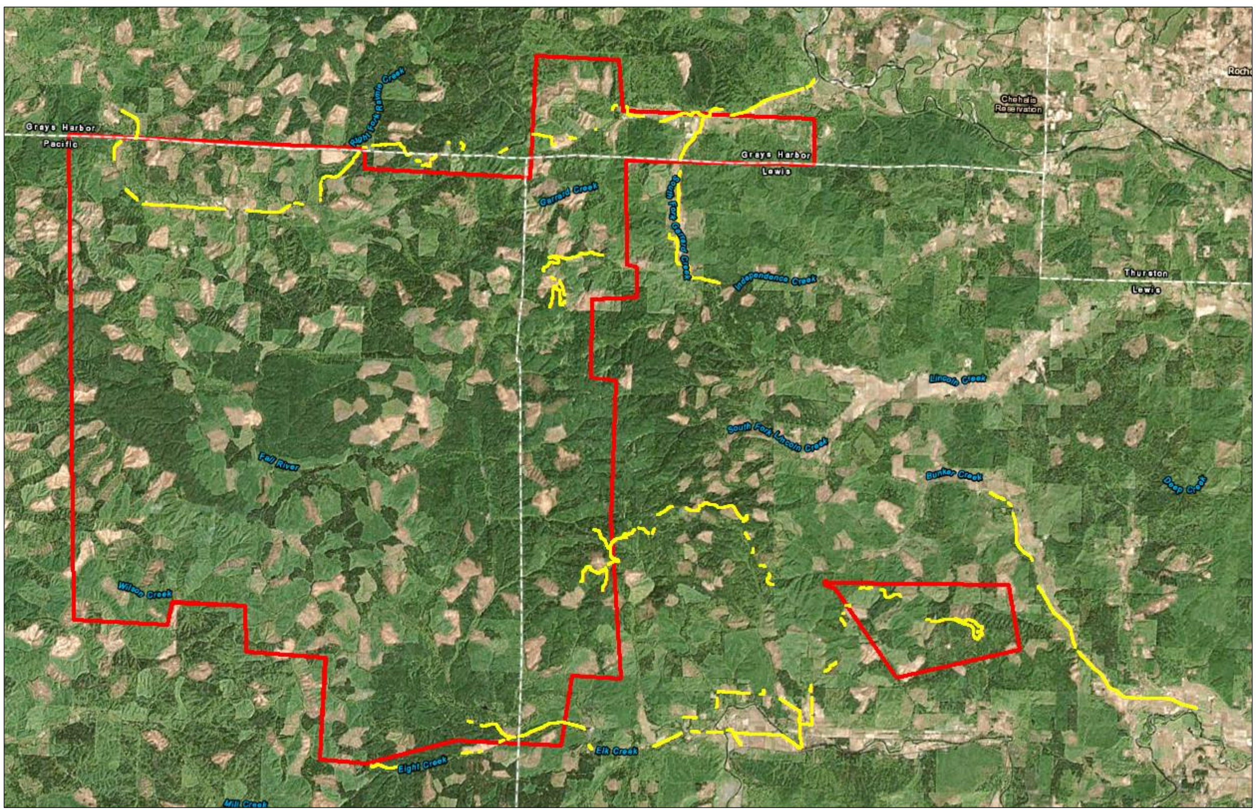


Figure 6: Layout of RTK points

Table 2: RTK accuracy assessment

Error Type	Accuracy
Vertical Error Mean:	-0.009
Vertical Error Range:	[-1.896,1.306]
Vertical Skew :	-0.653
Vertical RMSE:	**0.137**
Vertical NMAS/VMAS Accuracy (90% CI):	±0.226
Vertical ASPRS/NSSDA Accuracy (95% CI):	±0.269
Vertical Accuracy Class:	0.14
Vertical Min Contour Interval:	0.42

Out of 8151 points used in the statistical comparison only 21 points were outside of -0.5ft - 0.5ft range, making it 99.9% of points that fit within project specification.

