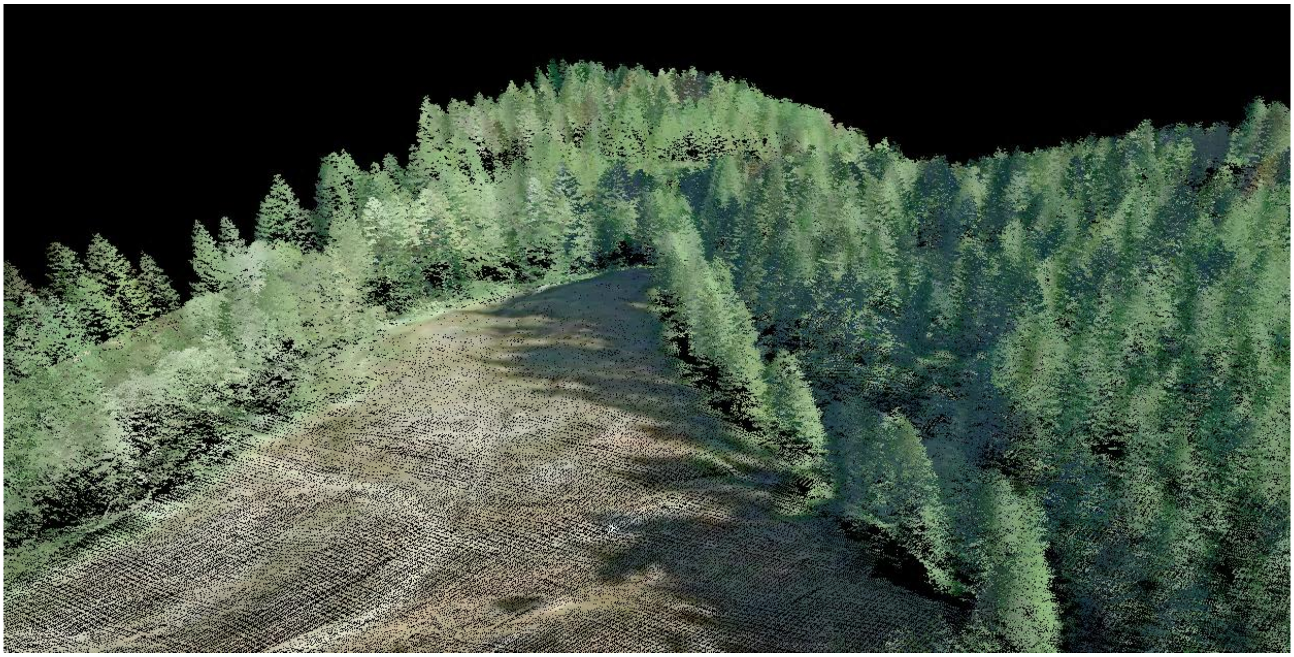

Lidar Mapping Project Report

For Submittal to USGS #G22AC00258

Project Name: OR Western Wildfires A22

Project ID: 218297

Date: December 14, 2022

Presented to:
Oregon Department of Forestry
For Contribution to USGS 3DEP
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1. Project Overview