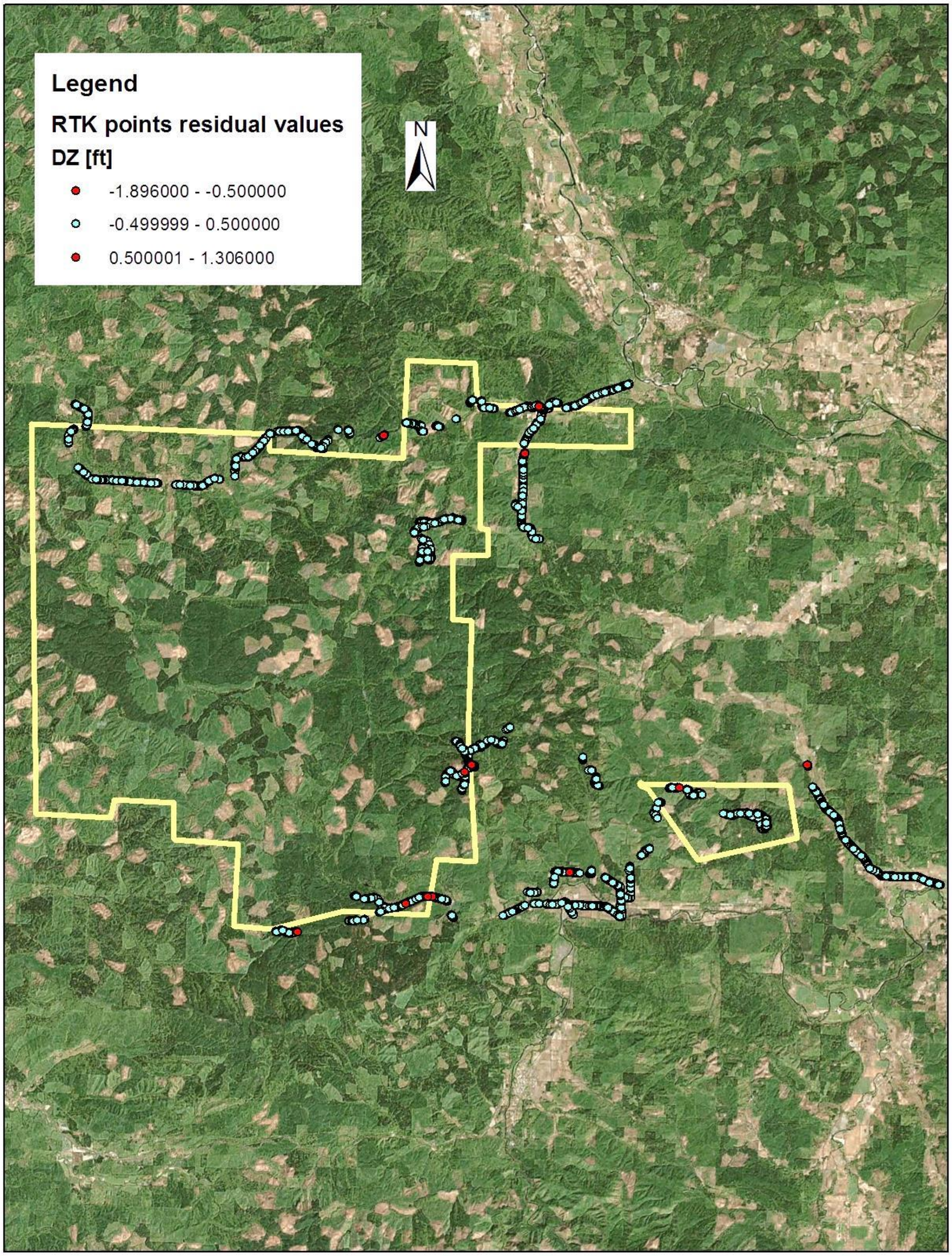


Figure 7: RTK Point analysis

3.3 Point Density

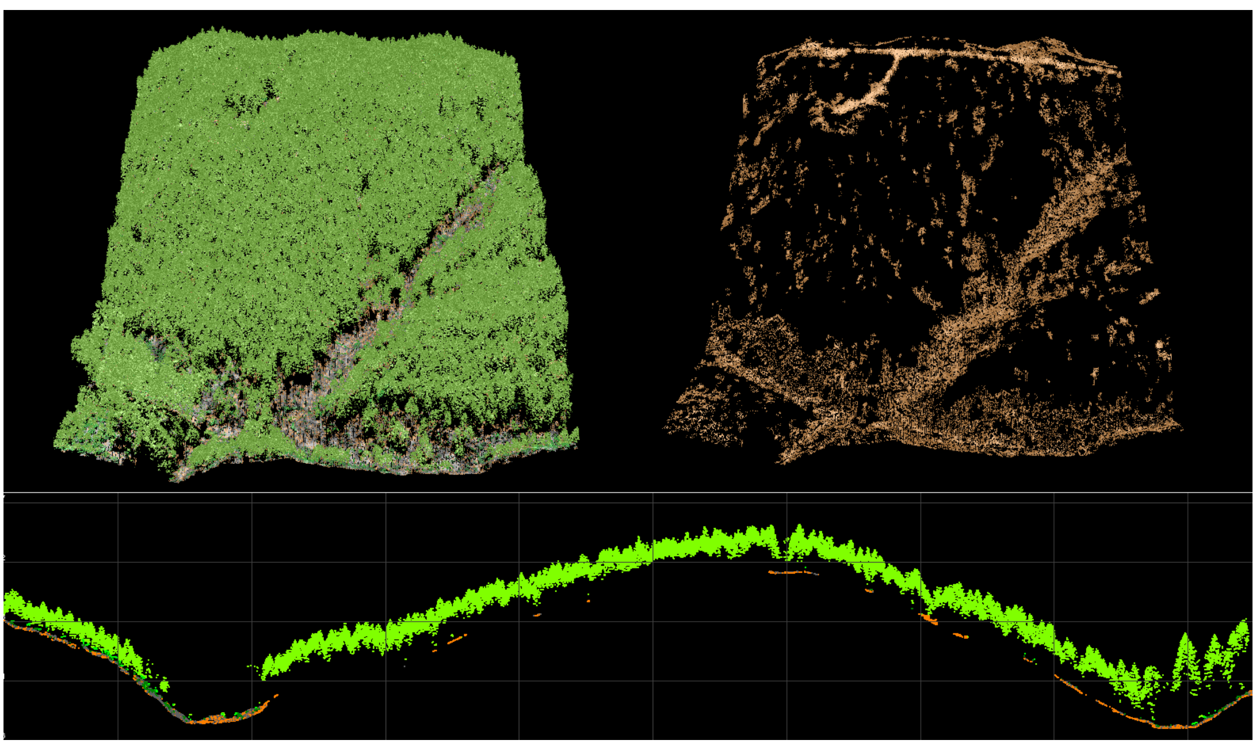
The final point density of all combined LiDAR strips within the project boundary was calculated for first returns using LP360. Point density is based upon acquisition at a 50% sidelap with a planned average of 4.4 points per square for each strip and meeting a final overall acquired density of not less than 8 points per square meter. First return density average and density maps can be found below.