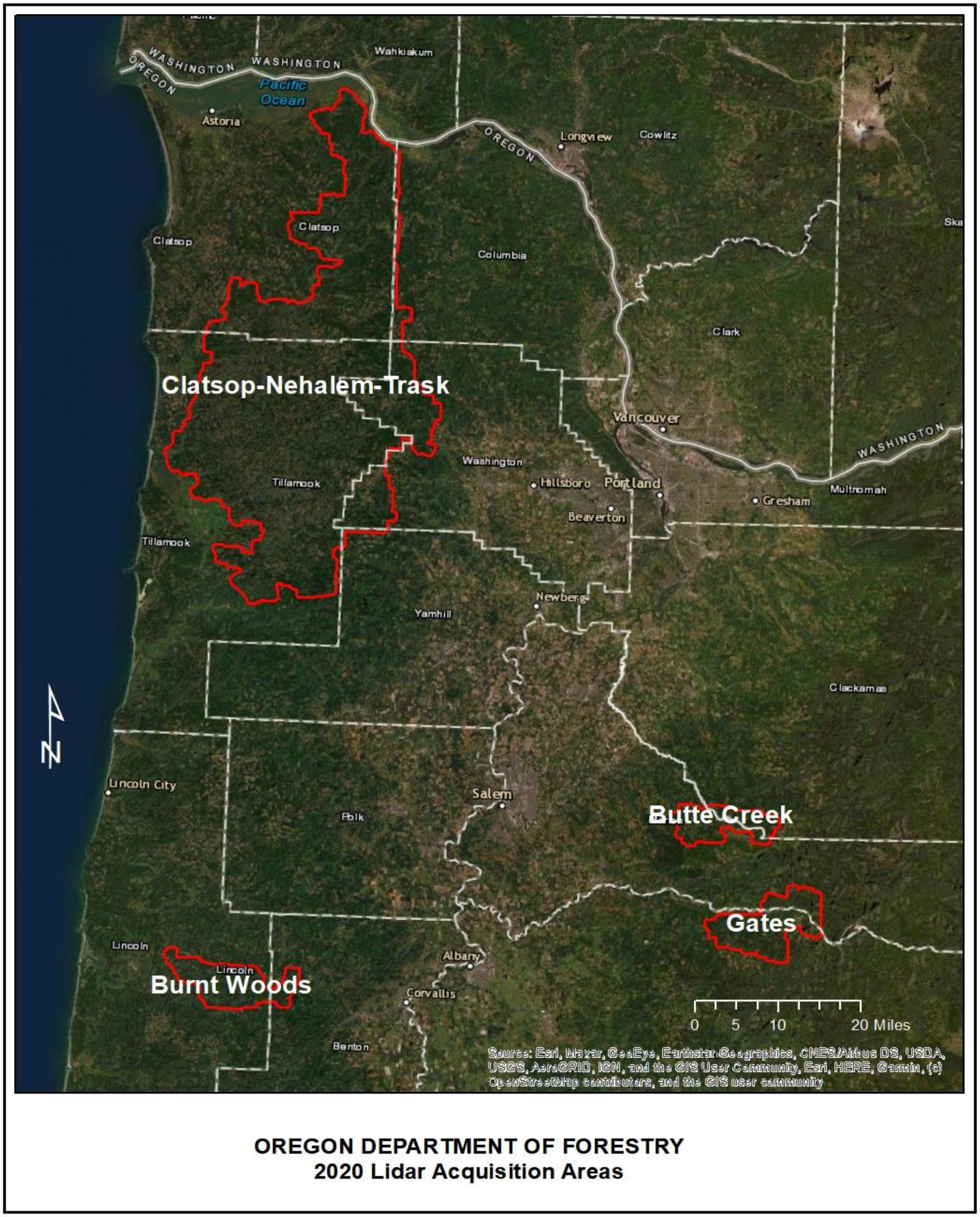

Figure 1. Boundaries of the 2020 ODF Lidar project. Note that Butte Creek and part of Gates were removed from re-processing due to the 2020 late summer Beachie Creek and Lionshead Fires that were subsequently re-flown in summer of 2022.

1.1 Description

GeoTerra, Inc. was selected by Oregon Department of Forestry (ODF) under contract #ODF-1109A-20 to provide new Lidar acquisition and subsequent products during the 2020 calendar year for four project areas identified as Clatsop-Nehalem-Trask (1,070 mi²), Burnt Woods (65 mi²), Butte Creek (49 mi²), and Gates (77 mi²), as shown in Figure 1. Specifications for Lidar were to meet or exceed a density of 8 points/m².

In the 2022 calendar year, GeoTerra was contracted by ODF to post-process a majority of the 2020 Lidar data to meet Quality Level 1 (QL1) specifications for submission to the United States Geological Survey (USGS) Three-Dimensional Elevation Project (3DEP). As a result of the Beachie Creek and Lionshead fires which burned through the area in late summer of 2020, all the Butte Creek area of interest (AOI) and about 57% of the Gates AOI were excluded from re-processing. The delivery boundary for 3DEP contribution was reduced to a total of 34 mi² (Figure 2 below). Note that QL1 Lidar was subsequently flown in summer of 2022 over the entire burn area as part of a separate contract. The following is a report explaining planning, procedures, results, and deliverables as performed for the entirety of the 2020 data, from acquisition and initial delivery through post-processing and re-submission of 1,174 mi² of Lidar data to meet USGS 3DEP QL1 specifications.

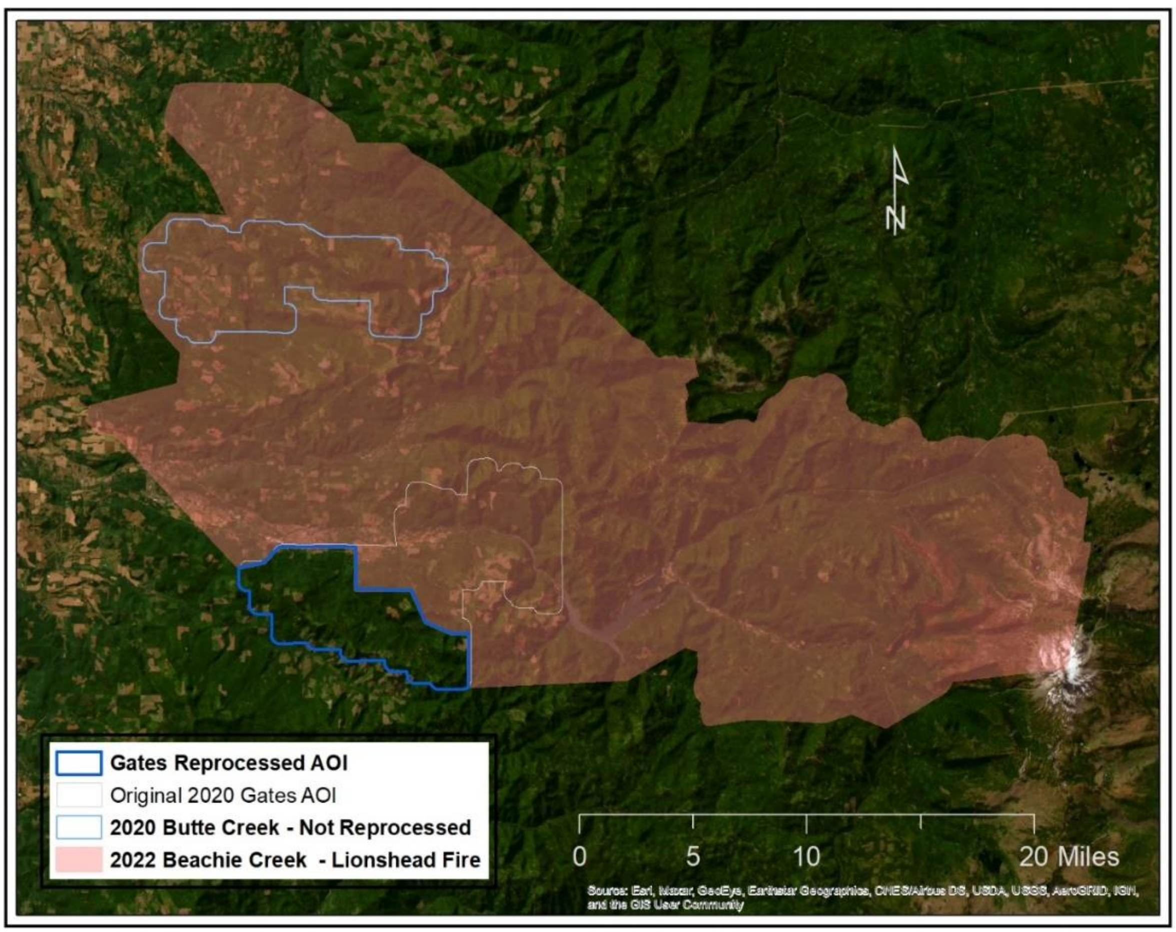

Figure 2. Butte Creek AOI was removed, and Gates AOI were reduced due to post-acquisition fire.

1.2 Purpose

This project was part of an agreement to support a project to expand 3DEP Coverage in Oregon while aiding post-wildfire recovery work by state and federal agencies.

1.3 Specifications

All data delivered for this project was produced to meet the USGS Lidar Base Specifications v2022 Rev. A

1.4 Spatial Reference

All data for this project were produced using the following spatial data reference system:

- Horizontal Datum: NAD83(2011)(Epoch 2010.0)
- Horizontal Projection: Oregon Statewide Lambert
- Horizontal Units: International Feet
- Horizontal EPSG Code: 6557
- Vertical Datum: NAVD88
- Geoid Model: 12b
- Vertical Units: International Feet
- Vertical Datum EPSG Code: 5703

1.5 Task Order Deliverables

Table 1, below, provides details of items that were processed and delivered for this project, with an indication of format and compliance to contractual specifications. The final tiling scheme of LAS and raster-formatted data was based on the provided ODF 3000'x3000' tiling scheme.

Table 1. Project delivery items and formats

Deliverable	Format	Compliance notes
Classified Point Cloud	LAS 1.4 PDRF 7	Each point includes GPS week and GPS second OR Posix time, easting, northing, elevation, intensity, return number, return classification, scan angle, point source ID.
Bare Earth Surface Model	GeoTIFF, 32-bit floating point	1-foot resolution hydro-flattened ground model
Max Surface Height Model	GeoTIFF, 32-bit floating point	1-foot resolution from binning interpolation type and maximum value for determining cell value.
Survey Report	PDF	Describes control and checkpoint locations acquired for this project and methodology used.
Survey Data Points	GeoPackage	Includes control and QC checkpoints used for this project
Lidar Technical Report	PDF	This report: provides methodology used for planning, processing, assessment and delivery of final data.
FGDC Metadata	XML	Per USGS 3DEP Lidar Specifications 2021 rev. A
Swath Separation Images	GeoTIFF	4-foot resolution; color-coded as required
Intraswath results	Geodatabase	Polygons used to test intraswath precision, with min-max of slope-corrected range and RMSDz.
Interswath results	Geodatabase	Polygons used to test interswath accuracy, with min-max of slope-corrected range and RMSDz.

Breaklines	Geodatabase	Use for hydro-flattened flattening and defining sharp breaks around bridge abutments.
Swath Outlines	Geodatabase	Polygon of each flight swath
Project Index	Geodatabase	Polygons of final project delivery areas.
Tile scheme	Geodatabase	3000’ x 3000’ tiles

1.6 Lidar Data Classification

Classified Lidar point cloud data were provided in las v1.4 format using the following classification scheme shown in Table 1:

Table 1. Lidar classification scheme applied to all point returns.

Lidar Classification Scheme	
Class 1	Processed, but not classified
Class W1	Processed, but not classified with a withheld flag
Class 2	Ground (bare earth)
Class W2	Ground (bare earth) with a withheld flag
Class W7	Low Noise – with a withheld flag
Class 9	Water
Class W9	Water with a withheld flag
Class 17	Bridge Deck
Class W18	High Noise – with a withheld flag
Class 20	Ignored ground near breaklines
Class W20	Ignored ground near breaklines with withheld flag

2. Acquisition

2.1 Flight Planning

Lidar acquisition was planned using Teledyne Optech Airborne Mission Manager to calculate optimum parameters to meet project requirements and accommodate terrain variations. FMS utilized an existing DEM surface to calculate best flight parameters and swath layout to meet desire point density. The project required a minimum aggregate density of 8 points per square meter. Point density was designed to be achieved through overlapping adjacent swaths by greater than 55%. Adjacent lines were flown in opposing directions. the Galaxy’s *PulseTRAK* and *SwathTRAK* technologies were employed during flight to allow the sensor to maintain regular point distribution and constant-width swaths despite changes in terrain.

GeoTerra utilized an Optech Galaxy Prime sensor, mounted in a Cessna 210 aircraft to acquire new lidar data for all areas. During flight, the on-board receiver logged GNSS data at 1 Hz interval and IMU data at

200 Hz interval. Acquisition parameters including pulse rate, flight altitude, orientation relative to terrain, scan angle, and ground speed were optimized to meet contract specifications and objectives. Acquisition conditions at the time of each mission were free of clouds, fog, snow, and flooding. The flight acquisition specifications for this project are shown in Table 2, below.

Table 2. Lidar Acquisition Specifications.

LiDAR Settings & Specifications	
Aircraft Used	Cessna 210
Sensor	Optech Galaxy Prime
Intensity	12-bit, scaled to 16-bit
Wavelength	1064 nm
Beam Divergence	0.25 mrad
Maximum Sensor Returns Per Pulse	8
Target Pulse Rate	450 kHz
Scan Frequency	65 Hz
Target Aircraft Speed	119 kts
Maximum Scan Angle	20°
Maximum Survey Altitude (AGL)	5700 ft (1737 m)
Swath-to-Swath Overlap	> 55%
Average Swath Width (Flat Ground)	4147 ft (1264 m)
Maximum Beam Diameter on ground	43.4 cm
Aggregate Resolution/Density	≥ 8 pulses/m^2
Aggregate Nominal Point Spacing	≤ 0.35 m
Planned Accuracy	$RMSE_Z$ ≤ 10 cm

2.2 Acquisition Timeline

Dates of acquisition for each area are shown in Table 3, below. The largest AOI known as Trask-Nehalem-Trask acquisition occurred in three logical blocks during the leaf-on over period from May 10 – September 3, 2020, as shown in Figure 2, below. The two remaining blocks known as Burnt Woods and Gates were flown in single missions on May 7th and May 24th, respectively.