Table 3: First return point density

	Δ first return point density
Willapa flown area	14.6 pts/m^2

	Δ ground return point density
Willapa flown area	2.3 pts/m^2

Some parts of Willapa AOI are covered with very dense evergreen vegetation. This causes an obstruction to laser light reaching the ground and producing many ground returns. Ground was manually checked in these places to ensure avoidable misclassifications. Below is an example graphic:



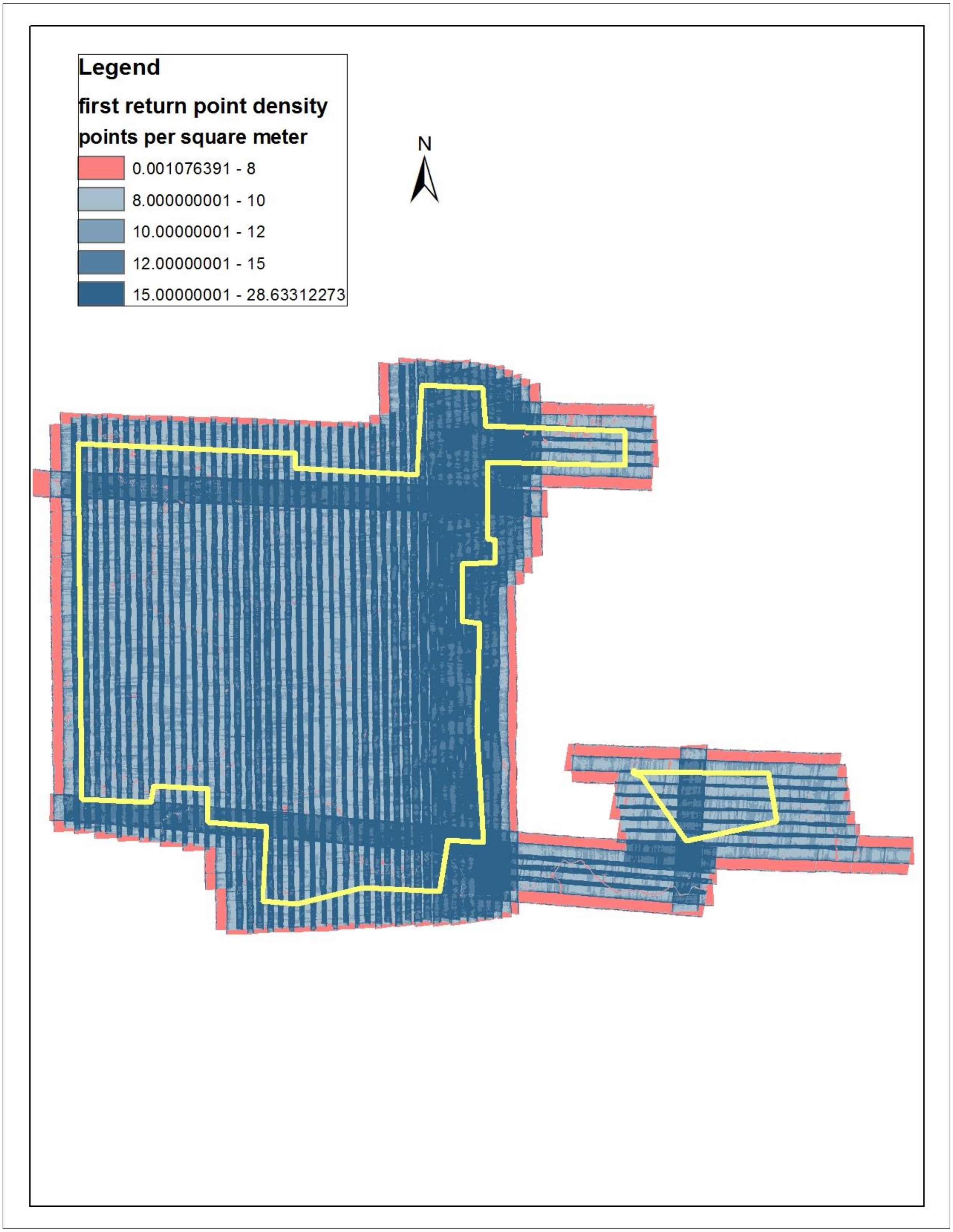


Figure 8: First return point density (100ft cell)