Table 2. Lidar acquisition dates by AOI

Area Name	Dates of Acquisition
Clatsop-Nehalem-Trask	May 7-10, 27, 28; April 18, 25; July 30 and Sept 3, 2020
Burnt Woods	May 7, 2020
Gates	May 24, 2020

2.3 Post-Flight Evaluation

Upon completion of each mission, GeoTerra immediately reviewed the raw data to identify any potential issues affecting accuracy and the need for re-flights. Laser points were evaluated to ensure complete coverage of the project area. Positional Dilution of Precision (PDOP) during flight was assessed to ensure it remained below 3.0 to provide the best geometry of satellites for post processing.

3. Processing

3.1 SBET Processing

Kinematic corrections for aircraft position data were performed using the Precise Point Position (PPP) method. PPP utilizes an autonomous positioning method whereby data from the aircraft receiver is processed using dual frequency data and precise orbit and clock files. Processed GNSS data were then combined with IMU data using a loosely coupled technique where Novatel Inertial Explorer v8.9 also computes lever arm offsets between the IMU and the L1 phase center of the aircraft antenna. The final combined GNSS/IMU solution was output as a Smoothed Best Estimate Trajectory (SBET). Laser point positions were calculated by associating the SBET position to each laser point's return time, scan angle and intensity; see Figure 3. Point positions were converted to orthometric elevations by applying a Geoid 12b correction. (Note: methods used for airborne processing are included in separate report.)

3.2 Laser Post-Processing and Calibration

Data was processed into LAS format by flight line and used to perform the relative calibration and check for erroneous data. An initial auto-classification was performed and resulting ground points were used to perform an automatic line-to-line calibration to adjust for pitch, roll and heading, GPS/IMU drift, and mirror flex. Calibrations were applied to all returns and data was adjusted to surveyed ground control to achieve final adjusted positions. Table 4, below, provides a detailed list of equipment, software and processes used to produce the final calibrated data.

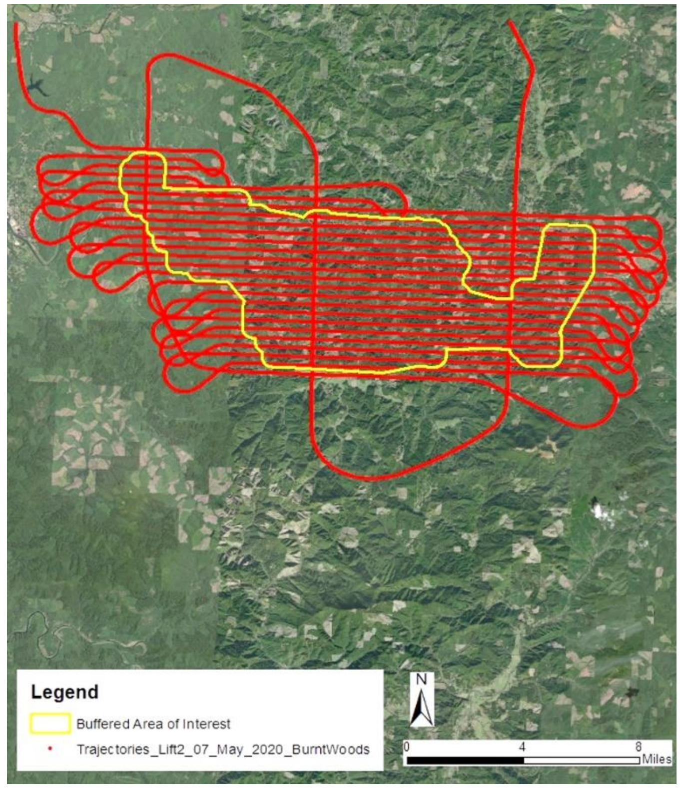

Figure 3. Trajectories for Burnt Woods AOI

Table 4. Planning and Post-Processing Overview

Process	**Software**	**Description**
Flight Planning	Teledyne Optech Airborne Mission Manager	Data acquisition was planned in consideration to terrain, environmental factors, and project objectives.
Flight Execution	Optech Galaxy Prime	Sensor equipped with POS AV™ AP50 (OEM); Up to and 8 range measurements and intensities for each pulse; Internal solid-state drive SSD
ABGPS Data Post Processing	Novatel Inertial Explorer Version 8.60.6323	The data collected during the flight is post-processed into Smoothed Best Estimate of Trajectory (SBET) binary file of the IMU trajectory which is combined processed data from both GNSS satellite data and IMU data and is used to geo-reference the laser point cloud.
Raw Lidar Post Processing to LAS Format	Optech LMS (Lidar Management Suite)	Data was processed from range format to LAS format and preliminary adjustment was made using tie plane methodology.
Lidar Strip Relative Adjustment	TerraMatch	Additional relative adjustment was performed using tie line methodology to further improve fit especially in areas where tie planes were not found.
Autoclassification	TerraScan	Rigorous selected as well as custom created algorithms built within TerraScan were used to automatically classify the data.
Lidar Strip Absolute Adjustment	LP360	Data was compared to non-vegetated control points set in appropriate terrain for absolute adjustment.

3.2 Boresight Calibration

Prior to acquisition, a Boresight Calibration was performed to determine exact angles between the IMU and lidar reference frame. A local site was chosen with slopes in different directions to provide viable observations for calculation of angle offsets. The determined offset values were then transferred to sensor instruction files to use for downstream processing.

3.3 Relative Adjustment

Relative and absolute adjustment of all strips was accomplished using Optech *LMS* and TerraSolid *TerraMatch* software packages. *LMS* was used to perform automated extraction of planar surfaces from the point cloud. Tie planes were determined to establish correspondence between overlapping flight lines. Planes from overlapping flight lines were then compared and measured for spatial accuracy and used to co-locate all lines to within an acceptable tolerance.