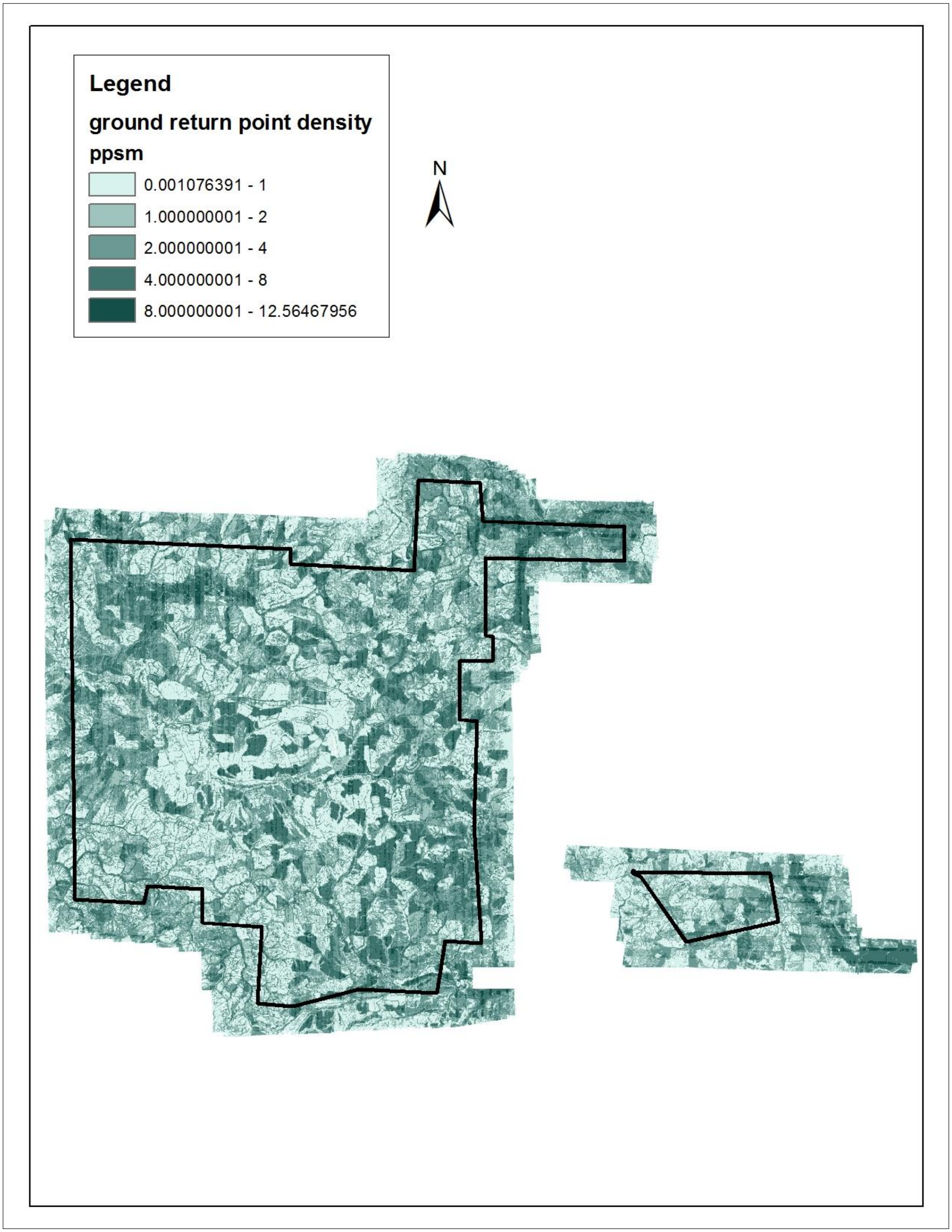


Figure 9: Ground return point density (100ft cell)

3.4 Point Cloud Classification

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

Data from the edges of the strips were omitted during the initial ground classification to maintain quality and "grounding" was initiated at low seed points and gradually increased. A tailored approach was formulated for different areas within the project. 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.

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 doesn't meet triangle edge length criteria – it ensures that some noisy points are excluded from ground surface.

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). 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.

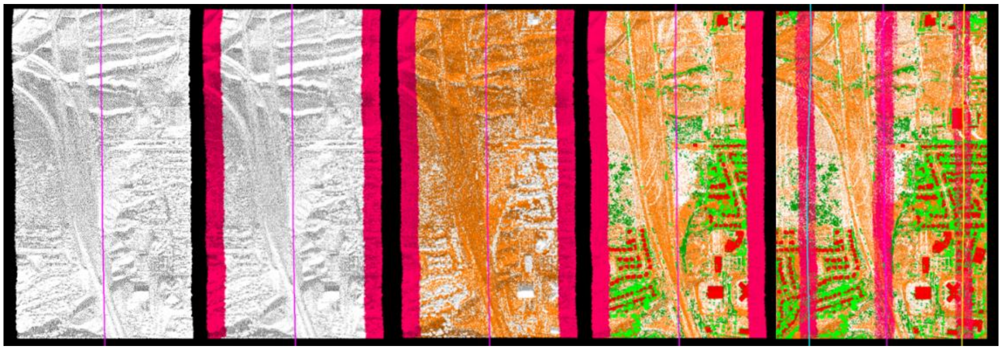


Figure 10: Process of determining 12-Overlap class

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

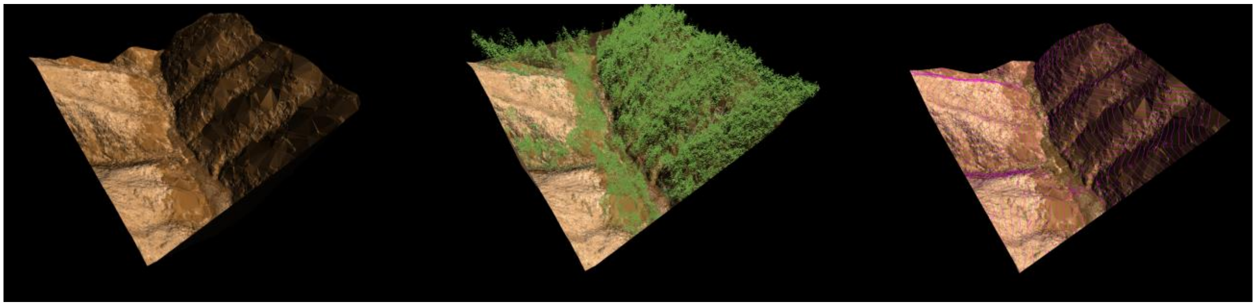


Figure 11: elected boxes of rotating 3D point clouds, viewed with toggled color-coded classification points, TINs and contours

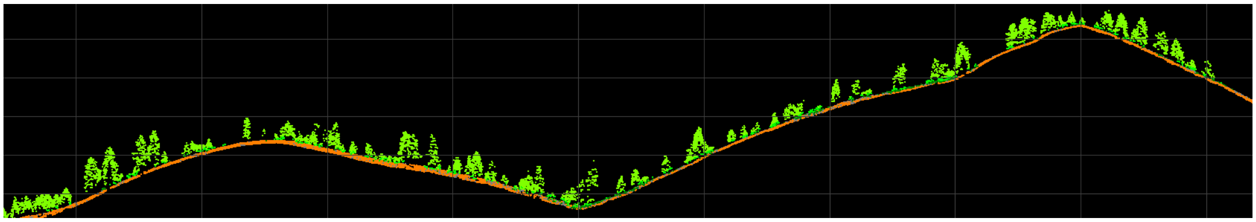


Figure 22: Point clouds viewed in profile view

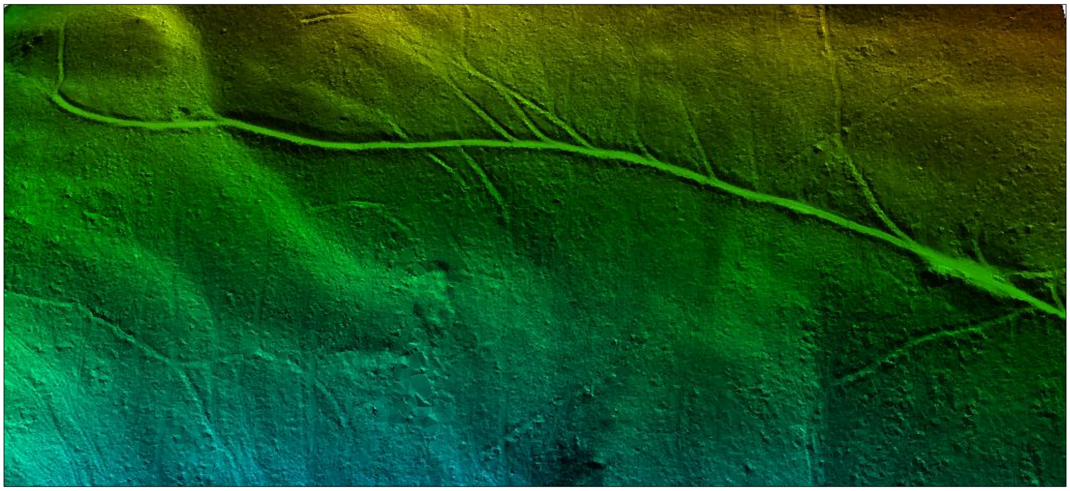


Figure 33: Temporary creation of TIN over ground points to assist in identifying points incorrectly classified as ground.

Below in Table 4 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 4: Point cloud classification scheme

Classification	Definition
00_Cross Strip	Points from cross flight lines used in calibration
01_Unclassified	Noise, and 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 10’ and above the 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. Tiles were created according to contractual division of USGS quadrangles. Data within a 100ft buffered boundary was reviewed for classification. Cross strips were left in the dataset as class 00 and were not used in other classification determinations or any LiDAR derivative products.