A set of accurately calculated tie planes were 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 a flight line, and a fitting error. These criteria have an effect an overall correction, as they determine the geometry of the adjustment. Self-calibration adjustment parameters were then determined and used to re-calculate laser point locations (x,y,z). Planar surfaces were also re-calculated for a final adjustment. Table 5 shows results of two sites.

Table 5. Results of relative adjustment for two project areas.

Block	Number of Measured Section Lines	RMS (ft)	Average Magnitude (ft)	Maximum Value (ft)
Burnt Woods	25,752	0.04	0.03	0.25
Gates	278,981	0.07	0.05	0.32

The largest project block of Clatsop-Nehalem-Trask was too large to efficiently fly and process in one block. Thus, it was broken into three blocks of roughly equal size. The three adjusted sub-blocks were shifted to match each other for a seamless, relative fit as one block. The relative adjustment results of each block are shown below in Table 6.

Table 6. Results of relative adjustment for three sub-blocks of the Clatsop-Nehalem-Trask site.

Block	Number of Measured Section Lines	RMS (ft)	Average Magnitude (ft)	Maximum Value (ft)
Clatsop	425,589	0.07	0.05	0.320
Nehalem	437,711	0.08	0.06	0.320
Trask-Gales	468,716	0.06	0.04	0.320

3.4 Absolute Adjustment

After relative fit was established, surveyed control points acquired for the project were utilized to perform the absolute adjustment of Lidar points to ground coordinates. (Note: a separate Survey Report for the project is included with this delivery). The point cloud was classified and used to compare Lidar ground values to control values. A mean vertical offset from was calculated from all control within a project AOI and used to apply a final adjustment of the point cloud to absolute position. See Table 7 shows results of ground control compared to final adjusted points.

Table 7. Results of absolute adjustment as compared to surveyed ground control on open flat ground.

Block	Clatsop-Nehalem-Trask	Burnt Woods	Gates
Number of Control	**28**	**11**	**13**
Vertical RMSEz	**0.06 m**	**0.04 m**	**0.03 m**

3.5 Relative Accuracy: Interswath Consistency

Swath to swath fit or interswath consistency is required to meet ≤ 8cm RMSDz. Consistency was assessed at multiple locations within overlap in non-vegetated areas with only single returns and with slopes of less than 10 degrees. Test areas were located across the full width of overlap, as much as possible. Each swath-to-swath area was evaluated using a signed difference raster with a cell size of 4ft. The difference raster was statistically summarized to calculate RMSDz. The project-wide results are shown below in Table 8; polygon assessment locations are shown in Figure 4.

Table 8. Interswath Results

FID	dZ_MAX (m)	dZ_MIN (m)	RMSD (m)
0	0.062	0.000	0.025
1	0.066	0.000	0.019
2	0.072	0.001	0.034
3	0.055	0.000	0.022
4	0.053	0.000	0.023
5	0.055	0.000	0.025
6	0.089	0.001	0.035
7	0.097	0.000	0.041
8	0.083	0.000	0.035
9	0.065	0.000	0.026
10	0.074	0.009	0.048
11	0.101	0.037	0.063
12	0.047	0.000	0.020
13	0.041	0.000	0.014
14	0.085	0.005	0.042
15	0.096	0.012	0.047
16	0.077	0.000	0.028
17	0.057	0.000	0.021
18	0.067	0.001	0.030

FID	dZ_MAX (m)	dZ_MIN (m)	RMSD (m)
19	0.043	0.000	0.012
20	0.076	0.000	0.037
21	0.062	0.000	0.021
22	0.087	0.000	0.028
23	0.104	0.017	0.069
24	0.073	0.001	0.043
25	0.051	0.000	0.020
26	0.049	0.001	0.025
27	0.051	0.000	0.015
28	0.056	0.000	0.025
29	0.057	0.000	0.023
30	0.064	0.000	0.018
31	0.145	0.000	0.049
32	0.076	0.000	0.035
33	0.060	0.000	0.021
34	0.067	0.000	0.027
35	0.102	0.000	0.041
36	0.047	0.000	0.015
37	0.109	0.007	0.057