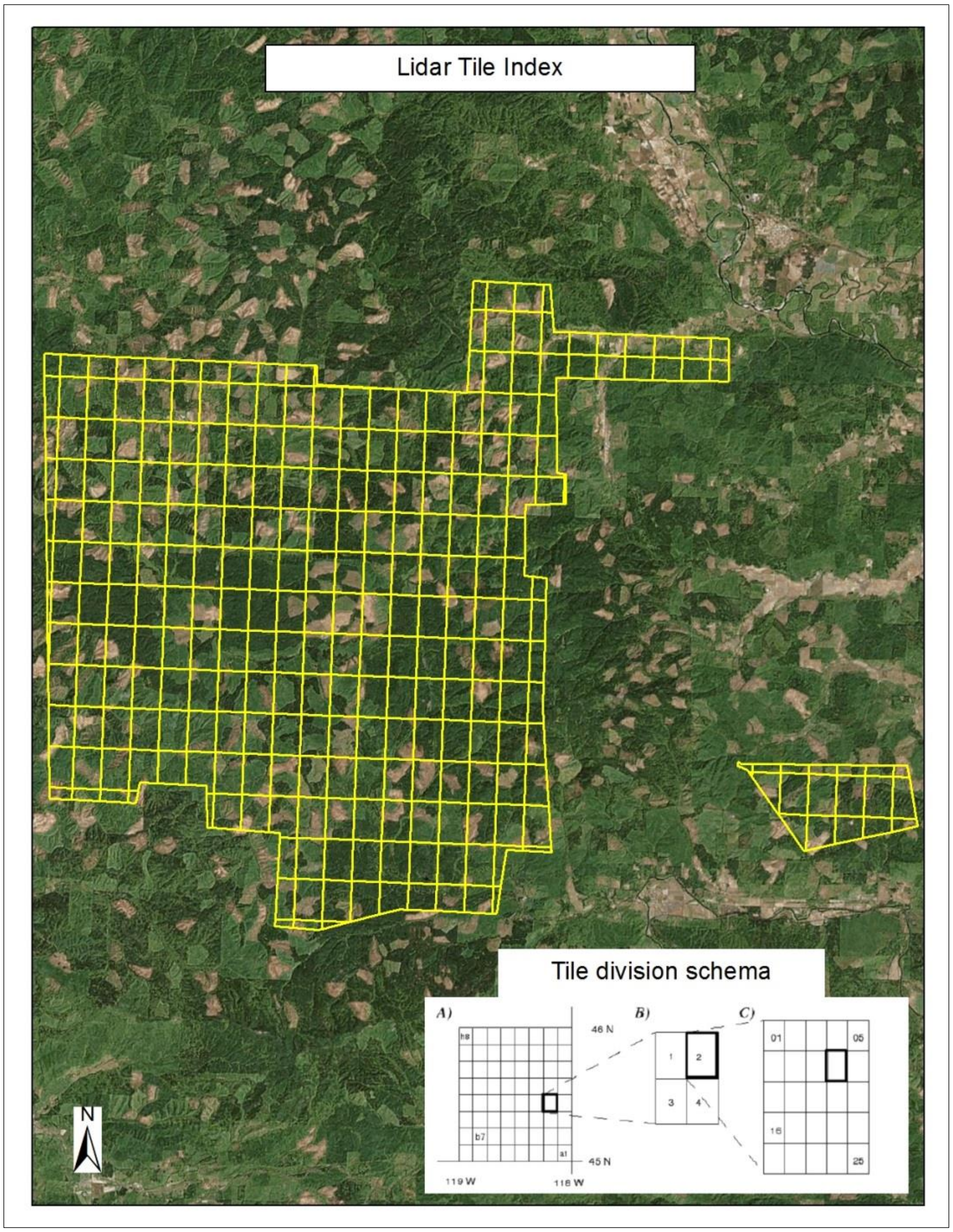


Figure 44: Tiling scheme for Lidar tiles

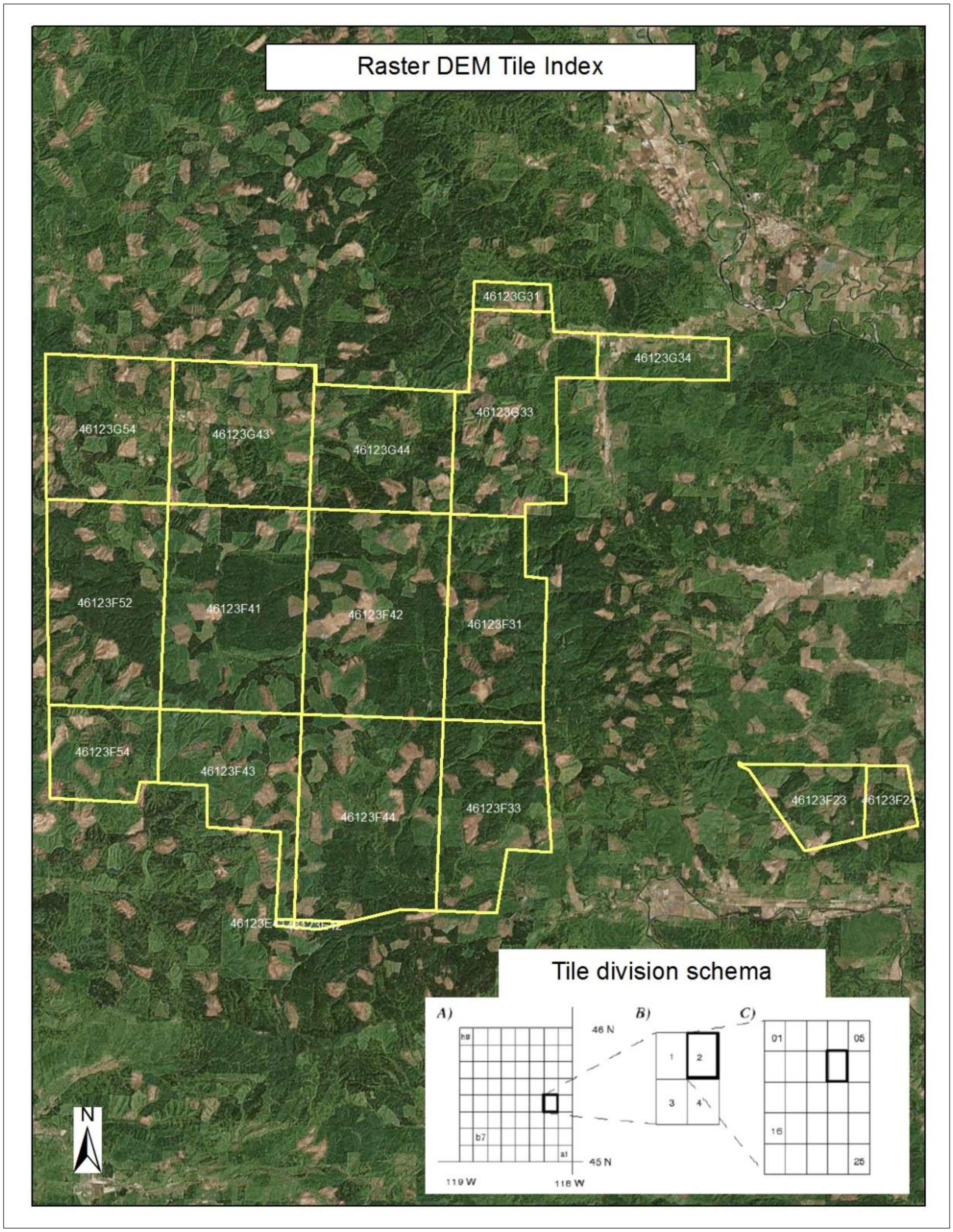


Figure 55: Tiling scheme for raster DEM tiles

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).