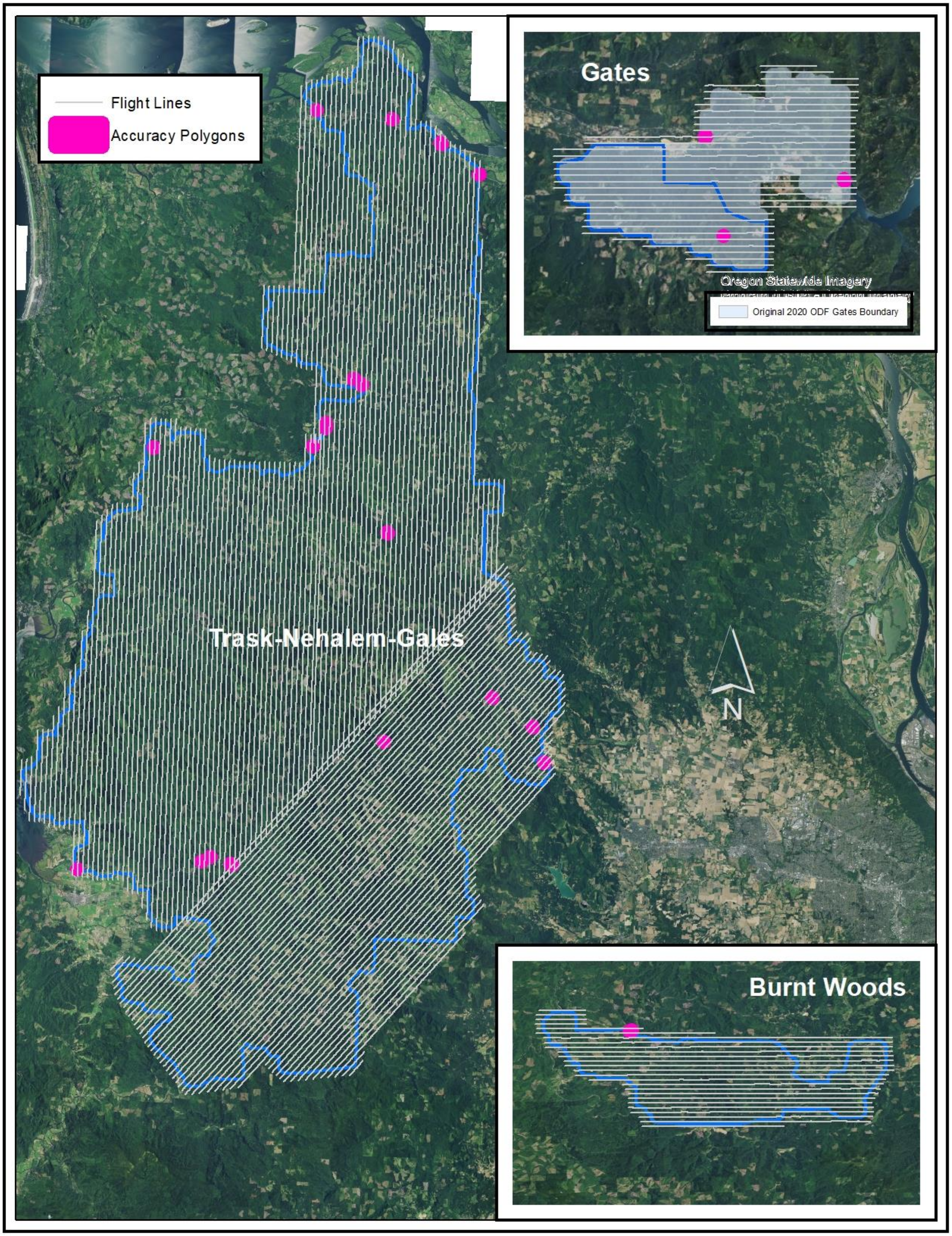

Figure 4. Location of polygons used to assess InterSwath accuracy.

3.6 Intraswath Precision

Precision within swaths was evaluated on flat (less than 10° slope) hard surfaces such as roads, parking lots and rooftops. All pulses with single returns were used for evaluation. Each lift was assessed with a minimum of one sample area encompassing approximately 100-pixels at a pixel resolution of 4ft. A slope correction was applied to the range within each cell as dictated by the equation provided in the Lidar Base Specifications. Results were required to meet ≤ 6cm RMSDz. Intraswath consistency results were submitted as polygons of each area tested and include the calculated minimum and maximum range and RMSDz for each polygon. The project-wide results are shown below in Table 8; polygons locations for the large block are shown in Figure 5.

Table 9. Intraswath Results

FID	dZ_MAX (m)	dZ_MIN (m)	RMSD (m)
0	0.054	-0.030	0.023
1	0.070	-0.053	0.026
2	0.100	-0.096	0.031
3	0.077	-0.226	0.055
4	0.068	-0.076	0.034
5	0.083	-0.067	0.035
6	0.078	-0.053	0.030
7	0.044	-0.054	0.015
8	0.082	-0.043	0.037
9	0.046	-0.050	0.024
10	0.052	-0.023	0.026
11	0.089	-0.051	0.044
12	0.093	-0.056	0.031
13	0.075	-0.032	0.025
14	0.063	-0.055	0.031
15	0.075	-0.089	0.040
16	0.058	-0.083	0.026
17	0.047	-0.110	0.035
18	0.077	-0.028	0.027
19	0.066	-0.090	0.028

FID	dZ_MAX (m)	dZ_MIN (m)	RMSD (m)
20	0.099	-0.057	0.032
21	0.072	-0.096	0.035
22	0.063	-0.104	0.021
23	0.063	-0.082	0.029
24	0.060	-0.100	0.027
25	0.072	-0.043	0.021
26	0.041	-0.040	0.013
27	0.061	-0.085	0.028
28	0.072	-0.092	0.027
29	0.058	-0.073	0.023
30	0.074	-0.034	0.025
31	0.085	-0.098	0.034
32	0.064	-0.148	0.058
33	0.056	-0.077	0.025
34	0.109	-0.040	0.029
35	0.065	-0.069	0.027
36	0.065	-0.074	0.024
37	0.038	-0.068	0.018
38	0.068	-0.074	0.022
39	0.083	-0.065	0.025