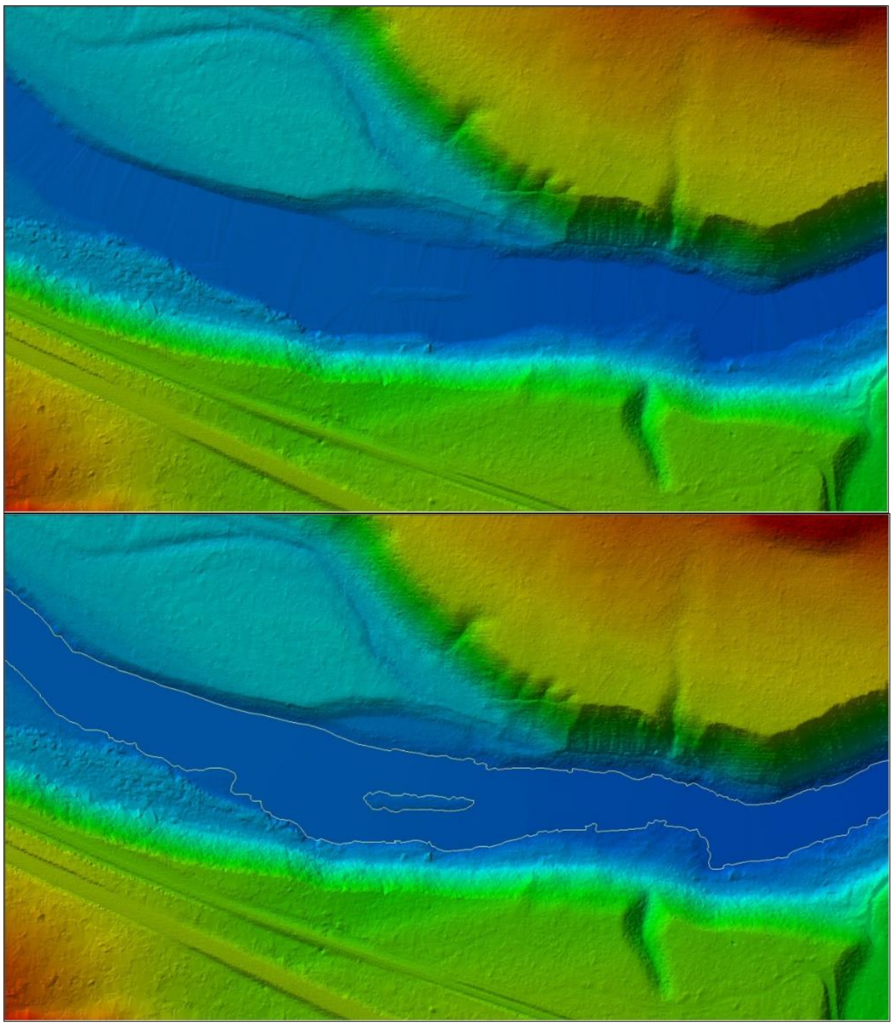


Figure 16: TIN Surface before implementing hydro breakline enforcement and after.

5. Raster DEM Generation

5.1 Bare Earth

Classified ground returns were used to create a LAS Dataset. The LAS Dataset was later converted into a 3ft-cell ESRI floating grid, using a triangulation method of interpolation, and linear method of void filling. Hydro-flattening ensured the most accurate surface near water bodies where flowing rivers were outlined maintaining downstream flow. Cell alignment of the raster product corresponded to an origin point of x=200,000, y=-200,000 (WA State Plane South, NAD83(HARN)).

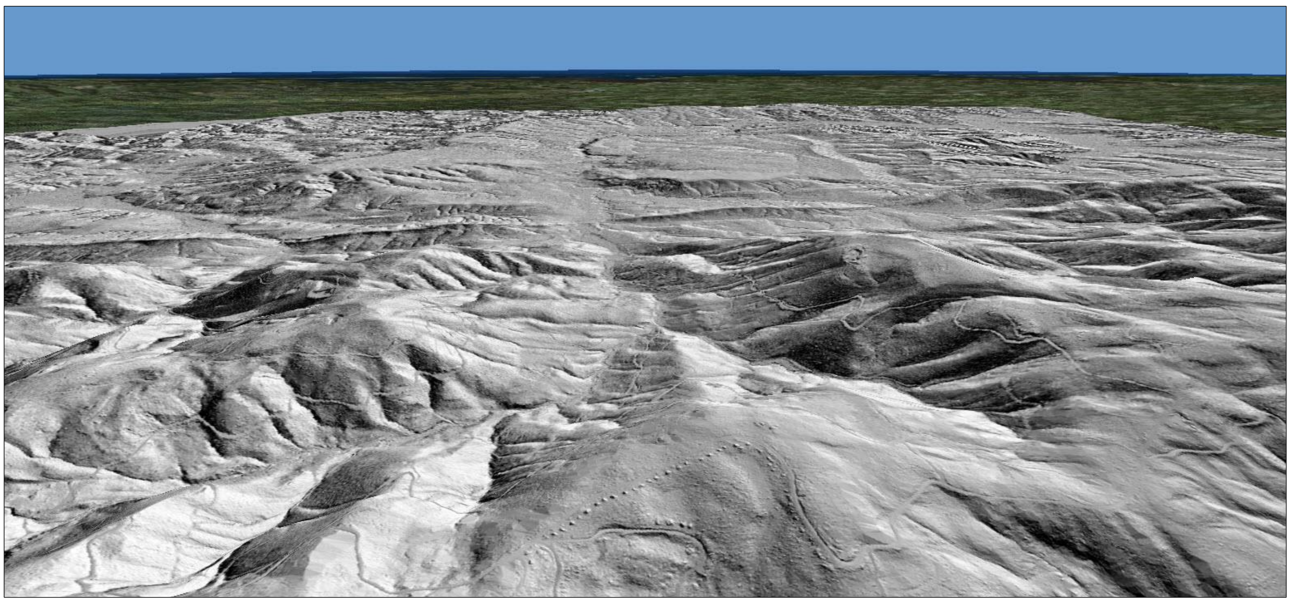


Figure 17: Example of Bare Earth DEM (hillshade)

5.2 Highest Hit

A highest hit model was created using all LiDAR returns. The layer was converted to a 3ft-cell ESRI floating 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.

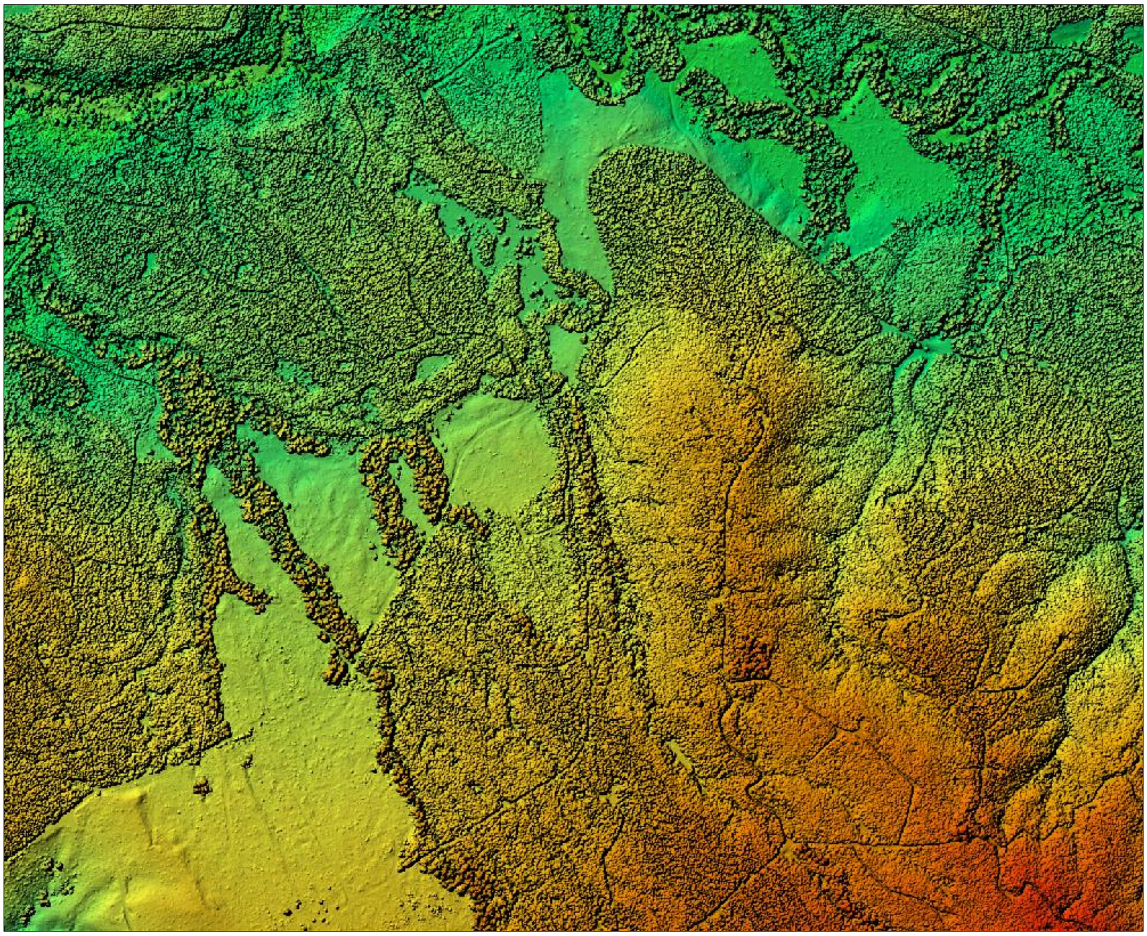


Figure 18: Hillshade representation of highest hit raster colored by height

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.

6. Final Deliverables

Final deliverables are listed below in Table 5.

Table 5: Deliverables

Deliverable	Format
Classified LiDAR	LAS 1.2 format (100ft buffered AOI)
3ft Highest Hit Model	ArcGIS format (50ft buffered AOI)
3ft Bare Earth Model	ArcGIS format (50ft buffered AOI)
Tile Index	Shapefile format
Aircraft trajectory	Shapefile format
Ground control points and survey report	ASC, KML and PDF format
LiDAR Technical Report	PDF
Formal FGDC compliant metadata	XML