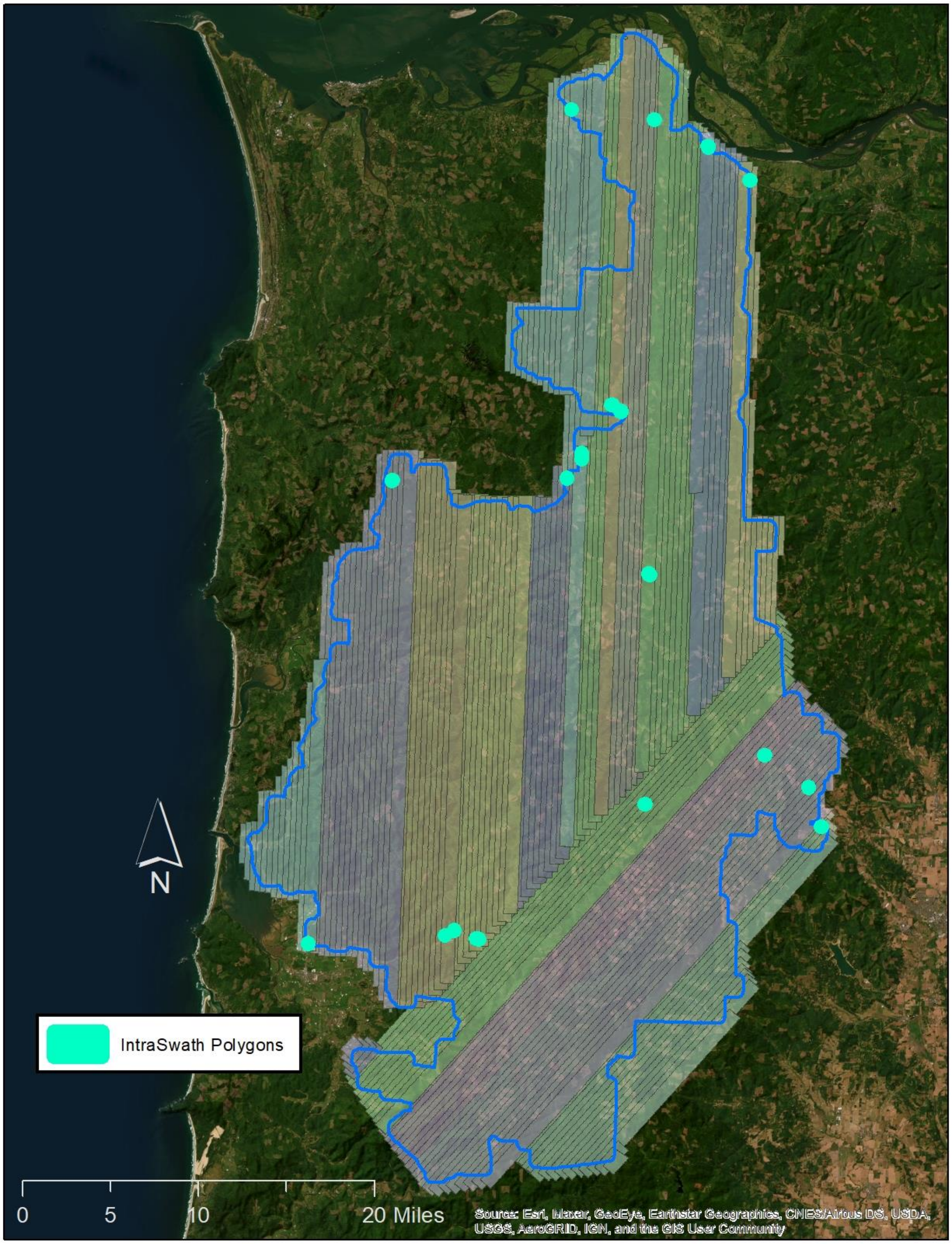

Figure 5. Location of IntraSwath polygons used for assessment of swath precision for the Clatsop – Trask-Nehalem AOI

3.7 Point Density

Aggregate point density within each project area is based upon acquisition at a > 50% swath overlap with a planned average of ≥ 4 points/m² for each strip to meet a final overall acquired density of ≥ 8 points/m² for first return pulses. Density for each site was calculated using *LP360* using nominally created 100'x100' tiles. First return and ground-classified lidar density for each project site is shown in Table 10, below.

Table 10. Lidar density results for first return and ground-only points, by area.

Block	**Clatsop-Nehalem-Trask**	**Burnt Woods**	**Gates**
First Returns (pts/m²)	13.9	14.0	13.6
Ground Returns (pts/m²)	2.0	1.8	1.3

3.6 Lidar Point Classification

Once the point cloud adjustment was achieved with desired relative and absolute accuracy, all data in LAS format were brought into classification software. Rigorous selection algorithms in *TerraScan* were used to automatically classify data and ensure accurate ground classification based on software parameters defined by the Lidar analyst. Data from the extreme edge of each swath, where most error occurs, was omitted during initial ground classification to increase quality. Ground identification was initiated at low-resolution seed points and increased in resolution and density with each passing review. A tailored approach was formulated for this project based on consideration of terrain and vegetation characteristics. While all identified high and low noise and overlap data was delivered with the final point could data, they are identified using a withheld bit flag are to be ignored.

A manual review of auto-classified point data was performed to refine the ground-classified surface points where the automated process had limited success, thus improving the final bare earth surface. Manual review was assisted by evaluation of maximum surface rasters for high noise and bare earth surface rasters to find low noise and other misclassifications. Finally, hydro-breaklines were manually created. All points within the bounds of identified hydro breaklines were classified as water points. In addition, bridge breaklines were manually collected and used to classify all points on the top of each bridge deck. Bridge points were removed from the final bare earth surface. Additional breaklines at the top and bottom of each bridge were collected to sharply defining these features in the final DEM. Software used for Lidar classification and review included TerraScan, LP360, and ArcGIS.

3.7 Hydrologic Flattening

Hydrologic breaklines were manually collected using ground-classified data on all bodies of water greater than 2 acres and on rivers and streams greater than 100-feet in width. A downstream constraint was applied to rivers and streams to ensure an equal elevation was maintained on both banks and provide an improved appearance to the final ground model. Ground points within 2-feet of hydro breaklines were reclassified as Class 20 (Ignored Ground).

3.8 Bare Earth or Digital Elevation Model (DEM)

Classified ground point data were combined with all breaklines to create a digital elevation model (DEM) at a 1-foot resolution. The resulting model was cut into 3000’x3000’ tiles and delivered in a 32-bit floating GeoTIFF format. A final QC was performed on the resulting Bare Earth raster data to verify no anomalies remained after previous review processes and edits.

3.9 Maximum Surface Height Surface Model (DSM)

An additional maximum height surface model or digital surface model (DSM) was created using all unflagged data (excluding all flagged noise points). The resulting data was used to create a 1-foot resolution raster data set which was cut into 3000’x3000’ tiles and delivered in a 32-bit floating GeoTIFF format.

3.10 Swath Separation Rasters

Swath separation rasters were created at a resolution of 4 ft using all unflagged data (excluding all unflagged noise points). Resulting data was utilized to analyze the difference in elevation between overlapping flight lines. Resulting date was delivered in GeoTIFF format and color-coded as required by USGS 3DEP Lidar Base Specifications.

3.11 Metadata

FGDC-compliant metadata was produced in XML format to include a complete description of the project, purpose, vendor information, acquisition planning, results and dates, processing steps, and quality control results. One XML-formatted metadata was submitted for each of the following products:

- Classified Lidar Point Cloud
- Bare Earth (DEM) Raster
- Max Surface Height (DSM) Raster
- Breaklines

4. Accuracy Assessment

4.1 Horizontal Accuracy

This data set was produced to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 0.57 ft (17.4 cm) RMSEx / RMSEy Horizontal Accuracy Class which equates to Positional Horizontal Accuracy = +/- 1.4 ft (42.7 cm) at a 95% confidence level.

4.2 Cloud Point Testing

Vertical accuracy of the point cloud data was tested for Non-Vegetated Vertical Accuracy (NVA) and Vegetated Vertical Accuracy (VVA) using independent QC checkpoints collected by a licensed surveyor. Points were distributed throughout the project as best possible given constraints of heavily forested and mountainous terrain and property access. All points were located on ground with less than 10° slope. NVA points were located on hard flat surface free of any vegetation and VVA points were selected in multiple vegetation types such as grass, brush, and forested conditions. A separate survey report provides methodology, data sheets and photos of field-collected QC points.

Assessment of the ground data was performed creating a Triangulated Irregular Network (TIN) from the final calibrated and classified point data and comparing it to the surveyed checkpoint. Results and number NVA and VVA for the assessment are shown in Table 11. A graphic showing distribution of all checkpoints and control are shown in Figure 6.

Table 11. Results of NVA and VVA Checkpoint Assessment

TYPE	Data Tested	RMSEz	95% CL	Points Used
NVA	Point Cloud	0.04 m	0.08 m	102
	DEM	0.04 m	0.08 m	
VVA	Point Cloud	NA	0.27m	77
	DEM	NA	0.27 m	

4.3 Digital Elevation Model Testing

Similar accuracy testing was performed on the Bare Earth surface. A hydro-flattened DEM raster model was created at a 1-foot resolution and used as a comparison of the same set of NVA and VVA checkpoints. The difference in accuracy results between the two data types were the same. Results are shown in Table 11, above. A graphic showing distribution of all checkpoints and control are shown in Figure 6, below.

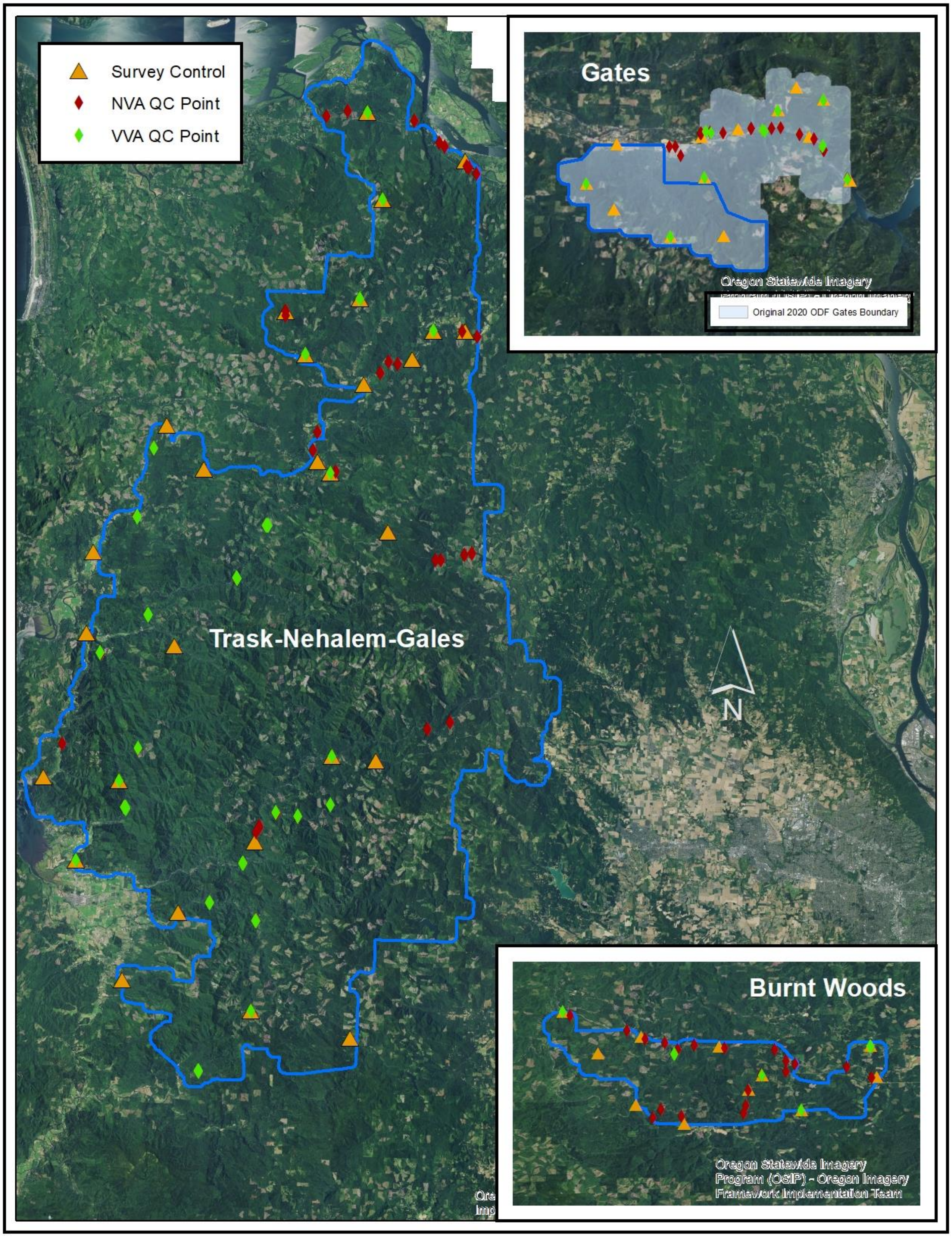

Figure 6. Location of all survey control and QC checkpoints used for adjustment and evaluation of the final data.